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FIRE STUDIES IN JARRAH (EUC.MARGINATA SM.) FOREST

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ABSTRACT

Jarrah (Euc. marginata Sm.) forms a dry sclerophyll forest in the south-west of Western Australia. In spite of the inherent fire resistance of this species the combination of hot, dry summers and inflammable fuels has resulted in many severe and damaging fires in this commercially important forest.

Fire control in jarrah relies heavily on large annual programmes of controlled burning as well as on efficient fire suppression. Experience with these operations showed the need for more detailed information on fire behaviour and for a reliable means of predicting it.

A review of literature and other fire danger systems suggested that rate of forward spread would be suitable for planning fire operations, and that moisture content, fuel quantity and wind velocity would be controlling influences. Information on these variables was gathered in two series of trials: one measuring rates of drying for jarrah leaf litter, and the other measuring experimental fires lit in the forest.

Practical difficulties in day to day measurement of moisture content made it necessary to select a proxy variable. This lay to hand in fire hazard, a standardized scale used daily during the fire season for forecasting the inflammability of forest fuels, and as a general fire warning to the public in Western Australia since 1934.

There were, however, several weak points in the fire hazard system which had to be overcome before it met the requirements for a fire danger rating. The prediction of fire hazard required the use of specially prepared pine hazard rods. Three rods are kept on a mesh screen, nine inches above the ground, and weighed at two-hourly intervals during the day. This made it impractical for small forest centres with a restricted staff. Furthermore, the hazard rods do not follow closely moisture changes in leaf litter after rain. Being placed nine inches above the ground, they generally dry much faster.

It was necessary, in the experimental work described here, to make two major additions to the fire hazard system. The first was to provide a means of predicting fire hazard during normal dry summer weather from measurements of air temperature and relative humidity. The second was to provide a more realistic adjustment for effects of recent rain.

The first requirement was met by a separate study (Hatch, 1969). The second requirement was met by using rainfall correction factors which depended on (i) amount of last rain, (ii) days since rain, and (iii) average daily temperature in the drying period.

Rate of forward spread of headfire was used to express the degree of fire danger. Fire hazard was linked with wind velocity and fuel quantity to predict rate of forward spread. Short-cut graphic analyses were used to define the effect of each variable on rate of spread. Finally all three variables were put together in five tables, which made up the fire danger rating now used in jarrah forest.

Part of the fire danger rating was later expanded to show the height of crown scorching from different spread rates, and the desirable spacing for fires in lighting of controlled burning. This information formed the basis of the controlled burning guide now used in jarrah forest.

Further analyses were undertaken with multiple regression methods to test the strength of wind, fuel quantity and moisture content in controlling rate of spread. Fuel weight proved a weak variable and would have been better expressed by fuel depth or cover. Moisture content of the litter profile seemed better replaced by surface leaves and weather variables. Wind was an overriding control over spread rate within the limits of this data.

Following the experimental work a management plan was drawn up for using this fire danger rating and controlled burning guide in planning fire operations. For controlled burning anticipated rates of spread were used to prescribe correct conditions for lighting and grid patterns for placing the spot fires lit to burn out the area. For fire suppresiion, anticipated rates of spread formed a basis for day-to-day disposition of fire suppression forces and aided the planning of fire attack strategy.

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Chapter 1

INTRODUCTION

The Fire Control Problem

Due to climate and fuels, the jarrah (Euc. marginata Sm.) forest has presented major difficulties in fire control since the West Australian Forests Department was established by the State Government in 1918. This forest covers approximately 3,000,000 acres, broken up for management purposes into divisional areas of 200,000 to 500,000 acres.

Fires in the jarrah usually occur during the summer months of every fire season, but the records of most divisional headquarters over the years show outbreaks on the scale of the Plavin's fire of 1950 which burnt over 20,000 acres in the Dwellingup division, the Bell fire of 1959 and the Boorara fire of 1969 in the Harvey and Walpole areas, which caused comparable economic losses, (Anon. 1969).

The greatest fire disaster in the State's history, the Dwellingup fires of 1961, burnt over 350,000 acres of prime jarrah forest, practically obliterated three small townships, the main one being the mill town of Dwellingup itself, and caused damage estimated at $2,000,000 (Rodger, 1961). Forest damage alone was approximately $700,000 (Peet and Williamson, 1968). The 1960-61 fire season was the most severe on record in Western Australia, and brought a series of outbreaks throughout the south-west of the State as well as the Dwellingup disaster.

Because of its durability, strength and finishing qualities jarrah is a valued commercial timber, used extensively in building, also for sleepers, poles, piles and fence posts, because of its resistance to decay, and to a lesser degree in furniture and veneers. The export market for jarrah is also important.

The proximity of the northern jarrah forest to the Perth metropolitan area, where the population has now reached 600,000, gives the State forests an additional value for water catchments and recreation.

Fires in the jarrah ignite from a variety of causes, including lightning strikes, associated with summer thunderstorms which often develop during severe fire weather. During the Dwellingup fires lightning strikes caused the almost simultaneous ignition of 23 fires scattered over a wide area. Since lightning will always be with us, it seems impossible to exclude fire from the jarrah forest altogether.

Fire control problems in jarrah forest have received considerable attention from West Australian foresters, and early studies on fire weather produced a system for forecasting or measuring fire hazard (Wallace, 1936). This is still used as a basis for planning fire control in jarrah forest. In addition to maintaining a large fire detection and suppression organisation, the W.A. Forests Department administers fire control within a two-mile radius of State forest boundaries under the Bushfires Act of 1954.

Experience in past years showed, however, that local co-operation, boundary control and an efficient detection and suppression organisation were not in themselves sufficient to exercise effective fire control. Consequently in 1953 these precautions were supplemented by an extensive annual programme of preventive controlled burning. This programme was increased in 1961 after the Dwellingup fires, and most of the jarrah forest is now burnt periodically, the programme (including aerial burning) covering about 750,000 acres annually.

The term "controlled burning" implies that fire is applied to the forest at a specified intensity compatible with an acceptable level of forest damage. Despite an inherent fire resistance small jarrah trees are damaged by intense fire, and it is essential that controlled burning be properly planned. To apply fire at predetermined intensities calls for the fullest possible information on fire behaviour, as well as the presentation of this information in a form suitable for field use.

Experience gained in extensive controlled burning programmes, as well as with improved fire suppression techniques, has thus demonstrated a need for intensive studies of fire behaviour in jarrah forest.

Furthermore, the growing awareness of conservation as an issue in Western Australia makes a sound knowledge of fire behaviour more important than ever. In the climate of public opinion now developing, large-scale controlled burning will only be an acceptable departmental policy if assurances can be given that the flora and fauna of the forest will be preserved at the same time. Neglect of fire behaviour studies could open up opportunities for criticism of ecological management of the jarrah forest. Foresters must not only forestall such criticism but be equipped with facts and figures to answer it.

The fire behaviour studies here described were, however, primarily aimed at improving the techniques for fire suppression and controlled burning. They were carried out by the author as part of the fire research programme of the W.A. Forests Department.

Fire behaviour studies in jarrah forest were started by A.G. McArthur* in 1958 and continued by the author between 1961 and 1965. The data collected by McArthur contributed to his controlled burning guide published in 1962 and his fire danger meter (1964-66), both of which are excellent examples of the practical utilization of fire behaviour information.

In 1964 a fire danger rating with an associated controlled burning guide was compiled for the northern jarrah forest (Peet, 1965). The controlled burning guide is used for planning and executing an annual controlled burning programme approximating 750,000 acres, and latterly has been linked to an advanced lighting technique involving the use of aircraft (Packham and Peet, 1967).

*Protection Officer. Forest Research Institute, Canberra.

The fire behaviour studies reported here have made a tangible contribution to management techniques for the jarrah forest. Their purpose was to provide an objective estimate of fire behaviour on which to plan controlled burning or fire suppression on any given day. From a management point of view most of the work has been productive and effective. It remains to set out what the investigations were, and how the data was analysed and put together in an expression of fire behaviour.

Outline of the Thesis

The research was centred at Dwellingup, a small township about 60 miles south-east of Perth. In the early years (1961-64) computer facilities were not readily available for this work, and the staff consisted of three men with limited experience of fire measurement and limited equipment. It was soon apparent that both the experimental techniques and analyses would have to be simple, and the data presented in an easily understood form suitable for field use.

It was decided to follow the techniques developed by McArthur for measuring forest fire behaviour. He recorded the performance of numerous experimental fires in the forest, then equated their intensities to changes in forest and weather variables. This was a simple technique which could be handled with the available facilities. One more experiment was added to measure rates of drying of jarrah leaf litter after rain.

Chapters 1 and 2 of this thesis describe the jarrah forest, the fire problem and the fuels. The question of what to measure to express fire behaviour is discussed in Chapter 3, and the experimental techniques in Chapter 4. Chapter 5 deals with the concept of fire hazard as a first step in the fire danger rating, and expresses fluctuations in moisture content of leaf litter on the fire hazard scale.

The fire danger rating is developed in Chapter 6, in which wind velocity and fuel quantity are added to fire hazard to predict changes in fire behaviour. These results are evaluated in Chapter 7 with further analyses using multiple regression techniques, and suggestions are made for future work. Chapter 8 sets out the controlled burning guide and how it is used.

A management plan incorporating both the controlled burning guide and the fire danger rating has been drawn up for use in planning day-to-day fire operations, and is considered an indispensable instrument of fire control in the jarrah forest to-day.

Chapter 2

THE JARRAH FOREST

Location

The jarrah forest lies in the south-west region of Western Australia, located in the area shown in Figure 1.

The northern jarrah forest forms a narrow belt extending from Mundaring in the North to Kirup in the South. This belt is approximately 120 miles in length and 20 to 30 miles in width. The main part of the commercial forest is found on the plateau of the Darling Scarp. The Scarp forms the western boundary of the commercial forest, following the Darling Fault, although a poor class of jarrah is also found on the coastal plain. To the east, rainfall tapers off and the jarrah forest grades into Wandoo, (*Euc. redunca* Sch., *var elata* Benth.).

The southern jarrah forest lies in the lower south-west region near the coast and forms a belt extending from Kirup to the south of Manjimup. The prime forest belt is approximately 60 miles in length and 20 miles in width and grades into poor forest types along the coast and in the eastern areas.

Climate

The climate of the jarrah forest is a Mediterranean type with hot, dry summers and cool wet winters (Gentilli, 1956).

The average rainfall isohyets for the south-west region are shown in Figure 2, and indicate that the main commercial forest lies within a limit of 30 inches a year. Certain areas along the Darling Scarp receive in excess of 50 inches a year.

FIG. I
FOREST TYPES

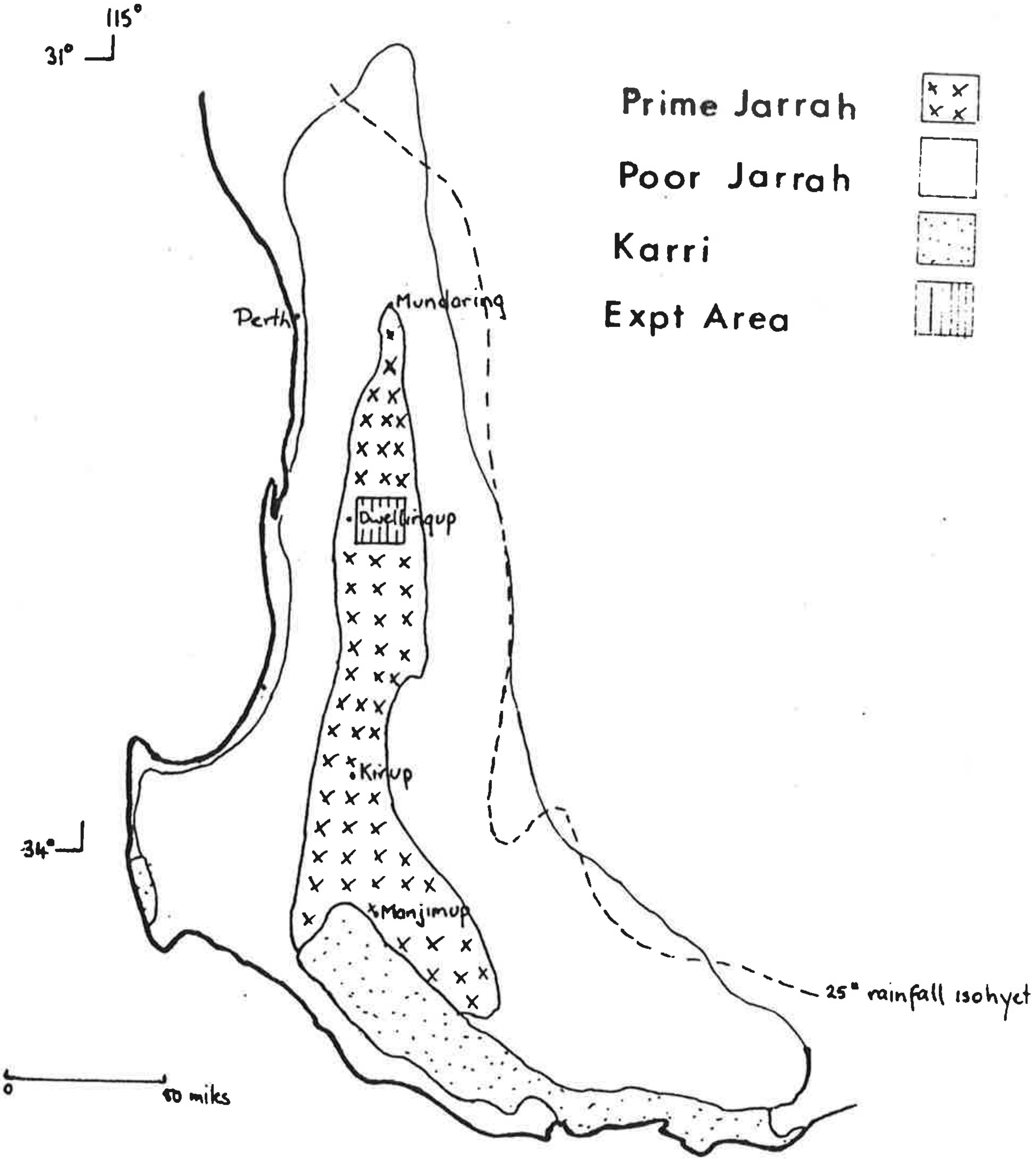
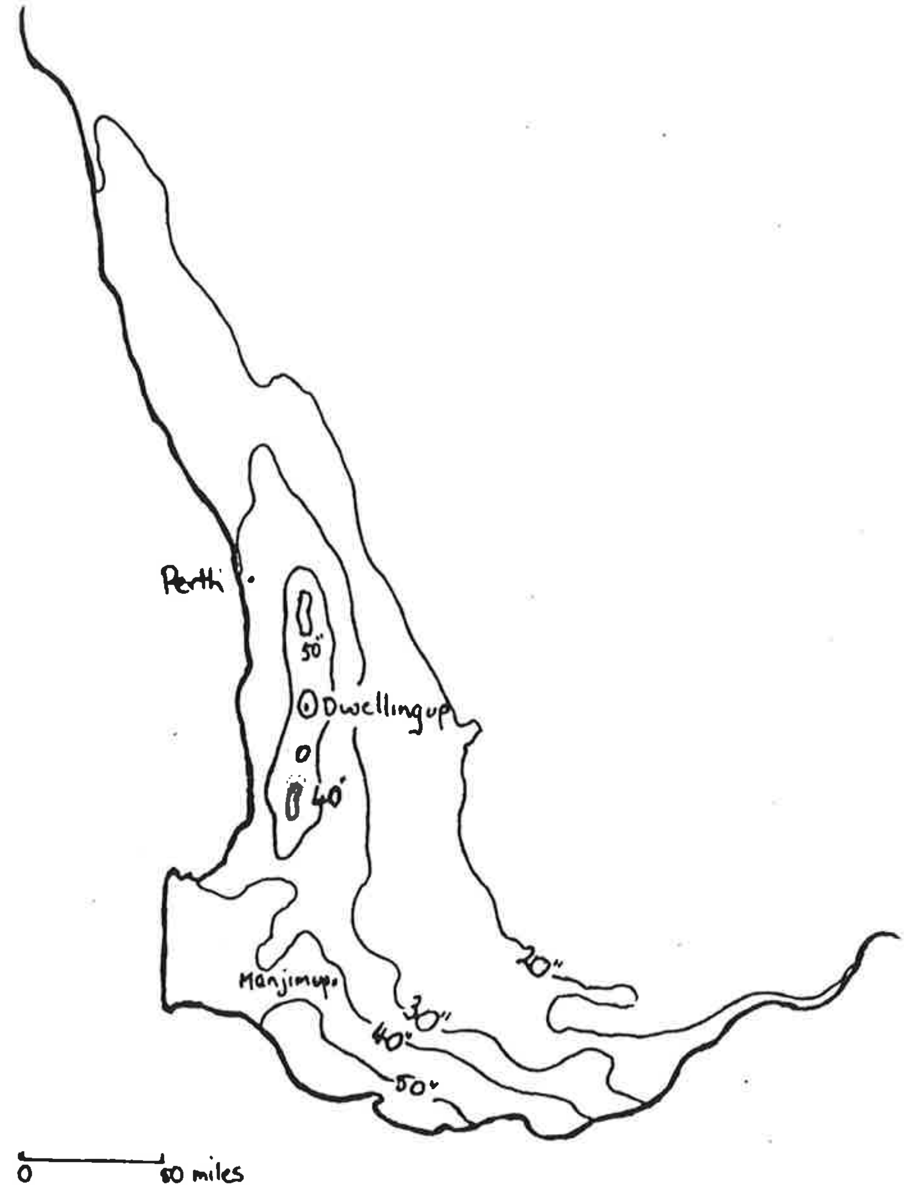


FIG 2

RAINFALL ISOHYETS



The long, hot dry summers experienced in the northern jarrah forest are illustrated by the monthly average for maximum temperature and rainfall at Dwellingup shown in Graph A. This climate moderates as the lower west and south coasts are approached, and in general the fire season in the southern forest is less severe (Hatch, unpublished data, 1961 to 1969).

A cross-Section of meteorological data for the jarrah forest is given in Appendix 1, which lists climatic averages for Perth, Dwellingup, Donnybrook and Manjimup. The averages suggest that rainfall increases and temperature decreases from Perth southwards to Manjimup, except for the Dwellingup area which has an unusually high rainfall.

The major part of these fire behaviour studies was conducted in the northern jarrah forest surrounding Dwellingup (Figure 1). Rainfall in the Dwellingup forest area is illustrated by Table 1. This shows the marked decrease in annual rainfall to the east and west of the Darling Scarp, while the Mediterranean character of the climate is evident in the monthly distribution, (Appendix 1).

Graph 1

Monthly Averages Dwellingup

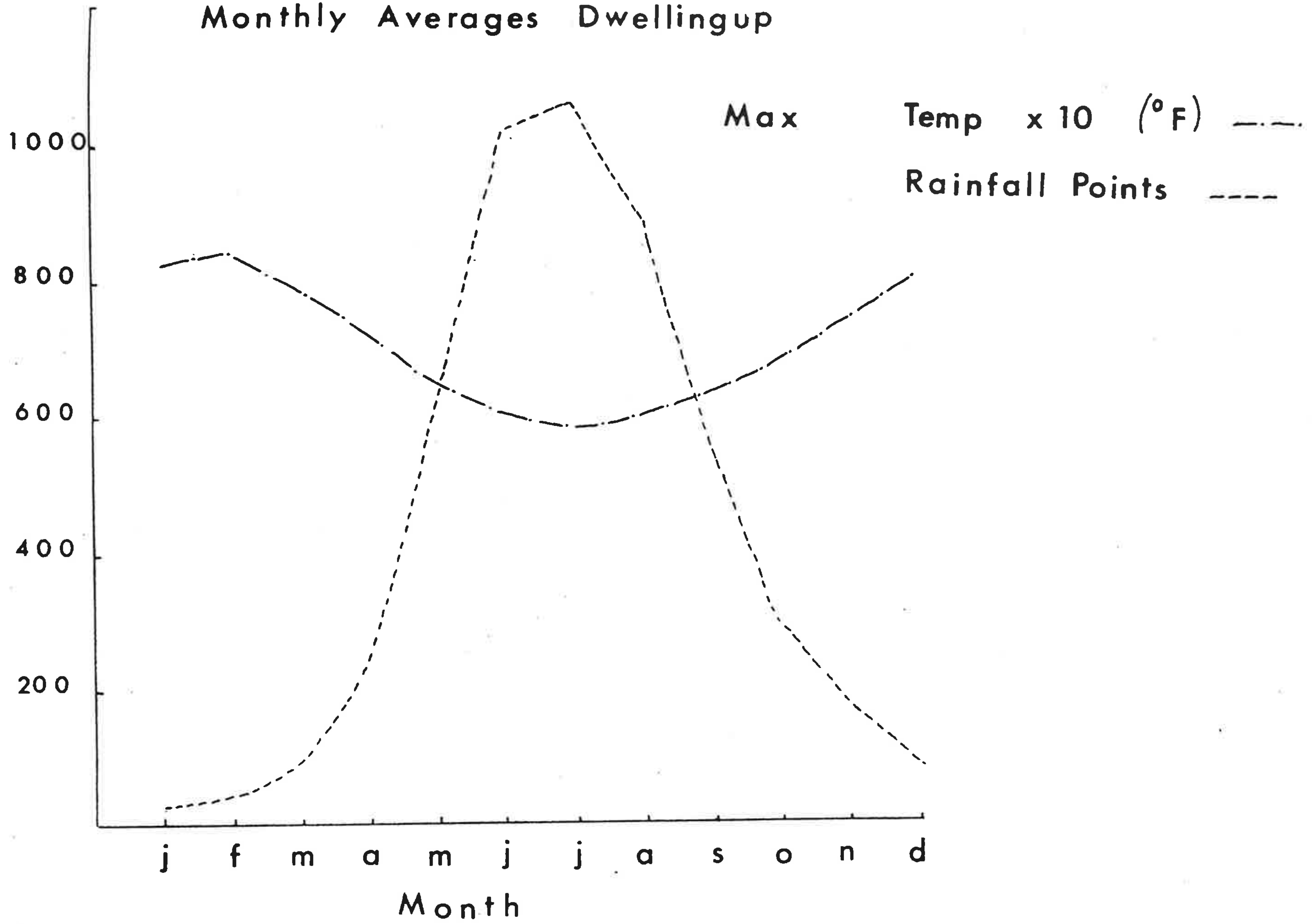


TABLE 1

(a) Annual Rainfall (inches) for Stations East and West of Dwellingup

Station	Height above s.l.	Distance from W. coast Miles	Annual rainfall ins.	Period of measurement
Mandurah	15	0	34.52	1911 to 1940
Pinjarra	28	14	36.74	1911 to 1940
Dwellingup	890	26	51.42	1927 to 1953
Duncan's Mill*	1000*	41	31.96	1934 to 1943
Marradong*	1000*	47	29.75	1911 to 1940
Wandering	1111	61	26.95	1911 to 1940
Narrogin	1114	69	20.93	1911 to 1940

* approximate values only.

No direct evaporative data is available for the jarrah forest, but Appendix 1 shows monthly values calculated from Prescott's Formula (Hatch, 1964).

From the calculated P/E ratio it can be seen that effective rainfall in the average year occurs in the seven-month period between April and October.

Topography and Soils

The topography on the plateau of the Darling Scarp for the most part is gently undulating. The plateau has suffered little dissection by erosion, and steep slopes are usually confined to the valleys of major watercourses and to the western edge of the plateau along the Darling Scarp.

The rocks of the Darling plateau are mainly pre-Cambrain granites, and often gneissic in structure (Julson, 1934). These granites are seamed by basic dykes, usually of epidiorite. Rock outcrops are rare because the whole plateau is covered by a mantle of laterite, which may be massive or lateritic gravel. The evidence suggests that the laterite cap was formed during the late Miocene or Pliocene period and that subsequent dissection occurred during the Pleistocene period.

The surface soils are generally well drained; they consist of more than 50 per cent lateritic ironstone gravel in a sand matrix, while at depth kaolinitic clay is encountered. These topographic and soil features create generally more uniform and rapid rates for the drying of litter beds than are found in the southern forest.

The soils of the Dwellingup area were described by Hatch (1955) and the geology of the nearby Gleneagle district by Holland (1949).

Forest Type

The study area of 200,000 acres of jarrah forest near Dwellingup (Figure 1) was a typical cross-section of the northern jarrah forest, from the Darling Scarp to drier eastern forest. This cross-section was fairly representative of forest types between Mundaring and Kirup which tend to show fairly uniform changes in a west-to-east direction through the forested belt.

General Description

The jarrah forest is a dry schlerophyll type. It is normally associated with a sparse scrub cover and undulating topography.

Jarrah (Euc. marginata Sm.) is usually found in association with marri (Euc. calophylla, Lindl.) which comprises about 10 to 15 per cent of the forest stocking.

On moister sites jarrah is found with West Australian blackbutt (Euc. patens, Benth.), bullich (Euc. megacarpa, F.V.M.) and flooded gum (Euc. rudis, Endl.). On the Darling Scarp wandoo (Euc. redunca, Sch., var. elata, Benth.) is found; and in the dry eastern forest jarrah grades into both wandoo and powderbark (Euc. accedens, W.V. Fitz.).

With the exception of bullich, wandoo and powderbark, most of the indigenous eucalypts in the jarrah forest are rough-barked.

The understorey species usually include casuarina (C. fraseriana, Miq.F.), bull banksia (B. grandis, Wield) and persoonia (P. longifolia, R.Br.)

The litter of both casuarina and bull banksia burns readily, and the crowns of casuarinas are highly inflammable.

Jarrah itself is a stringy-barked tree with persistent fibrous bark extending to the smaller branches. This bark is inflammable during summer (Peet and McCormick, 1965), and girth decrements of up to 2 inches have been measured on pole-sized trees after intense fires (Peet, unpublished data, 1964).

The mature jarrah tree in good-quality forest is usually 90 to 130 feet high, but prime ones may reach 150 feet (Loneragan, 1961).

As with most eucalypts, lateral shade is greater than vertical shade, and the crown is composed of heavy branches with a thin, leaf canopy. These crown characteristics assist in creating fairly rapid drying conditions for the underlying beds of leaf litter.

Crown cover varies between 40 and 70 per cent of the forest floor, which can have quite marked effects on the rate of litter accumulation.

Jarrah has the ability to develop epicormic shoots, a characteristic that enables it to recover from defoliating fires and is thus an important feature of its inherent fire resistance.

Evidence suggests that jarrah forms annual growth rings (Loneragan, 1961; Podger and Peet 1964) and that the main part of this annual growth is laid down in two surges, one in spring and a second in autumn.

Loneragan (1961) suggested that new leaves in the jarrah crown are developed annually, commencing in December and maturing by March.

The surges in annual growth, and the period of leaf replacement, are considerations in minimising damage from controlled burning (Peet, 1964).

<u>Stand Structure</u>

The jarrah forest near Dwellingup includes a range of size classes from large over-mature trees to saplings. Table 2 presents the distribution of girth classes for jarrah trees on 220 one-acre plots randomly located in the study area. Numbers of trees per acre are averages from these plots, and have been listed in size classes for girth breast height over bark.

TABLE 2

Dwellingup Study Area

Number of jarrah trees per acre in G.B.H.O.B. size classes

dbhob cm	G.B.H.O.B. size classes	Number of trees per acre	St/ha
29	1" to 3'	239.100	591
39	3'1" to 4'	6.700	17
49	4'1" to 5'	3.700	9
58	5'1" to 6'	2.500	6
68	6'1" to 7'	2.000	5
78	7'1" to 8'	1.500	4
87	8'1" to 9'	0.900	2
87 - 114	9'1" to 12'	1.000	2
	12'1" to 15'	0.200	
	15'1" to 18'	0.020	
	over 18'	0.005	
	Total	257.625	

It will be seen from Table 2 that although the forest in the study area includes a wide range of girth classes, by far the greatest number of trees per acre lies in the small-pole and sapling sizes.

Scrub Types

Scrub is recognised as an important fuel component of fire behaviour in jarrah forest, and one whose effect varies with species, age, density and height.

McCormick (1966) showed density and moisture content of scrub foliage to be important for regulating rates of burning of scrub species. Foliar moisture content varied seasonally and diurnally, suggesting that inflammability of foliage may not be constant. In addition, this work demonstrated that scrub in jarrah forest should usually be considered as additive fuel - one which burns after pre-heating and ignition from fires in litter.

This evidence suggested the need for detailed fire behaviour experiments to study the effect of scrub foliage as fuel. Before commencing this work it was considered desirable to provide quantitative estimates of scrub species and their density, so that the more important ones could be selected for study.

The assessment described here attempted to define scrub species and density in the experimental area near Dwellingup. It was designed to provide a broad definition of these species in the main forest area; particular site differences were therefore minimised as much as possible.

Three factors of environment were considered in the design of the assessment.

Site differences were minimised by confining the plots to upper slopes or ridge tops. Observation suggested that moister sites in gullies or flats supported rather different scrub types than the drier slopes. These moister sites would confuse the results unless treated separately, and did not represent a major part of the experimental area.

Table 1 shows averages of annual rainfall in this area to decrease from the Darling Scarp eastwards. Canopy cover of the forest also lessened in the east, although influenced by past cutting for sawmilling. In view of these changes a decision was made to subjectively divide the experimental area into three strata, each eight miles in width on an east-to-west axis and 20 miles in length. Stratum 1 lay in the high rainfall area on the Darling Scarp, and Stratum 3 in the drier eastern forest. Stratum 2 covered the forest belt between these two extremes.

Scrub type in each stratum was described from 50 systematically located plots, spread as evenly as possible over the area on a 1.5 miles grid. These plots provided 2000 square feet of assessed forest floor in each area stratum.

The area strata were an attempt to provide some control over decreases in annual rainfall. This concept agreed with a theory by Byram and Keetch (1968) that the density of vegetation could be considered a reflection of annual rainfall.

Past fire history was the third factor of the environment considered in the design of this assessment. Research in Canada and South Africa (e.g., Dixon 1965) suggested fire frequency and intensity to be variables affecting the structure and type of scrub. This was supported by field observations in jarrah forest, where it appeared that members of the family Leguminosae, in particular, were affected in their regeneration by past fire intensity.

Part of the experimental area was burnt by the Dwellingup fires of January 1961 (Rodger 1961, Peet and Williamson 1968). After these fires a map of forest crown damage was prepared from aerial photos. This map showed three main classes of crown damage: defoliation, fully scorched, and lesser damage which left the upper crowns green. To these three classes was added a fourth, controlled burning with limited crown scorch above 20 feet in height. These four classes were used to represent the intensity of past fires, ranging from very intense, which caused defoliation, (Peet and Williamson 1968), to the mild ones used for controlled burning, (Peet, McCormick and Rowell, 1968).

The damage classes were compared by assessing five or six plots in each for Strata 1 and 2. Stratum 3 was deleted from this study because of very little defoliation or full scorching had occurred in this area. For Stratum 1, 200 square feet of assessed area was compared in each class and for Stratum 2, 240 square feet was compared.

Each plot consisted of 10 sampling units spaced at 1 chain intervals along a 10 chain line (Figure 3). One sampling unit covered four-square-feet of forest floor.

Figure 3.

Diagram of a Scrub Assessment Plot

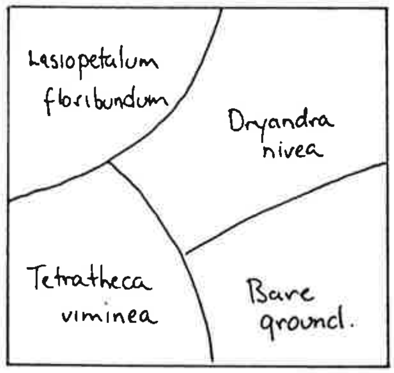
Scale 1 inch = 2 chains

Within each sampling unit species were identified and mapped for area coverage by ocular estimate. (Figure 4)

Figure 4

Example of a Mapped Sampling Unit

Scale 1 inch = 1 foot



The 10 sampling units in each plot were combined to provide 40 square feet of forest floor where species and their area coverages were recorded. Finally the plots within an area stratum or crown damage class were combined to provide an area of forest floor where scrub species and their area coverages were listed individually. This detailed analysis for the area stratum is shown in Appendix 2.

Table 3 presents a summary of results from the area stratum by listing the number of species, the number of times they were observed, and the area covered by scrub in the 2000 square feet of assessed area.

Table 3

Summary of Scrub Coverage in each of the Three Strata

Stratum 1				Stratum 2				Stratum 3			
No. Fam.	No. Spec.	No. Obs.	Area covered sq.ft.	No. Fam.	No. Spec.	No. Obs.	Area covered sq.ft.	No. Fam.	No. Spec.	No. Obs.	Area covered sq.ft.
27	107	783	630	31	105	1058	982	31	112	1120	970

There were between 105 and 112 species, suggesting roughly equal numbers in each stratum. These species were observed more frequently in Strata 2 and 3 than in Stratum 1 and covered a greater part of the assessed area.

There was no apparent relationship between decreasing annual rainfall and a lowering of scrub density; in fact, scrub density seemed to increase in Strata 2 and 3.

For Stratum 1, with the highest rainfall, identified species covered 31.5 per cent of the assessed area, 49 per cent in Stratum 2, and 48.5 per cent in Stratum 3, where annual rainfall was lowest. To these must be added areas of scrub which were not identified due to lack of flowers or fruits These covered 4.7 per cent of the assessed area in Stratum 1, 5.1 per cent in Stratum 2, and 7.4 per cent in Stratum 3.

The total percentages for Strata 2 and 3 were similar and higher than the less dense scrub in Stratum 1.

The list of species in Appendix 2 shows some species to occur more frequently and cover greater areas than others. This assessment set out to define the most common and dense species for future fuel studies.

From Appendix 2 a list was made of those species observed on more than 10 plots in a stratum, and the area covered by each was recorded. This list defined the most common species in each stratum, and they covered between 69 and 92 per cent of the total scrub area in the three strata. This suggested that they were the most important ones for fuel studies.

Some of the common species covered a considerably greater area of forest floor than others. A further subdivision was employed to define the former.

Species covering more than 20 square feet of the assessed area in each stratum, and observed on more than 10 plots are listed in Table 4. They were divided subjectively under two headings: inflammable types and less inflammable types. This division was based on field observations of flare in the various scrub species during experimental fires, and an assessment from that of their inflammability.

The species listed under "Inflammable Types" in Table 4 are those which should receive priority in further fuel studies Their inflammability will depend on the age of foliage, which affects degree of curing. This is quite evident in Xanthorrhoea foliage, which burns readily once several years of dead needles have accumulated.

TABLE 4

Species covering more than 20 square feet of Forest Floor

Stratum	Inflammable Types	Less Inflammable Types
Stratum 1	Xanthorrhoea preissii Endl. Loxocarya flexuosa (R.Br.)Benth. Xanthorrhoea gracilis Endl. Dryandra nivea R.Br.	Acacia strigosa Link. Hibbertia amplexicaulis Steud. Bossiaea ornata (Lindl.)Benth. Adenanthos barbigera Lindl.
Stratum 2	Xanthorrhoea gracilis Xanthorrhoea preissii Dryandra nivea Acacia pulchella R.Br. Pterdium aquilinum	Hibbertia amplexicaulis Hibbertia montana Steud. Scaevola striata R.Br. Bossiaea ornata Lasiopetatum floribundum Benth Macrozamia reidlei (Gaud) C.A. Gard Acacia strigosa Acacia drummondii Lindl. Trachymene compressa
Stratum 3	Loxocarya flexuosa	Macrozamia reidlei Hibbertia hypericoides (D.C) Benth. Patersonia occidentalis R.Br. Hibbertia montana Brachyachne prostrata Bossiaea ornata

Loxocarya flexuosa, R.Br. has a fine foliage which seems to burn at faster rates than either *Dryandra nivea* R.Br. or *Hakea lissocarpa*, R.Br.

Acacia pulchella R.Br. often grows in dense clumps after severe fires and can produce intense flames.

Assessment results for the four crown damage classes are summarized in Table 5. Defoliation was deleted from Stratum 2 because this damage class was lacking in the area.

TABLE 5

Summary of Scrub Coverage in Four Classes of Past Fire Intensity

Stratum	Defoliation				Fully Browned				Lesser Damage				Control Burn			
	No. Fam	No. Sp.	No. Obs	Area cov. sq.ft	No. Fam	No. Sp.	No. Obs	Area cov. sq.ft	No. Fam	No. Sp.	No. Obs	Area cov. sq.ft	No. Fam	No. Sp.	No. Obs	Area cov. sq.
No. 1	19	45	73	81	20	48	83	77	15	50	88	52	19	42	76	41
No. 2					20	59	136	158	22	64	137	113	22	50	96	79
Total					40	107	219	235	37	114	225	165	41	92	172	120

There were no pronounced differences in number of species between the four damage classes, except perhaps for controlled burning, where slightly fewer were recorded. The number of observations, and particularly the area covered by scrub, did appear to increase with rising fire intensity. The area covered rose from a 120 square feet total for controlled burning to 235 square feet for full scorch, and a similar trend seemed likely into defoliation. This trend could be expected from the observations of Harris and Wallace (1959) that the opening of the forest canopy by utilization and intense fire was important in increasing the density of scrub.

Rising fire intensity appears to have increased the suitability of sites for scrub growth rather than to have affected the number of species in the scrub layer. Further investigation revealed that some species were better adapted to make use of the environment created by intense fires than others. Members of the Leguminosae covered 38 per cent of the total scrub area in defoliation, 40 per cent in full scorching, 33 per cent in lesser damage, and only 21 per cent in controlled burning. The main species favoured by rising fire intensities were Acacia strigosa Link., Acacia pulchella R. Br., and Bossiaea aquifolium, Benth.

These species usually regenerate in dense clumps after a severe fire and could well be added to the list of species receiving priority for fuel studies, except perhaps Acacia strigosa, which is not generally considered highly inflammable.

Fire History

Historical records suggest that periodic fires have been a part of the environment of the jarrah forest since long before the coming of white man.

Early navigators saw fires along the coast of Western Australia, and some of their reported observations are listed below, (Table 6).

TABLE 6

Fire Reports from Early Explorers of Western Australia.

Explorer	Date	Latitude	Report
Pelsart	June 1629	24°S	Smoke at distance
Vlaming	Dec-Jan 1696-97	25 to 32°S	Fires
Jonck	March 1658	30°to 25°S	Fires at four points, one burning through the night
Volkerfen	February 1658	30° 40'S	Several fires

(References, Battye Library, Perth)

With the advent of British colonization, many more reports of fires became available to the researcher. In the summer of 1801-1802 R. Brown described fires burning close to the south coast of Western Australia. The Perth Gazette and Western Australian Journal reported native fires on 22nd February, 1833. In 1845 the Swan River News published a report by G.J. Webb describing native fires in the Perth area. In 1846 J.L. Stokes described the use of fire by natives for hunting.

In a recent review of West Australian fire history Harris and Wallace (1959), concluded that fires had been part of the environment prior to European settlement.

These authors point out that the aborigines were acquainted with the use of fire, and moved continuously over the forest area in search of food. Under these conditions it is inconceivable that accidental fires did not occur, apart from fires lit for hunting, to which must be added the perennial risk of fires from lightning strikes.

These early fires were probably periodic, and undoubtedly covered large areas, but is is doubtful whether they ever achieved the intensity of fires which followed forest and land utilization.

With the beginning of European settlement in Western Australia, in 1829, the exploitation of the forests resulted in the accumulation of masses of felling debris. These fuel accumulations supported conflagrations which increased in intensity as utilization progressed.

Early records indicate that utilization and fire resulted in marked changes in the stand structure. The virgin forest was open, with a sparse scrub cover. Utilization caused gaps in the canopy, resulting in a heavier growth of scrub and understorey species. The increase in ground fuel supported fires which reached up into canopy, causing severe crown damage. The damaging of tree crowns resulted in decreased competition for the site, and thus the density of scrub cover increased.

The intense fires that followed utilization led to severe, widespread forest damage in the ninety years preceding the passing of the Forests Act by the State Parliament in 1918. Since then the W.A. Forests Department has progressively overcome the problem of establishing fire control in the jarrah forest, at a considerable cost in expenditure and effort.

Early foresters in this State were alarmed by the extent of fire damage in the jarrah forest, and attempted to implement a policy which almost entirely excluded fire from the main part of forest areas. Policy at that time required light advance and top disposal burns, before and after a trade operation, after which the area was protected to permit regeneration to develop. These areas were protected by surrounding them with a burnt firebreak and maintaining an efficient suppression force.

After 15 to 20 years of this protection policy had elapsed, the accumulation of fuel on the forest floor was such that even heavy expenditure on men and equipment failed to contain fires under severe summer weather conditions. With the realization that total exclusion of fire was no longer a practical objective, a policy of area controlled burning was introduced into the jarrah forest in 1952.

This policy has resulted in periodic burning over the main part of the forest area at a prescribed fire intensity. These light periodic fires are applied to all areas excepting those requiring protection for regeneration purposes or for research.

Chapter 3

FACTORS AFFECTING FIRE DANGER

The principal objective for the studies reported in this thesis was the development of a fire danger rating for jarrah forest.

Davis (1959) defined fire danger and fire danger ratings in the following statement.

> Fire danger is the resultant of both constant and variable fire danger factors, which affect the inception, spread, and difficulty of control of fires and the damage they cause. Fire danger rating is a fire control management system that integrates the effect of selected fire danger factors into one or more qualitative or numerical indices of current protection needs.

This definition posed too large an objective for an initial attempt at a fire danger rating for jarrah forest. However, it was considered feasible to provide a simple basis for estimating one measure of fire behaviour, such as rate of spread. This would provide a valuable guide for planning fire control operations.

Nature of the Fire Danger Variables

Fons (1946) provided an example of one approach to the analysis of fire behaviour, using direct variables. He explained this concept by the theory of liquid flow, i.e.

> In the theory of liquid flow it is generally accepted that when a gas or liquid moves over a solid a thin film of liquid forms on the surface. This becomes thinner as the velocity of the fluid increases, and the thinner the film the more rapid will be the transfer of heat to the solid by convection, conduction and radiation.

This theory, and experimental work, led Fons to list several variables as having a direct effect on the propagation process of a fire. These included: Film conductance, a heat transfer factor for radiation, ignition temperature, fuel particle spacing, surface to volume ratio of the fuel, specific heat, density of the fuel and fuel temperature.

Instrumentation and facilities for measurement of direct variables posed fairly complex problems for this research section. These requirements were described by Fons (1946) and by Fons and Pong (1961). They involve measuring fire behaviour in regularized fuel beds within strictly controlled environments such as that produced in a wind tunnel. These requirements were not financially feasible here.

Another factor mitigating against the use of direct variables was the difficulty of measuring them under forest conditions, nor were they readily understood by practising foresters or the public. For these reasons the direct variable approach was not pursued in these studies.

Davis (1959) provided an example of a second approach to the measurement of fire behaviour; the use of indirect variables. Here, variables such as wind velocity, fuel quantity, fuel type and fuel moisture content were used to express rates of energy release from forest fires.

In the past, indirect variables have been more commonly used for fire behaviour studies. They are generally quite well understood by foresters and the public, and their measurement in the forest can often be achieved with fairly simple experimental techniques. For these reasons they were adopted for this study.

The use of indirect variables did, however, introduce errors of measurement into the data. By definition these variables tend to be substitutive rather than directly additive within an expression of fire behaviour. Also it seemed likely that interaction between the individual variables would occur.

McArthur (1962) used indirect variables in a fairly simple experimental technique which measured fire behaviour in the forest. This technique involved measuring the performance of individual fires and forest and weather variables which created changes in these fires.

Past researchers have compiled lengthy lists of forest and weather variables which affect fire behaviour, e.g. Davis, (1959). Measurement of some of these, e.g. air stability, required fairly complex instrumentation, beyond the facilities available for this project.

It was decided to adopt McArthur's experimental technique, but to limit the measurements to variables which could be handled with the available equipment.

A review of fire danger ratings (McArthur, 1962, Nelson, 1964) suggested fuel quantity, its moisture content and wind velocity to be controlling influences on fire behaviour. Each could be measured with McArthur's experimental technique.

The expression of fire behaviour for the fire danger rating required some consideration. After discussions with field foresters and a review of the McArthur and U.S.A. systems, it was decided to adopt rate of forward spread of headfire as the measure of fire danger. This expression of fire behaviour is extremely useful for planning both controlled burning and fire suppression (Peet, 1967).

The literature review which follows sought answers to the question of whether fuel quantity, fuel moisture content and wind velocity would exert major controlling influences over rate of forward spread.

Literature Review

Fuel Quantity

Byram (1957) considered fire behaviour as an energy phenomenon, with fuel constituting a fundamental control. He listed four aspects of fuel which affect the rate of energy release from a fire. These were: the combustion period, critical burn - out time, available fuel energy and total fuel energy.

As rate of spread is a resultant of fire energy, it is apparent that fuel would provide a controlling influence over it. All four of the fuel variables influencing fire energy are affected by moisture content. It was likely, therefore, that total fuel quantities would have little meaning unless considered in terms of moisture content or the amount of fuel available for burning.

The amount of forest fuel available for burning varies not only with moisture content but also with stand characteristics. These variations were pointed out by Davis (1959), who stated:

> Any forest stand, whether hardwood or softwood, even or uneven aged, constantly undergoes cyclic periods of change. The amount, character, arrangement and inflammability of forest fuels are a direct result of species composition, age and condition of the forest stand. Since a forest contains many types of fuel, a systematic approach is necessary for their identification and analysis.

In Chapter 2 an attempt was made to classify scrub fuels on a systematic basis. Here it was deemed necessary to place litter sampling on a similar basis.

The necessity for a systematic method of sampling was shown by Byram (1957), who described variations in the size and arrangement of fuels as having a major effect on rate of combustion for woody fuels. This observation was supported by Curry and Fons (1939), Jemison (1944), and Anderson and Rothermel (1965). All these researchers agreed that fuel particle size and the porosity of fuel beds were important determinants of rate of spread.

McArthur (1967) showed rate of spread to be directly proportional to the quantity of eucalypt litter available for burning. These quantities were obtained with quadrat samples from the forest floor. This seemed a satisfactory and simple technique to adopt for the experimental fire in jarrah forest.

Thomas (1967) demonstrated the depth of fuel beds to be important for regulating the mechanism of fire propagation; hence its rate of spread. Litter depth, related to its weight, also provides a useful measure of density. It was decided therefore to include estimates of litter depth at each fire site.

Fons, Clements, Elliot and George (1962) showed rate of spread to vary with the wood species used for crib fires. These effects were thought to be associated with different oil and resin contents. These observations found support in results quoted by Pompe and Vines (1967), for eucalypt leaves. Here, heat yield decreased after distillation of the volatile oils from the leaves.

The theory was tested for jarrah forest by comparing burning rates of jarrah leaf litter with that of banksia litter (Peet, unpublished data, 1963). The results were sufficiently conclusive to warrant the identification of litter type at each experimental fire site.

The review of literature suggested recording litter weight, depth and type at each experimental fire site. This was implemented with methods explained in the next chapter.

Research had indicated that fuel quantity would be an important variable for including in a fire danger rating, not solely for its effect on rate of spread but also for its effect on fire intensity.

The influence of fuel on fire intensity was demonstrated by Byram (1959) in this formula:

$$I = H.W.r$$

Where I = Fire intensity in B.T.U. (British Thermal Units) per second per foot of fire front.

H = Heat yield, in B.T.U. per pound of fuel.

W = Weight, in pounds of available fuel per square foot of forest floor.

r = Rate of forward spread of headfire in feet per second.

This relationship has proved to be important for estimating damage to the forest from fire, and particularly for specifying acceptable conditions for controlled burning (Peet, McCormick and Rowell, 1968).

As mentioned earlier, rate of forward spread was selected in this study to express fire danger. Fuel amount would form part of the calculation of fire danger. It would be a simple procedure, therefore, to transform estimates of fire danger into estimates of fire intensity.

Wind Velocity

A review of the relevant literature left little doubt that wind velocity would exert a controlling influence over rate of forward spread.

Its importance was explained by Davis (1959):

> Air movement is one of the major fire behaviour factors. Wind directly affects the burning rate of forest fuel by influencing the rate of oxygen supply to that fuel. Also,

> strong winds increase the rate of fire spread by tilting the flames forward so that the unburned fuel receives energy by radiation and convection at an increased rate. These two mechanisms are especially important in causing smaller fires to build up their intensity.

This statement left little doubt that wind velocity would constitute an important component of the fire danger rating. However, its measurement and function required further investigation.

Fons (1964) used the direct variable, film conductance to explain the relationship between wind velocity and rate of forward spread. Film conductance is a measure of heat transfer through fuel. Its effect was explained by Fons in terms of a temperature ratio coefficient. This coefficient defined the temperature gradient between fuel near the flames and that ahead of the flames. Wind velocity changed this coefficient by bending the flames forward so increasing the rate of preheating for unburned fuel.

These results suggested that flame angle, which is influenced by wind velocity, would affect rate of forward spread. It was decided to record both wind velocity and flame angle during the experimental fires.

Fons's experiments indicated rate of forward spread in crib fires to be proportional to wind velocity raised to the power of 1.0 for velocities under 5 miles per hour, and to the power of 1.5 for velocities between 5 and at least 12 miles per hour. These powers suggested a curved relationship, resembling

$$y = a + bx^2$$

Similar curved relationships between wind velocity and rate of forward spread were put forward by Davis (1959), Luke (1961), and were supported by the more detailed observations made by McArthur (1962).

If these curved relationships are correct, comparatively small increases in wind velocity could produce large increases in rates of spread. It was important, therefore, to adopt a reasonably accurate method for measuring wind velocity.

Many difficulties arose in deciding on a suitable method of measurement.

Instrumentation for recording wind velocity proved reasonably straightforward. Sensitive cup anemometers, of similar design to those recommended by the Bureau of Meteorology, has been tested on experimental fire work by McArthur. It was decided that the same instrument would be used for this study.

The actual position of measurement was less easily solved. From a fire operations viewpoint, measurements within the forest were unlikely to be readily available to foresters. The most suitable sites for these purposes would be fire detection towers, which are manned each day during the fire season.

There were difficulties in obtaining wind velocities at the towers which truly represented wind at particular experimental fire sites. These difficulties were demonstrated by Simard (1969). The ratio between tower wind velocity and wind velocity in the forest tended to change as the actual velocity increased, and to change between sites due to topographic effects.

For the experiments it was considered essential to measure wind flow over the fire area, in order to derive relationships between wind velocity and rate of spread. These measurements should be taken at a constant height above ground level (Simard, 1969).

It was decided to adopt McArthur's standards. Wind velocity would be recorded from wind run over two-minute periods, at anemometers placed four feet above the forest floor. These anemometers would be located one and two chains up-wind of the fire's edge.

As mentioned above, wind recordings in the forest are not wholly satisfactory for general fire control purposes; because of practical difficulties in obtaining these measurements. Hence further experiments were programmed to study ratios between tower winds and those at four feet above the forest floor.

<u>Moisture Content of Litter</u>

The moisture content of fuel is one of the most important variables affecting ease of ignition and rates of combustion for woody fuels (Byram, 1959). Comprehensive experimental evidence has been produced to show that fuel energy, hence fire intensity, will decrease as moisture content increases (Byram, 1959, Pompe and Vines, 1966).

Both ease of ignition and fire intensity are fundamental controls over rate of spread.

The effect of moisture on fuel availability, and the resultant effect on fire intensity, has already been discussed.

These results suggested that moisture content of fuel would exert a controlling influence over rate of spread. It was decided to include measurements of this variable in experiments for the fire danger rating.

Two problems of measurement and estimation immediately presented themselves:

Firstly, the measurement technique to be used for sampling of experiments.

Secondly, the development of systems for estimating moisture content during day to day fire operations.

For the experimental work it was decided to restrict sampling to the litter layer in the forest. Many other fuels such as scrub and bark contribute to fire behaviour in the jarrah forest. Each requires separate consideration for moisture determinations, and sampling of the whole fuel complex was considered too comprehensive for the existing facilities.

For litter fuels the sampling positions had to be considered quite carefully.

McArthur (1962) showed the necessity of separating moisture content of surface leaves in the litter profile from moisture contents deep within the profile. Surface leaf moisture content fluctuated markedly with changes in temperature and relative humidity, (Van Wagner, 1970). These changes could be quite independent of the lower litter layer, especially where these were still damp from recent rain.

This concept was well supported by field observations. Saturated litter beds invariably started by drying at the surface, and this drying gradually progressed into the litter profile. As drying progressed, more fuel became available for burning.

This drying process was recognized in part by Gisborne (1928), Stickel (1933), and Wright (1932), who defined zones of inflammability for forest fuels. These zones represented risk of successful ignition.

Gisborne (1928), provided further evidence of the need to separate moisture sampling within the litter layer. He showed that fine fuels came quickly into equilibrium with relative humidity, while heavier components such as logs took weeks to dry from the saturated state.

Using these research findings as a basis, it was decided to sample moisture content of the surface leaves separately from moisture content of the whole litter profile.

Sampling within the litter profile posed the next question.

Ashcroft (1967), showed the quantity of litter available for burning to be directly related to the average moisture content for the litter profile.

In turn, the quantity of litter available for burning directly affects the rate of spread (McArthur, 1967). It was decided therefore that a second sampling would be undertaken, to express the average moisture content of the litter profile.

Suitable methods for estimating moisture contents of litter for fire operations purposes were not easily resolved. Standard methods of sampling and oven-drying were too slow and otherwise impractical for daily use by field foresters. It was necessary to investigate easily measured weather variables which could be used instead.

Again the problem fell into two parts: variables for estimating the moisture content of surface leaves, and variables for estimating the moisture content within litter profiles.

For surface leaves evidence has already been presented to show that they fluctuate with temperature and relative humidity. However, this relationship was not necessarily clearcut. King and Linton (1963) attempted to show relationships between moisture content equilibriums of eucalypt leaves and relative humidity. They found considerable dispersions about the mean values, depending on initial moisture content and on the geometric positioning of fuel on the forest floor.

Wallace (1936) developed a relationship between the moisture content of pine rods and the estimates of fuel inflammability in jarrah forest. Moisture fluctuations of the rods were expressed on a scale of 0 to 10, known as fire hazard scale.

Hatch (1969) developed relationships between temperature, relative humidity and fire hazard. The fire hazard scale has been used for fire weather forecasting in Western Australia since 1934.

For these experiments it was decided to measure air temperature and relative humidity at each experimental fire. Attempts would then be made to relate the moisture content of surface leaves to these measurements. Finally a relationship between fire hazard and surface leaf moisture content would be sought.

The use of a fire hazard scale held considerable advantage for this fire danger rating. It is generally understood and accepted by both field foresters and the public. Under the regulations of the Bushfires Act for Western Australia it has remained as the method of expressing fire weather.

Wright (1932) provided a guide to the weather variables likely to affect the moisture content of litter profiles. He related the amount of moisture absorbed by litter to amount of rain, moisture content before rain and to the duration of rain.

While the amount of rain was an obvious choice for inclusion in estimates of profile moisture content, the drying process after rain and the variables affecting this process required further investigation.

McArthur (1962) used the amount of rain and the number of days since rain to estimate the degree of dryness in beds of eucalypt litter. This was expressed in terms of fuel availability. Later McArthur (1966) incorporated the Byram-Keetch drought index into this estimate.

Byram and Keetch (1968) developed a drought index to express the dryness of heavier fuel components such as duff and branch wood. Rates of drying for these fuels are much slower than for fine types such as surface leaves. The variables used for this drought index were amount of rain, days since rain, and maximum temperature on each day after rain.

For estimating averages of the profile moisture content it was decided to establish separate experiments. Here the moisture content of litter samples would be related to amount of last rain, days since rain and to air temperature in the drying period.

Conclusions

In previous research two approaches were made to measurement of fire behaviour: use of direct variables and, secondly, use of indirect variables.

Practical considerations of cost of instrumentation, and then application of results, mitigated against adopting the direct variable approach.

It was decided that indirect variables would be used for this fire behaviour study, and they would be measured under forest conditions using McArthur's experimental fire technique. This technique, as will be explained in the next chapter, allowed for the measurement of several indirect variables while the fire was burning.

At the time this research programme started there was some urgency to develop fire danger tables. It was accordingly decided to simplify the experiments as much as possible. Fire danger would be expressed in terms of rate of forward spread of headfire. The effect of fuel quantity, its moisture content and wind velocity on rate of forward spread would be studied.

The relevant literature was reviewed to ensure that these three independent variables would exert a controlling influence over rate of spread. Results were sufficiently conclusive to suggest that they would, although they could not provide a full explanation.

Methods of measuring each of the three variables were investigated.

Litter quantities would be recorded by quadrat sampling of the forest floor. Litter depth and type were important and should also be recorded.

It was decided to measure wind velocity at one height, four feet above the forest floor. This would be recorded with a sensitive cup anemometer placed one to two chain up-wind from the fire's edge.

It seemed desirable to separate sampling for moisture content of litter into two parts. Firstly, surface leaves and, secondly, an average for the whole litter profile.

While sampling and oven-drying of litter moisture was suitable for the experiments, it was not a practical solution for estimations by field foresters. For this reason weather variables would also be measured, with the objective of later equating fluctuations in moisture content with them.

A review of the literature suggested a relationship between air temperature and relative humidity with the moisture content of surface leaves. Rainfall, the number of days since rain and temperature in the drying period would also be recorded for estimating average moisture content of the litter profile.

Chapter 4

EXPERIMENTAL METHODS

Most of the data used in the development of the fire danger rating for jarrah forest were collected from two series of field experiments. These were, firstly a litter drying trial and, secondly, experimental fires. Since these experiments formed the basis of much of the analyses which follow, it is necessary to consider their design in some detail.

Litter Drying Trial

The purpose of this drying trial was to measure rates of drying for jarrah leaf litter on successive days after rain.

The trial plot lay in a jarrah pole stand of medium density, on a gently sloping lateritic soil surface. The litter bed covered the forest floor completely, was two to three inches deep, and weighed about 3.5 tons per acre. A weather station was established nearby, consisting of a Stevenson screen, thermohygrograph, wet and dry bulb thermometers and a rain gauge.

The weather station was designed to collect information on rainfall, temperature and relative humidity, while the litter bed was drying. This information would be used to equate the progress of drying with changes in the three variables.

The thermohygrograph was fitted with a seven-day chart, (Casella, model T9 154), which covered a temperature range of 10 to 110 degrees Fahrenheit (F) and a range for relative humidity from 0 to 100 per cent. The manufacturer's specifications for accuracy were ± 1 degree for temperature and ± 3 per cent for relative humidities between 20 and 80 per cent. The temperature and relative humidity traces were checked each time the trial was sampled, from the wet and dry bulb thermometers.

To avoid interception of rain by the overhead forest canopy, the rain gauge was placed in an open area near the trial.

Litter samples were collected from the trial after rain and thereafter until the profile was dry. The first sampling after rain was done as soon as possible after rain ceased. The sampling thereafter was done twice daily, at 9.a.m. and 3 p.m.

The trial area was 100 feet square. This area was subdivided into 10-foot squares with numbered posts. The grid of posts provided a reference for randomly locating positions for sampling within the trial. These positions were fixed with four random numbers, two to indicate the square and two more for the sampling position in the square. The numbers identified axes within the grid and within the square.

Five samples of the litter profile were collected each time. The best method of collecting a sample was to use a sharpened six-inch square made from thing steel plate. This was pushed through the litter to the soil surface. The sample was lifted whole from within the square as a vertical section of the litter profile from surface leaves to duff.

Each sample of litter weighed about 50 grammes. They were sealed in tins with adhesive tape to prevent loss of moisture through the lids.

The moisture content was calculated from the difference between air-dry and oven-dry weights. The samples were oven-dried at 105 degrees Centigrade for periods from six to twentyfour hours, depending on the dampness of the sample. When a constant weight was reached the moisture content was calculated with this formula:

$$\text{Moisture Content (per cent)} = \frac{\text{A.D.W.} - \text{O.D.W.}}{\text{O.D.W.}} \times 100$$

Where A.D.W. = air dry weight of the sample

O.D.W. = oven dry weight of the sample

Drying trends for the litter bed were extracted at the end of each week. Daily drops or rises in moisture content were plotted from the average of samples collected at 9.a.m. and 3 p.m.

Averages of daily temperature and relative humidity were taken from the thermohygrograph trace. These were the averages of recordings at 10 a.m., 12 noon, 2 p.m. and 4 p.m.

The reason for using averages for temperature and relative humidity was to avoid basing drying trends on peaks in the day's weather. Rather than using maximum or minimum values, it was thought that an average through the day might provide a better representation of drying conditions.

The significance of day-to-day changes in moisture content had to be considered in relation to the standard error imposed by the sampling technique. These errors were quite high in some cases, and tended to rise with increases in average moisture content. The percentage standard error for each sampling was worked out and the range shown in Table 7. These ranges were listed for moisture content classes of 40 per cent, up to 120 per cent, and thereafter for 120 to 200 per cent.

TABLE 7

Standard Errors from Sampling the Drying Trial

Range of Moisture Content (per cent)	Range of Percentage Standard Error
0 to 40	5.1 to 31.0
41 to 80	9.5 to 25.3
81 to 120	10.8 to 14.9
121 to 200	5.1 to 53.8

Experimental Fires

Information on fire behaviour was gathered with a series of experimental fires lit in jarrah forest during spring, summer and autumn. The technique for measuring these fires had been developed by McArthur (personal communication, 1961).

This technique involved describing the forest by tree species and sizes; scrub by species, height and percentage cover over the forest floor; and litter by weight, depth and type.

A field weather station was established one to two chains up-wind from the point of lighting. Wind, temperature, relative humidity and moisture content of the litter were measured during the course of the fire.

The fire's perimeter was marked at two and four-minute intervals, while flame characteristics such as height, length and depth were described at the same time.

After the fire the tags marking the fire's perimeter were surveyed. This survey formed the basis for a plan showing rates of spread. It was followed by ocular estimates of forest damage and protection value of the burn.

Before Lighting

Sites for the experimental fires were selected on ridges and slopes of normal undulating jarrah forest. Those considered atypical of the main forest, such as dense scrub or steep topography, were avoided. The reason for this was to minimise variations in site which were not readily defined in the experimental record.

Forest type was described by tree species and by ocular estimates of density and size. These descriptions were kept simple: e.g., a dense jarrah pole stand or a mature stand of jarrah and marri, medium in density.

Aspect was used to describe topography. Again descriptions were simple: e.g., ridge top or west facing slope.

Scrub cover was delineated by ocular estimates of the species present, percentage cover over the forest floor and height. Weights of scrub foliage were not measured at this time because of difficulties with the experimental technique and limited manpower.

Litter was described by type and ocular estimates of depth. These depths were separated into loose surface litter and the underlying duff. An additional ocular estimate was made of the percentage of forest floor covered by litter. Litter type referred to the tree species from which it originated.

These observations set down the site characteristics at each fire area. The information was recorded on a standard form, an example of which is shown in Appendix 3.

During the Fire

Weather Station

The fire was started at the base of a wooden peg marked with the fire's identification number. This peg was the base point for the survey which took place the next day.

A weather station was established one to two chains up-wind from the peg, the distance depending on the fire's intensity. The intention was to locate the station as close as possible to the fire so as to measure wind flow over the fire area.

The weather station had a sensitive cup anemometer (Casella, three-cup, model 1530) fixed on a tripod four feet above the forest floor, an Assman psychrometer (Casella, fan type, model 3689), and large airtight tins for holding moisture samples.

The most suitable size of tin was 3.5 inches in diameter and five inches high. This held a 50-gramme sample of litter.

The Assman covered a temperature range from 20 to 120 degrees. The manufacturer's specification for accuracy was ± 1 per cent of relative humidity. The starting speed for the anemometer was three feet per second.

After lighting, wind velocity in the forest was recorded at two-minute intervals from the run of the anemometer. The experimental fires were usually measured for a 32-minute period, and the average wind velocity calculated from the mean of 16, two-minute readings.

Air temperature and relative humidity at four feet above the forest floor were measured at 30-minute intervals with the Assman psychrometer. These measurement times roughly corresponded with the start and finish of a fire.

Averages of the two measurements expressed these variables for each fire.

Moisture Content.

Samples for estimating the moisture content of the litter bed were collected at 30-minute intervals. Two samples were collected each time, a tin of surface leaves and another of the profile.

The profile samples were taken through the litter bed in the same manner as described for the drying trial.

Surface leaves were collected from the top inch of the profile.

Sites for collecting moisture samples were mottled shade zones near the fire's edge. Mottled shade, approximating 50 per cent shade, was assumed to represent an average between bright sunlight and dense shade. These two situations produce differences in moisture content, particularly in surface leaves, (McArthur, 1968).

The selection of mottled shade was by no means a complete control, as the amount of shade previous to sampling varied with the sun's diurnal traverse. It was only possible to pick sites where canopy was sufficiently dense to indicate that mottled shade had covered the site for one hour previously.

The collection of only two samples of surface leaves and two of profile at each fire naturally introduced fairly high sampling errors. This restriction was imposed by limited facilities for oven-drying.

The magnitude of these errors was illustrated in Table 8. Standard error of the mean moisture content of both surface leaves and profile was worked out for a number of fires. The range of percentage standard error was listed in classes of average moisture content.

TABLE 8

Standard Errors for Surface and Profile Moisture Samples Collected at Experimental Fires

No. of	Type of Sample	Range of Average Moisture Content %	Range of percentage standard error
5	Surface leaves	5.0 to 15.0	9.3 to 14.8
5	" "	15.1 to 25.0	15.8 to 34.4.
5	Profile	10.0 to 25.0	21.4 to 24.6
5	"	25.1 to 40.0	27.3 to 38.9
5	"	40.1 to 55.0	46.4 to 53.3

Litter Quantity.

Litter samples were collected at 10-minute intervals in front of the headfire.

A thin, steel quadrat with a sharpened edge was pushed through the litter layer to the soil surface. The litter within it was gathered into a bag. The sample included all leaves, duff and twigs up to 0.5 inch in diameter. Larger wood was excluded on the ground that it burnt away behind the main fire front, hence did not contribute to the flash fuel sustaining rate of fire spread.

A representative litter sample was collected with each quadrat. This was taken through the litter profile and alongside the quadrat. The moisture content of this sample was used to express litter weight on an oven-dry weight basis. These weights were derived in tons per acre. The formula was:

$$\text{Equivalent oven dry weight} = \frac{100 \times \text{A.D.W.}}{100 + x}$$

Were A.D.W. = Air dry weight of sample

x = Moisture content of the sample.

During the course of these studies two sizes of quadrat were tried, for reasons which will be explained later. Table 9 lists the range of standard errors for average litter weights obtained with a four-square-feet size of quadrat and a one-foot-square one.

TABLE 9

Standard Errors for Quadrats of Litter Quantity.

(Range from 5 fire sites)

Number of Quadrats	Size of Quadrat	Range of Average weights tons/ac.	Range of Standard Error tons/ac.	Range of Percentage Standard Error
5	4 square feet	4.0 to 7.7	0.3 to 1.3	7.5 to 17.0
5	1 square foot	2.7 to11.0	0.1 to 1.3	2.7 to 18.4
10	"	2.7 to11.0	0.3 to 0.8	5.7 to 13.1
15	"	"	0.2 to 0.5	4.1 to 9.1
20	"	"	0.2 to 0.2	3.0 to 4.3

Measurement of the Fire.

After lighting, the edge of the headfire was marked at intervals of two minutes, and the whole fire perimeter at intervals of four minutes. The edge was marked by dropping numbered metal tags at strategic points along it, which showed changes in the fire's perimeter as it increased in size.

Difficulties in accurately marking the fire's edge rose as the intensity of the flames increased. For flames up to two feet high, the men could generally place the tags within 0.5 feet of the actual edge. As the flames increased it was necessary to throw the tags to the edge, hence their placement became less accurate.

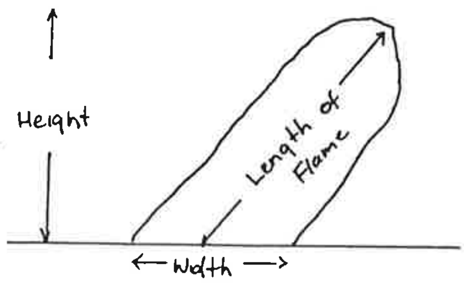
Due to manpower limitations it was sometimes difficult to place sufficient tags around the perimeter to mark it fully. This happened especially in the faster-spreading, intense fires. Generally the fires were marked by placing one tag on the headfire every two minutes, and on alternate markings another four tags around the whole perimeter.

Ocular estimates were made every four minutes for average flame height, length, depth and angle of the headfire. At these times flame height of the flankfire and backfire was estimated in the same way.

The estimation of flame height, depth and length is illustrated in Figure 5. Flame height was the vertical distance above ground, length the actual length of the flame, and depth the width of the flames across the ground.

Figure 5

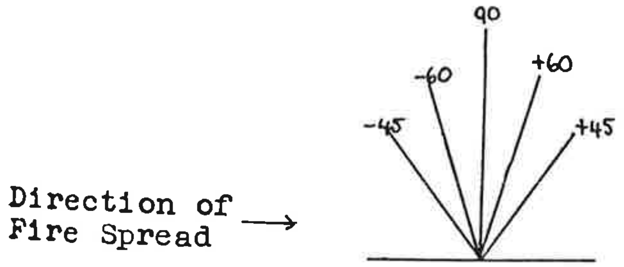
Estimation of Headfire Flames



Flame angle was estimated from variations to the vertical above ground level, which was 90°. Flames bending forward ahead of the burnt area were positive, and those bending into the burnt area were negative. The procedure for these estimations is illustrated in Figure 6.

Figure 6

Estimation of Flame Angle



During each four-minute observation ocular estimates were made of smoke colour and volume. These were recorded in simple terms: e.g. a white, thin smoke, or brown, dense smoke.

These measurements and observations of fire behaviour, forest and weather variables were recorded on standard report forms. Examples of these, (Forms 1 and 2), filled in for one of the fires, are shown in Appendix 3.

After the Fire.

The position of each tag marking the fire's perimeter was surveyed by bearing and distance from the base peg. A compass was used for the bearings and a 100-foot tape for the distances.

The surveyed points were plotted on graph paper, and this plot was used to construct the fire plan. An example of this plan is shown in Figure 7.

The plan was drafted by handdrawn lines which joined points along the perimeter at each marking. When completed, the plan showed the fire's perimeter at each four-minute interval, and the position of the headfire in the intermediary two-minute intervals.

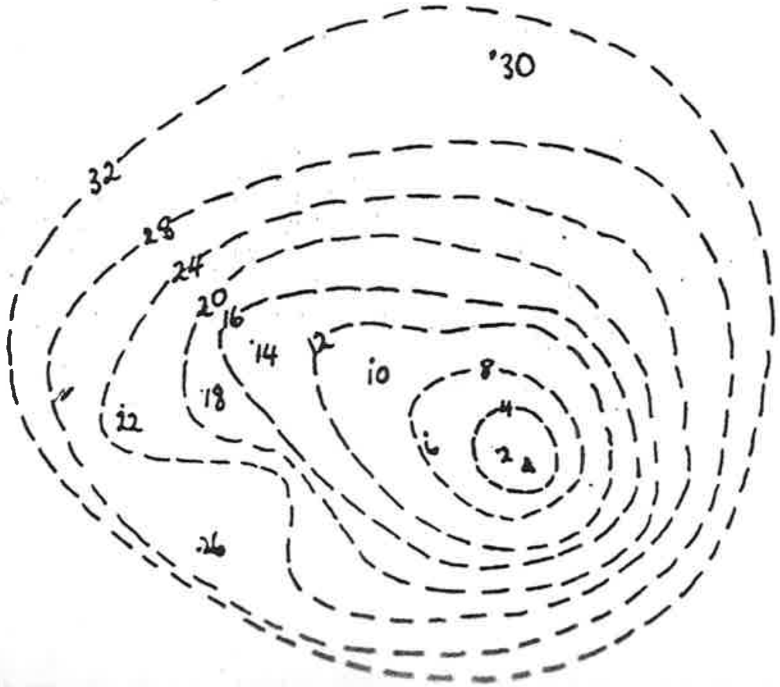
The fire plan was analysed to calculate rates of spread for headfire, flankfire and backfire. These rates were expressed in feet per minute.

The headfire rates were measured along the central axis of the fire, as were backfire rates (Figure 8). The averages were means of the two axes and of four-minute measurements (refer Figure 7).

Rate of spread for flankfire was calculated by averaging two measurements on either side of the central axis. These were taken along axes at 60° to the central one (Figure 8).

FIG 7 Fire Spread Plan

Fire. No 1.S.

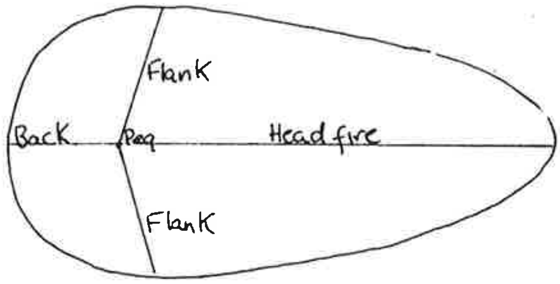


Time	H/ROS.	F/ROS.	B./ROS.
2	0·75 ft/min		
4	0·75	0·68 ft/min	0·50 ft/min
6	1·25	[illegible]	
8	0·25	0·43	0·25
10	1·75		
12	1·75	0·56	0·31
14	2·00		
16	0·75	0·25	0·25
18	1·50		
20	0·25	0·75	0·25
22	1·75		
24	0·25	0·62	0·31
26	0·50		
28	1·00	0·50	0·44
30	1·00		
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

When fires assume an ovoid shape the maximum rate of spread for the flankfire moves forward with the headfire (Peet, 1967). If the measurements had been taken at right angles to the central axis, they would, after a period, be reflecting backfire spread rather than flankfire.

Figure 8

Axes for Measuring Rate of Spread of an Experimental Fire.



Unfortunately these specifications for measuring rates of spread could not always be followed. The direction of the headfire changed sometimes, with variations in topography, fuel, or a wind directional shift. In such cases the direction of the headfire axis, and the others, were moved accordingly as the fire changed direction.

As mentioned above flame characteristics were recorded at four-minute intervals. These were averaged to describe flame height, depth and angle for each fire.

Ocular estimates were made of scorch height of tree crowns, in the direction of the headfire. Quadrat samples were taken next to the previous samplings, to measure the quantity of litter consumed by the fire. This quantity was the difference between the fuel weight before the fire and after the fire.

The nature of the fuel bed after the fire was further described by an ocular estimate of the percentage of scrub remaining unburnt.

The purpose in recording scorch heights and condition of the scrub was to separate fires of suitable intensity for controlled burning from others either too mild or intense.

An Abney Level was used to measure slopes in the direction of the headfire, flankfires and backfire.

Records of the survey and other observations were kept on a standard report form, (Form 3, Appendix 3).

Review of Experimental Methods.

During this study certain flaws were revealed in the experimental technique. Investigations into the methods have led to revised techniques which are in use today.

Measurement of Moisture Content

The moisture content of litter proved a most difficult variable to measure with any degree of accuracy. Tables 7 and 8 indicate the large number of samples necessary to achieve a significant drop in percentage standard error. This could not be achieved with limited facilities.

The percentage errors tended to increase with rises in profile moisture content. This seemed logical, since fuel beds are rarely even in depth, usually changing with depressions in the soil surface. An uneven depth of litter affects rate of drying, particularly moisture content of the lower duff. In the first few days after rain variations in litter depth created a large range of moisture contents, even within a comparatively small area of forest like the drying trial.

Averages of litter quantity during the experimental fires ranged from four to six tons per acre. It was shown that litter depth affected the upper limit of profile moisture content at which fires would spread. In deep beds fires burnt over profile moisture contents of 160 per cent, whereas in thin ones 50 per cent was sufficient to extinguish them. These differences revealed the importance of relating sampling errors in moisture content to the depth of litter.

Large variations in moisture content and problems in sampling are inevitable in the destructive sampling of litter beds. These were recognised by Van Wagner (1970), who used baskets of litter placed in the forest in as natural a position as possible, as a substitute. This method was tried for jarrah litter, and provided much closer relationships between fluctuations in moisture content and changes in weather (Sneeuwjagt, 1970).

Measurement of Scrub

A fairly detailed assessment which measured the cover of scrub on the forest floor, and defined some important scrub species for fuel studies was described in Chapter 2. The intention was that this information would be linked to experimental fires to form an expression for scrub foliage as fuel.

Due to difficulties with the experimental technique and manpower shortages it was not feasible to obtain a direct and quantitative measure for amount of scrub foliage before each fire. Recently this experimental problem was overcome with a technique based on point sampling (Levy and Madden, 1936). The adaptation of this technqiue to measure scrub as fuel was described by Sneeuwjagt (1971).

The method involves passing a metal rod vertically through the foliage. The number of contacts of foliage on the rod was counted in two-foot height classes. The number of contacts, expressed as a percentage of number of rods, provides a measure of scrub density on the forest floor, also changes in density with height.

Species and density provided a basis for classifying scrub fuels on individual fire sites. It remained to link density to weight of foliage.

For each scrub type foliar weights were measured in two-foot height classes. These weights were separated into living and dead material, also into sizes. After each fire the size and type of foliage consumed was recorded, giving a direct measure of foliage weight, its type and distribution consumed by the fire.

Measurement of Litter Quantity

Some investigations were made into improvement of sampling for litter quantity. Four-square-feet quadrats were compared with one-foot-square; also the number of samples required for a reliable estimate received attention.

Quadrat size was in question because of practical problems with the larger, four-feet-square. The sharpened edge of the square was pushed through the litter with the objective of cutting out exactly four-square-feet of litter. In practice the edge was often ragged, sticks and stones preventing a clean cut. The smaller quadrat was easier to use and gave better control over the size of sample.

Use of a sub-sample for estimating moisture content immediately introduced a source of error into the calculation of litter weights. The accuracy of this calculation depended on the sub-sample representing the quadrat as a whole, which was difficult to achieve with thick, damp litter.

The bulk of litter in a four-foot-square prevented oven-drying the whole. The smaller quadrat was manageable, and all the litter could be oven-dried, thus eliminating one source of error.

Table 9 summarized tests with the two sizes of quadrat. For five samples the larger quadrat provided a smaller range in percentage standard error, but this advantage disappeared once 10 or more of the smaller quadrats were taken.

Following this investigation it was decided to abandon litter sampling at 10-minute intervals in front of the headfire in favour of more detailed measurements prior to lighting. Now, 20 samples are collected at each fire site, using randomly placed one-foot-square quadrats.

Chapter 5

FIRE HAZARD

Introduction

Three major factors affecting fire danger in the jarrah forest are fuel quantity, wind velocity and the moisture content of litter. Moisture content, however, is difficult to measure in the forest and these difficulties make it quite impractical for operational use. It was necessary therefore to find a proxy for moisture content which could be predicted or measured quite readily, and would be easily understood. Fire hazard was the proxy variable chosen.

Fire hazard has been used for forecasting day to day changes in the inflammability of forest fuels in Western Australia since 1934 (Wallace, 1936). Estimates of the days hazard are included in daily fire weather forecasts issued by the Bureau of Meteorology.

The degree of hazard each day is spoken of in terms of normal summer weather: that is to say, if it is above or below what is regarded as an average summer day (Stoate and Harding, 1940). If hotter, drier weather than average is expected the days hazard will be called High, Severe summer or Dangerous in that order of severity. If below the average the days hazard will be either Moderate, Low or Nil. Other things being equal, the higher hazard rises the greater is the possibility of a fire starting from an ignition agent and the more rapid will be its spread (Wallace and Gloe, 1938).

The original scale for fire hazard was built by equating changes in the inflammability of forest fuels to changes in the moisture content of 0.5-inch diameter pine (*P. radiata* D. Don) hazard rods. Estimates of changes in inflammability were provided by nine experienced forestry officers (Wallace, 1936). It was found that moisture content of the rods followed almost identically the average of hazard estimates by the forestry officers. The estimates were divided into seven classes of hazard ranging from Nil to Dangerous on a scale of 0 to 10 (Table 10).

TABLE 10

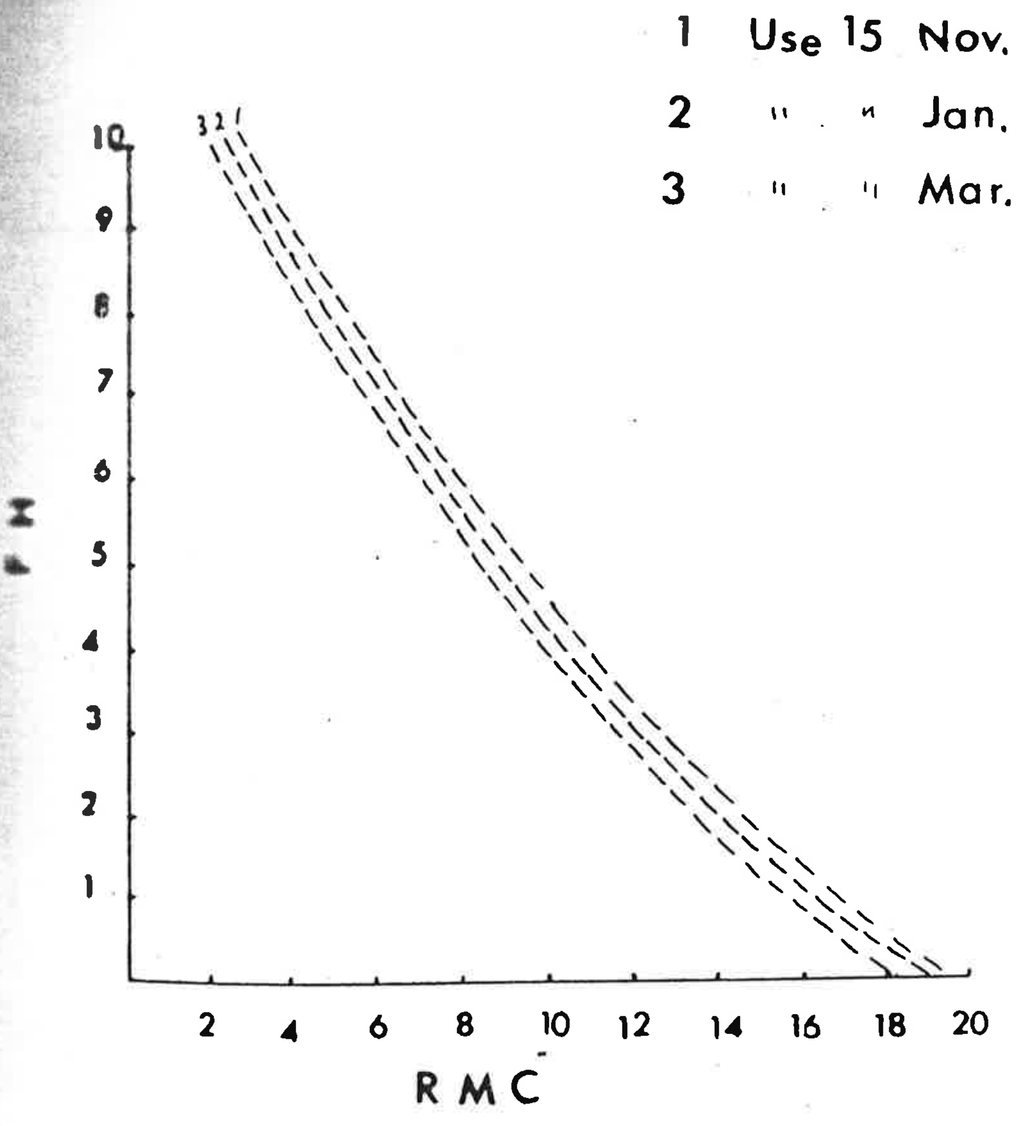
Classes of Fire Hazard

Fire Hazard	Descriptive Class
0 to 1.0	Nil
1.1 " 4.0	Low
4.1 " 6.0	Moderate
6.1 " 7.0	Average Summer
7.1 " 8.0	High Summer
8.1 " 9.0	Severe Summer
9.1 "10.0	Dangerous

The relationship that was worked out between fire hazard and moisture content of the rods is shown in Graph 2. This refers to peak conditions for the day when hazard is highest and consequently moisture content is lowest. Three curves were drawn, to be used consecutively during the fire

Graph 2

Fire Hazard and Rod M.C. %



season as the surface of the rods weathered (Hatch, 1969).

There were however, several weak points in the fire hazard system which had to be overcome before it could be incorporated into the fire danger rating. It required the use of specially prepared hazard rods - three rods on a screen nine inches above the ground, which had to be weighed every two hours during the day. This made it impractical for forest stations with restricted staff. Furthermore, the hazard rods do not follow closely moisture changes in leaf litter after rain. Being placed nine inches above the ground they generally dry much faster than a litter bed.

It was necessary, in the experimental work described here, to make two major additions to the fire hazard system. The first was to provide a means for predicting fire hazard during normal dry summer weather from measurements of weather variables such as temperature and relative humidity. The second was to provide a more realistic adjustment for effects of recent rain.

Hatch (1969) introduced a new concept into the forecasting of fire hazard by showing that it could be predicted from maximum temperature and minimum relative humidity each day, providing rain effects were absent. The inclusion of moisture content for rods improved the prediction but temperature and relative humidity alone accounted for 80 per cent of the variation in hazard.

Hatch's system was much easier to apply to numerous centres throughout the forest than was Wallace's original hazard rod concept. Very few forest centres are equipped with hazard rods. While this limitation was not very important for general forecasting of fire weather, it was a major difficulty in making the local adjustments of fire hazard which proved a necessary first step for reliable calculations of fire danger. All forest stations were, on the other hand, equipped to measure air temperature and relative humidity as well as rainfall.

For the fire danger rating Hatch's work was used to express day to day fluctuations in hazard during dry summer weather. Experiments were established to provide realistic adjustments to hazard for the effect of recent rain. This work aimed at providing a means for calculating fire hazard using only wet and dry bulb thermometers and a rain gauge.

Basic Fire Hazard and the Moisture
Content of Surface Litter

During dry summer weather the moisture content of hazard rods ranges between five and twenty per cent of oven-dry weight. Within this range there was found to be similar changes in surface litter.

King and Linton (1963) reported: There is a roughly comparable trend between the moisture behaviour of hazard rods and that of a bed of eucalypt leaves.

The evidence suggested that this relationship was true for surface leaves in a profile of jarrah litter (Peet, unpublished data, 1963).

Three wire-mesh baskets, each one foot square and three inches deep, were filled with jarrah leaf litter. Because of aeration in the baskets these samples represented surface leaves rather than a natural litter profile in the forest.

The baskets and a set of hazard rods were kept on the ground under a screen which represented 50 per cent shade. Each day both were weighed at 10 a.m., 12 noon, 2 p.m. and 4 p.m. An average for moisture content of the baskets was plotted against moisture content of the rods at each weighing. Finally a relationship between rods and leaves was drawn up from 75 observations, which covered a range of moisture content for the rods between five and 20 per cent. The relationship was linear, i.e.

$$y = 0.020 + 1.134x \quad (1)$$

Where y = Moisture content of jarrah leaves, per cent

x = Moisture content of hazard rods, per cent.

Regression 1 was significant at the 95 per cent level of confidence. The value of "a" (constant) and "b" (coefficient) suggested that for all practical purposes the relationship could be assumed to be a direct one: i.e., the regression line passes through zero and the slope is 1.0. This indicated that hazard rods and surface leaves in the same micro-climate will fluctuate in moisture content during the day in a similar manner.

There was, however one important proviso; the results were only applicable to dry summer weather. The experiment was discontinued on wet days and the baskets and rods removed to a dry place.

Regression 1 and Graph 2 provided the basis for defining the relationship between fire hazard and moisture content of leaf litter. These two relationships are shown in Table 11, which lists fire hazard with equivalent moisture contents for hazard rods and leaf litter. This table led to the conclusion that differences between the two were of little practical importance. The tables and graphs showed that -

1. There was a linear relationship between moisture content of hazard rods and moisture content of surface leaves (Regression 1). Between moisture content of hazard rods and fire hazard the relationship was curved (Graph 2). It follows that the relationship between moisture content of leaf litter and fire hazard is also curved.

11. For any one hazard the greatest difference between rods and leaves was in the order of 2.6 per cent (Table 12), introducing a discrepancy of 1.0 in the Nil hazard range (Graph 2)

111. The magnitude of differences in moisture content decreased as fire hazard rose.

1V. On this basis variations between rods and leaves seemed of minor practical importance in estimating fire hazard for forecasting purposes. This was supported by measurement errors in sampling surface leaves in the forest, which were usually much higher than 2.6 per cent (Chapter 4)

TABLE 11

Values of Fire Hazard Related to Moisture Content of Hazard Rods and Jarrah Leaves

Fire Hazard	Moisture Content of Hazard Rods per cent	Moisture Content of Jarrah Leaves per cent
7.8	5	5.7
4.3	10	11.4
1.5	15	17.0
0	19	21.6

Although the original fire hazard concept was a subjective measure of maximum inflammability based on weather forecasts and moisture content of pine rods, there is a close relationship with surface litter. Fire hazard proved a useful variable for the fire danger rating because forecasts of hazard are made each day during the summer by the Bureau of Meteorology, and it is a familiar term to foresters and the public. This was the basis for deciding that Graph 2 could be used in the fire danger rating to express fire hazard, and that fire hazard would reflect the moisture content of surface leaves. To avoid confusion with rainfall effects, this measure of fire hazard was called basic fire hazard.

Prediction of Basic Fire Hazard from Measurements of Temperature and Relative Humidity.

Each morning during summer the Bureau of Meterology issues a forecast of fire hazard for the jarrah and karri forest regions. These forecasts are based on the moisture content of hazard rods and a consideration of weather (Wallace and Gloe, 1938).

Since these forecasts are regional, and are made early in the morning, they do not completely meet the requirements of fire operations. They are not applicable where local variations in rainfall occur; and, moreover, fire operations often require estimates of hazard during the day. It was necessary to establish procedures through which fire hazard could be measured for any forest centre at any time of the day. This was done with Hatch's (1969) relationship between fire hazard, maximum temperature and minimum relative humidity each day. His regression was:

$$y = 0.109x_1, - 0.046x_2 - 0.539 \qquad (2)$$

Where y = Fire hazard.

x_1 = Maximum temperature in degrees F.

x_2 = Minimum relative humidity per cent.

Rain-affected data was rejected from this study. The regression was significant at the 99.9 per cent level of confidence for 197 degrees of freedom. It accounted for 61 per cent of the variation in the data.

It is arguable that little comparability exists between peak and instantaneous values of temperature and relative humidity. This objection had to be met before fire hazard could be predicted at various times during the day.

Regression 1 showed daily fluctuations in moisture content hazard rods and surface leaves to be similar. Assuming these fluctuations are controlled by temperature and relative humidity, it is reasonable to expect that they act the same way in regulating instantaneous or peak values.

This hypothesis was tested by plotting instantaneous values of surface leaf moisture content with relative humidities measured at the same time (Graph 3, Appendix 4). The data was gathered during experimental fires. The relationship approximated to a linear one and could be expressed by:

$$y = 0.10 + 0.25\,x \qquad (3)$$

Where y = Moisture content of surface leaves, per cent.

x = Relative Humidity, per cent.

Similarly, a plot of air temperatures measured at the same time indicated a linear relationship with moisture content. These results suggested that instantaneous measurements of temperature and relative humidity were linearly related to moisture content in a similar manner to the peak measurements used by Hatch.

Hatch's formula, in tabular form, formed the first stage in the production of fire danger rating (Table A, Appendix 6). For fire operations this table provided a means for calculating fire hazard at forest centres not normally equipped with hazard rods. In addition, it can be used to predict fire hazard at any time during the day. Since this method ignores overnight conditions it forms a substitute rather than a replacement for fire hazard calculated by the normal hazard rod system (Hatch, 1969).

Adjustments for Rainfall and Subsequent Drying.

It was decided that rainfall effects on fire hazard would be expressed through changes in profile moisture content for a 3.5 tons per acre litter bed. This was the fuel amount in the litter drying trial.

Saturated litter profiles ~~collected~~ dry first at the surface, and this drying gradually extends deeper into the profile. This process alters in dry fuels where only the surface is wetted by light rain, but the data was not sufficient to separate the two conditions.

Rainfall factors were calculated on the supposition that litter beds were saturated and drying from the surface.

The rainfall correction factors adjusted basic fire hazard to an expression of the average moisture content for the litter profile. As the drying process starts at the top, the surface leaves would be drier than the underlying layers. Basic fire hazard would have to be reduced for the relative dampness of the lower litter.

It was decided that the format for the rainfall factors would be multipliers ranging between 0 and 1.0: a factor of 0 meant the profile was saturated and 1.0 that it was completely dry. Between 0 and 1.0 the depth of drying would be progressively greater as the factor approached 1.0.

Basic fire hazard would be adjusted in this formula:

A.F.H. = B.F.H. x R.C.F.

where A.F.H. = Adjusted fire hazard.

B.F.H. = Basic fire hazard.

R.C.F. = Rainfall correction factor.

The data for rainfall correction factors came from the litter drying trial (Chapter 4).

Three criteria were necessary to calculate the rainfall correction factors. These were: The profile moisture content immediately after rain, rates of drying each day thereafter (including effect of average daily temperature on this rate), and, thirdly, moisture content equilibriums after rain effects had disappeared.

The amount of drying before rain effects had disappeared was the difference between moisture content immediately after rain and the moisture content at equilibrium. The rate of drying on successive days after rain specified the magnitude of the rainfall factor between these limits.

Each of the three criteria was studied in partial experiments. Once the function of each was defined, they were combined to calculate rainfall factors.

Profile Moisture Content After Rain

Samples of the litter profile were collected as soon as possible after rain stopped. The time between cessation of rain and sampling was not always constant; e.g., when rain ceased at night. Generally the samples were collected two to six hours after rain stopped.

The average moisture content of the samples was plotted with the amount of rain. The graphical distribution of these points was used to eye-fit a curve expressing the relationship (refer Graph 4). The curve was approximated by this formula:

$$y = 103 \log x - 25.0 \qquad (4)$$

where y = Profile moisture content, per cent.

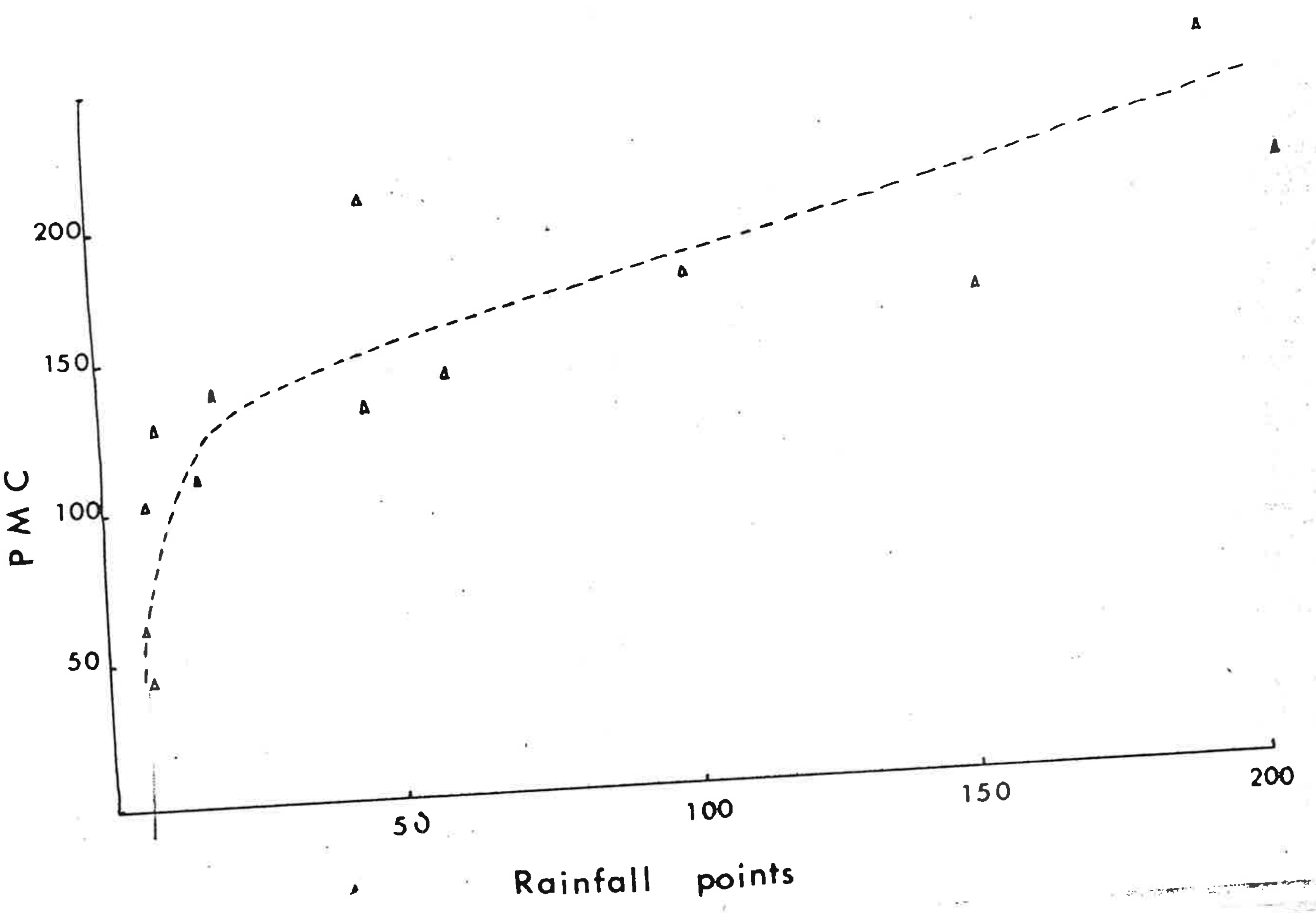
x = Amount of last rain in points.

Graph 4 shows a considerable dispersion of points about this curve. This dispersion may have been accentuated by the effect of initial moisture content which was not considered in the analysis.

King and Linton (1963) showed initial moisture content to be important for regulating the response of litter to wetting. Had the data for this experiment been less limited, this variable would have been considered.

Graph 4

Amount of Last Rain and Profile Moisture Content



A relationship of the type shown on Graph 4 seemed acceptable after consulting King and Linton's (1963) work. Initial rates of moisture absorption for eucalypt leaf litter were high, but decreased to a slow rate when the leaves approached saturation.

The relationship between profile moisture content and amount of rain should be expressed by a similar type of curve. When leaves are dry the rate of absorption of moisture is highest. This rate decreases as moisture content increases until at saturation more rain merely produces free water in the litter bed.

Wright (1967) showed the period of rain to be important for regulating moisture content of litter. Unfortunately instrumentation was insufficient to include this variable in the data.

To define rain effects on profile moisture content, the curve in Graph 4 was divided into seven classes. An average moisture content for each class was taken from the Graph. These initial moisture contents after rain were listed in Table 12.

TABLE 12

Averages of Profile Moisture Content Immediately after Rain

Amount of Rain Points	Profile Moisture Content per cent
5 to 10	85
11 to 20	100
21 to 50	120
51 to 100	175
101 to 150	195
151 to 200	215
greater than 200	230

Subsequent Drying After Rain

The measurement of rates of drying for jarrah litter beds formed the next problem for this investigation.

Byram and Keetch (1968) showed drying of litter to be a cumulative process with time, its rate varying with maximum temperature.

Pech (1969) showed that fluctuations in daily weather were more important for regulating the moisture content of slash fuels than the number of drying days since rain.

These results suggested both time and rate to be the criteria requiring definition for the drying process.

King and Linton (1963) formed the opinion that relative humidity was a controlling influence on rate of drying. Hatch (1969) showed fire hazard to be affected by maximum temperature and minimum relative humidity, and suggested that they each had an independent effect.

It was decided that average daily temperature would be selected to interpret rates of drying. Average daily temperature was the mean of measurements at 10 a.m. 12 noon, 2 p.m. and 4 p.m. Temperature was selected rather than relative humidity because it tends to fluctuate less during the day and would provide a better expression of a daily average. Also, during normal summer weather there is usually reasonable correlation between temperature and relative humidity.

Four classes of average daily temperature were established, each covering a 10 degree F. range. The lowest was 61 to 70 degrees F. and the highest 91 to 100 degrees F. Drying trends on successive days after rain would be determined for each temperature class.

Graph 5 shows an actual drying trend from the litter drying trial, after 200 points of rain and on days with average daily temperatures between 61 and 70 degrees F.

Several drying trends were examined before deciding on a curve form to express rate of drying on successive days after rain, i.e.

$$y = \frac{1}{a + bx}$$

This hypothesis led to the acceptance of the curve form. Rates of drying will be at a maximum while moisture content is high, but the rate will decrease progressively as moisture content approaches equilibrium. This process

P M C on Days after 200 Points of Rain

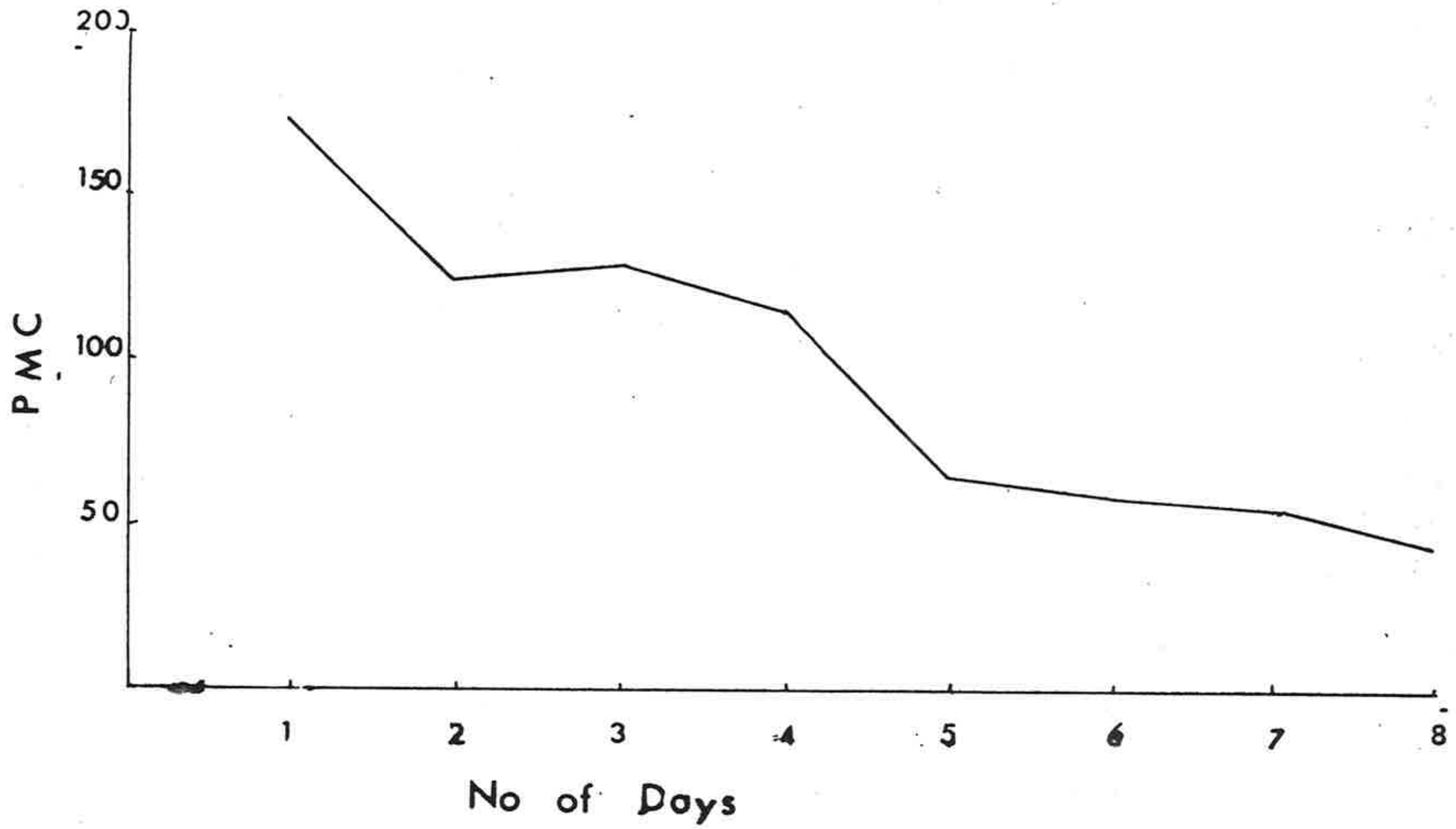


TABLE 13

Drop in Profile Moisture Content per day in Average Daily Temperature Classes

number of days since rain

Average Daily Temperature class (^{o}F)	1	2	3	4	5	6	7	8	9	10	11	12	13
61 to 70	50	34	25	19	16	14	12	11	9	8	7	6	5
71 to 80	60	41	30	23	18	15	13	12	10	9	8	7	6
81 to 90	70	48	35	27	22	18	15	13	11	10	9	8	7
91 to 100	80	54	39	30	24	20	17	15	13	11	10	9	8

was approximated by the curves in Graph 6.

The curves in Graph 6 were used to calculate rainfall correction factors. There were a number of graphed points to indicate the form of curves for the 61 to 70 and 71 to 80 degrees °F classes. However, data for the higher temperature classes was sparse, and these curves were extrapolated for compiling rainfall correction factors.

The form of the curve for the 61 to 70 degrees F. temperature class approximated:

$$y = \frac{1}{0.014 + 0.009x} \qquad (5)$$

where y = Drop in profile moisture content per cent

x = Number of drying days since rain.

Table 13 was compiled from Graph 6 and shows daily drops in profile moisture content on succeeding days after rain. This Table formed the basis for calculating the magnitude of rainfall corrections between saturation and equilibrium.

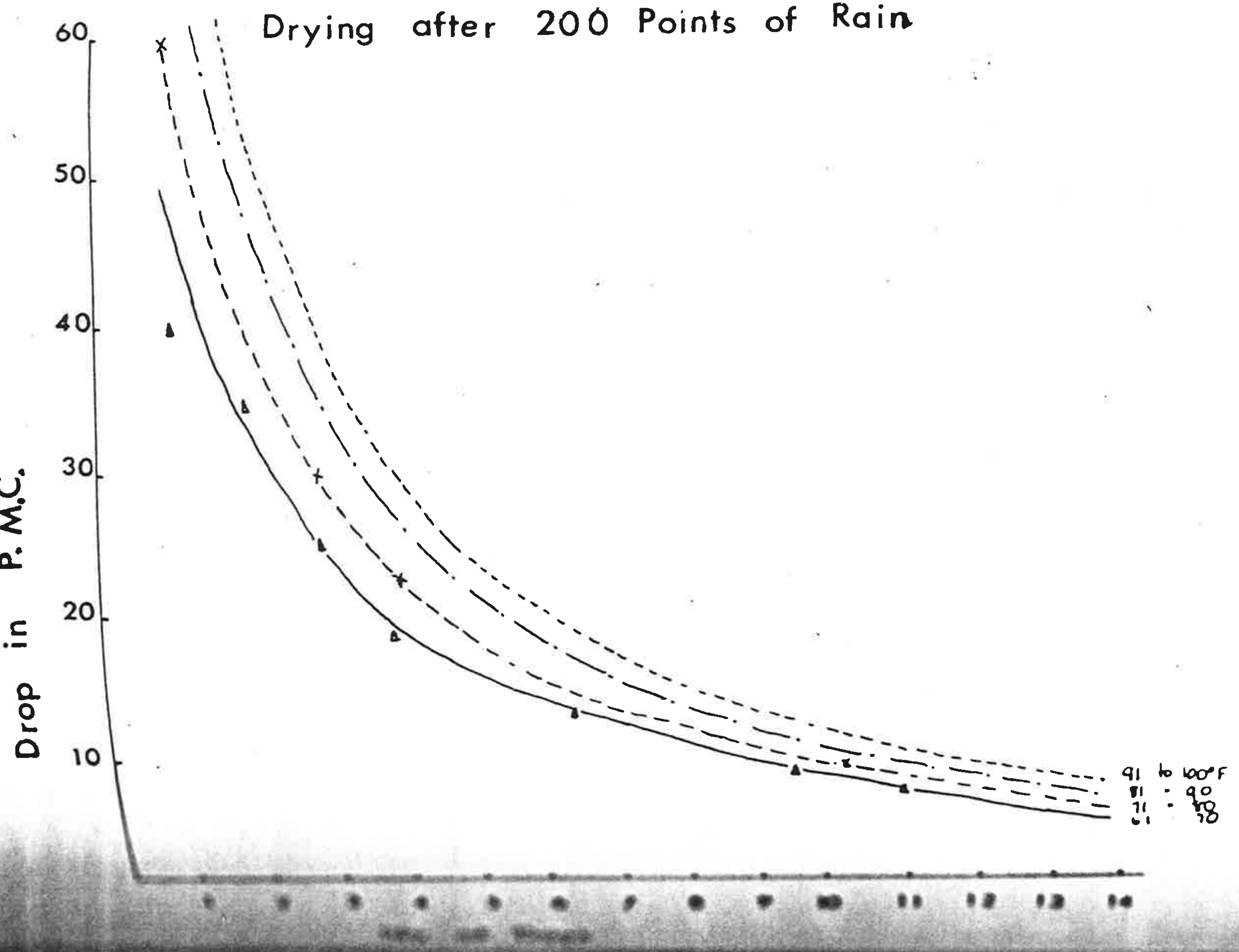
Equilibirum of Profile Moisture Content

The last requirement for calculating rainfall corrections was an estimate of equilibrium moisture content once rain effects had vanished.

The data were profile moisture contents and temperatures recorded at 100 experimental fires. In each sample the duff was dry with no apparent rain effects. However, it was not possible to keep the fuel depth constant, and it ranged

Graph 6

Drying after 200 Points of Rain



from 2.0 to 4.0 tons per acre.

The moisture samples were divided into temperature classes of five degrees F. and average percentages were calculated for each. This broad analysis was considered adequate for defining equilibrium of moisture content in temperature classes as wide as 10 - degrees.

Graph 7 (Appendix 4) plotted average moisture contents for each temperature class. There was a discernible trend, and a curve was eye-fitted to express the relationship. The expression for this curve was:

$$y = 1.39 \times 10^4 \times \left(\frac{1}{1.17}\right)^x + 7.4 \qquad 6$$

where y = Equilibrium of profile moisture content, per cent

x = Mid-point of average daily temperature class, degrees F.

This relationship showed the equilibrium moisture contents to rise quite sharply when temperatures fell below 61 degrees F. This led to the belief that very little drying takes place in jarrah litter when air temperatures are below 61 degrees F.

A drying day was defined as one with average daily temperature exceeding 61 degrees F. with no rain after 9 a.m.

Graph 7 was used to extract equilibrium of profile moisture content for five classes of average daily temperature. These are listed in Table 14.

TABLE 14

Equilibrium Moisture Contents for Classes of Average Daily Temperature

Average Daily Temperature degrees F	Equilibrium of Profile Moisture Content per cent
61 to 70	12
71 to 80	9
81 to 90	8
91 to 100	7

The assumption that equilibrium moisture content varied solely with temperature had one obvious flaw, the effect of response time. The influence of response time and changes in relative humidity was pointed out by King and Linton (1963).

Calculation of Rainfall Correction Factors

The three criteria necessary to calculate rainfall correction factors were now defined. The calculation was made in two steps.

Step 1

Rain-affected fuel was that with a moisture content between saturation (Table 12) and equilibirum (Table 14). The amount of drying required was the difference between these moisture contents. These amounts were listed in rainfall and average daily temperature classes.

Step 2

Each daily rainfall factor was the cumulative drying per cent (Table 13) divided by the amount of drying required, per cent.

An example of the calculation of rainfall correction factors is given in Table 15.

Table 15 sets out the calculation of rainfall factors for over 200 points of rain and average daily temperature between 61 and 70 degrees F. The initial moisture content was 230 per cent and the equilibrium was 12 per cent.

TABLE 15

A Calculation of Rainfall Correction Factor for over 200 points of rain

61 to 70 degrees F

No. of drying days	Drying Rate per day, table 7 (M.C. per cent)	Calculation	Rainfall Correction Factor
1	50	50 ÷ 216	0.23
2	34	84 ÷ 216	0.39
3	24	109 ÷ 216	0.50
4	19	128 ÷ 216	0.59
5	16	144 ÷ 216	0.66
6	14	148 ÷ 216	0.73
7	12	170 ÷ 216	0.78
8	11	181 ÷ 216	0.83
9	9	190 ÷ 216	0.87
10	8	198 ÷ 216	0.91
11	7	205 ÷ 216	0.95
12	6	211 ÷ 216	0.97
13	5	216 ÷ 216	1.00
Total 13	216		

The drying required was 230 per cent minus 12, equalling 218 per cent. Table 15 lists rainfall correction factors for each day up to a cumulative drying of 216 per cent, a close approximation to the amount required.

The same procedure as that shown in Table 15 was used to calculate rainfall correction factors for all seven rainfall classes (Table 12). The completed list formed Table B of the fire danger rating (Appendix 6).

The fire danger rating was now provided with facilities for calculating basic fire hazard, which represented moisture content of surface leaves, and for calculating adjusted fire hazard representing profile moisture content in a three-tons-per-acre litter.

Adjusted Fire Hazard and Profile Moisture Content

In the last sections of this chapter several partial experiments were put together to form adjusted fire hazard. It was important that this concept be properly tested to ensure that, in fact, adjusted fire hazard was a good proxy variable for profile moisture content.

Since the fire hazard scale is limited to 0 to 10, changes in it express the magnitude of fluctuations in profile moisture contents rather than a direct representation of actual values. It remained to establish the relationship between adjusted fire hazard and profile moisture content, and so give sound reasons for accepting fire hazard as a proxy variable.

This study was undertaken with data from 130 experimental fires. These fires burnt in litter beds between 2.0 and 4.0 tons per acre, the closest approximation that could be achieved to 3.5 tons per acre. The average profile moisture contents recorded at these fires ranged between 8 and 52 per cent.

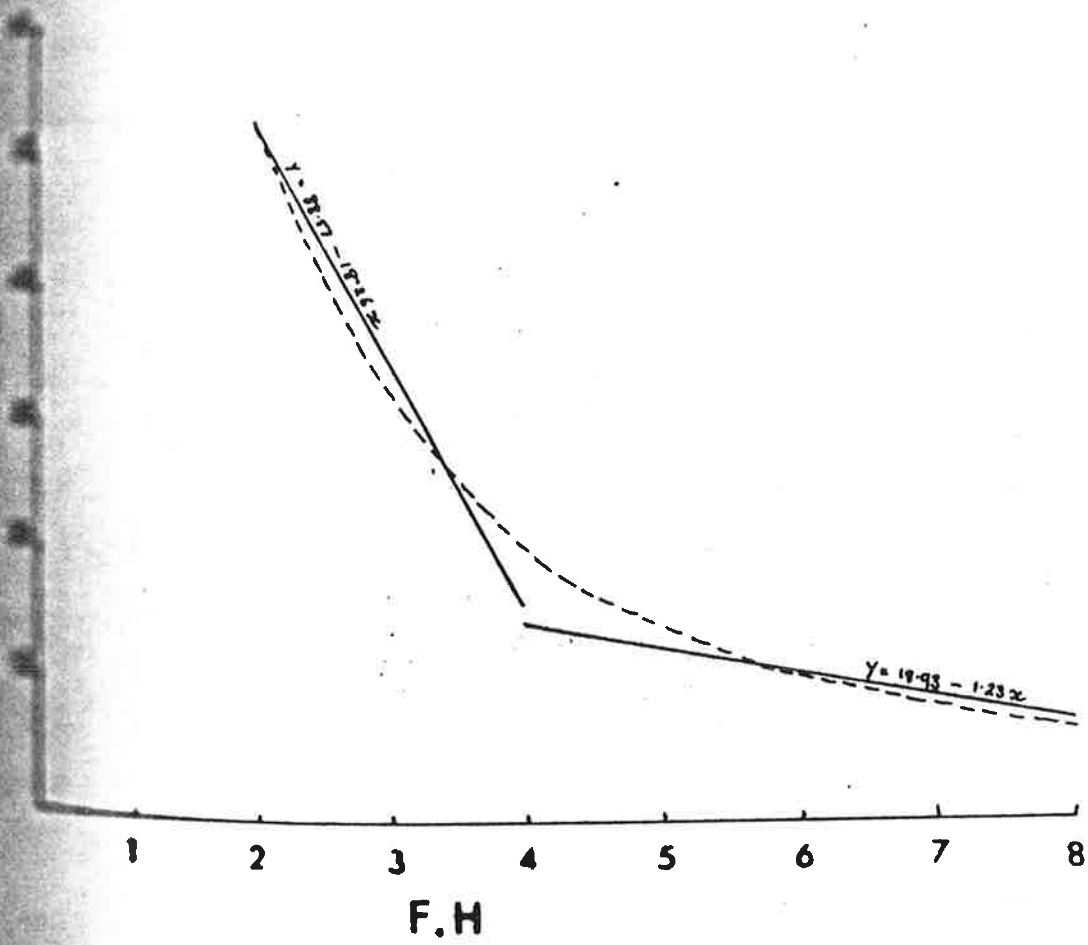
Adjusted fire hazard was calculated for each fire from weather data at Dwellingup. This station lay within 10 to 15 miles of most of the fire sites. The following data was used: air temperature, relative humidity, rainfall, number of drying days and average daily temperature in the drying period. The method of using this data in the fire danger rating will be explained later.

The measurements of adjusted fire hazard and profile moisture content were graphed together. The distribution of points suggested a curved relationship.

The data was divided into two groups of fire hazard and linear regressions were fitted to each. The two groups of fire hazard were 1.7 to 4.0 and 4.1 to 8.6. The division between them was the point where the exponential curved relationship appeared to rise sharply, (Graph 8). An eye-fitted curve was drawn over the two linear regressions to express the relationship.

Graph 8

Profile Moisture Content and Fire Hazard



The linear regressions were:

Adjusted Fire Hazard 1.7 to 4.0

$$y = 88.57 - 18.26x \qquad (7)$$

$$n = 17$$

$$r = -0.849 \text{ (sig. at 99 per cent)}$$

Adjusted Fire Hazard 4.1 to 8.6

$$y = 18.93 - 1.23x \qquad (8)$$

$$n = 113$$

$$r = -0.340 \text{ (sig. at 99 per cent)}$$

where y = profile moisture content, per cent

x = adjusted fire hazard.

The dispersion of points about the curve decreased as fire hazard rose. Dispersions were in the order of ± 10 per cent of moisture content for hazards between 1.7 and 3.0, ± 5 per cent between 3.0 and 6.0 and ± 3 per cent between 6.0 and 8.6. Moisture contents of the litter profile tended to be more uneven at the lower hazards, presumably due to differences in depth, hence rates of drying.

DISCUSSION OF RESULTS

The Concept of Fire Hazard

The objective for this study was to develop an expression of fire hazard which reflected moisture changes in a standard litter profile. Was this objective achieved? And is the logic of basic fire hazard and rainfall factors open to question?

Basic hazard and rainfall factors represent a separation of moisture trends in surface litter from trends in the profile. The need for this separation was supported in the format of the newly developed Canadian forest fire weather index (Canadian Forest Service, 1970). This index separates fuel inflammability into three components: fine fuels, duff and drought effect. Each component was measured separately with weather variables in much the same way as adjusted fire hazard. Finally the three components were combined for the Canadian index into a measure of inflammability.

Initially, fire hazard in the West Australian investigation represented changes in the moisture content of hazard rods. Experiments indicated that its relationship with jarrah leaf litter was similar (Table 12). In this context fire hazard covered a range of moisture content from five to 20 per cent. At 20 per cent the fire hazard was rated Nil, meaning negligible risk of ignition; at five per cent the fire hazard was rated Dangerous and fuels were extremely dry. This relationship is quite valid for surface leaves in a litter profile, where ignition is difficult to sustain at moisture contents exceeding 20 per cent. It is not valid for an average of a 3.5 tons-per-acre profile where ignition is sustained for moisture contents up to 50 per cent (Graph 8).

In Graph 8 a direct relationship was established between adjusted fire hazard and profile moisture contents up to 50 per cent. At 50 per cent the fire hazard was 1.7, or approaching Nil.

To maintain the fire hazard concept the range of moisture content covered by the scale must alter with type and depth of fuel.

For the jarrah litter beds considered here moisture contents up to 50 represent a small part of the whole, which extends to over 200 per cent at saturation (Table 12). Moisture contents above 50 are not of much significance in this fire hazard concept; they represent increasing degrees of wetness in a generally non-inflammable fuel. They are, however, important in defining stages of drying, especially when moistures are passing from a Nil hazard to a Low one.

In the adjusted fire hazard scale moisture contents between 50 and 230 per cent were assumed to cover the fire hazard range between 0 and 1.7.

The step-by-step build-up of adjusted fire hazard was similar to Van Wagner's (1970) construction of a duff moisture code for the Canadian forest fire weather index. Both systems used similar concepts, i.e. differences between moisture contents after rain and equilibrium, and an exponential expression for drying in between.

In these analyses actual measurements of the weather variables were used for the various relationships. In practice forecasts of fire hazard are used in many cases for planning of day to day fire control. The use of forecast rather than actual measurements must add erros to estimations of fire hazard.

Basic Fire Hazard

Basic fire hazard was used to express the moisture content of surface leaves. The relationship between maximum temperature, minimum relative humidity and hazard was the same for both hazard rods and surface leaves (Table 11).

Hatch (1969) showed that the estimate of fire hazard could be improved by adding a measure of overnight conditions, the morning moisture content of hazard rods. Similarly it could be expected that the estimation of basic fire hazard would improve with the addition of some measure of overnight weather. Sneeuwjagt (1970) showed that the number of hours that relative humidity remained above 70 per cent was a good indicator of overnight moisture increases. The minimum moisture content on that day depended on the initial moisture content in early morning. In turn, initial moisture content was regulated by overnight relative humidity. These results showed that the concept for basic fire hazard could be improved by including initial moisture content for the day and a measure of the overnight weather which affected it.

The inclusion of additional weather variables into basic fire hazard could also be profitable. The fine fuel moisture code for the Canadian index incorporates wind as well as relative humidity, for example.

The basic fire hazard relationship refers to surface leaves unaffected by rain, and a range of moisture content between 5 and 20 per cent. Like the profile, surface leaves may be saturated to moisture contents over 200 per cent. The same situation exists, however: these are all Nil hazards, and the difference between moisture contents merely express the dampness of already non-inflammable fuel. As such, they all fall within the Nil fire hazard.

Response time to changes in temperature and relative humidity may well affect the accuracy of prediction for basic fire hazard. These times could create discrepancies between predicted and actual moisture, and require further investigation.

Rainfall Correction Factors

The rainfall correction factors were intended to reduce basic fire hazard to an expression of profile moisture content for a 3.5 tons per acre litter bed.

The basis for this concept is fairly well supported by current theory on how layers of wet material dry. Perry et. al (1963) showed that wet layers including free water dry at a constant rate like a pool of water. As the wet surface decreases the layer dries at a diminishing rate, the rate being controlled by ambient vapour pressure deficit and affected by wind. As the moisture content falls still lower, drying is controlled by internal diffusion, and the moisture gradient governing this diffusion rate is affected by temperature and humidity.

If temperature and relative humidity are naturally well correlated in day-to-day weather, temperature could express drying rates quite satisfactorily. In this study there was some graphical evidence of drying differences between average daily temperatures, but the data was insufficient for a meaningful statistical appraisal. While evidence is sufficient to suggest that temperature is a controlling influence on drying, its measurement requires investigation, and also the question of whether averages through the day are sufficient.

Van Wagner (1970) summarized a considerable volume of evidence showing that drying was exponential with time. Similar relationships were used in this study, the rate changing with average daily temperature.

Van Wagner used noon measurements of temperature relative humidity and a third variable day length to measure rates of drying. These variables provided close correlation between predicted and actual drying rates, and gave a valuable basis for further work on the drying process.

Like average daily temperature, there was inconclusive evidence that noon measurements were sufficient to express the daily effect of either temperature or relative humidity. Firstly to separate these variables, then specify the best way to measure them in the mass of daily weather variables affecting drying was extremely complex. Rather than persue this approach, future studies could be better directed towards searching for a suitable integrator - nett radiation perhaps.

Van Wagner's treatment of rain effects posed other interesting comparisons. Light rains were separated from heavy ones on the basis of different wetting. The effect of rain was influenced by the initial moisture content as well as amount. This concept was a considerable advance on the profile moisture relationships after rain used here, and suggested a sound basis for expanding this section of the study.

The work of Sneeuwjagt and Van Wagner provided some valuable suggestions on how basic fire hazard and rainfall correction factors could be re-modelled. This remains for future investigations.

Chapter 6

THE FIRE DANGER RATING FOR JARRAH FOREST

One of the first considerations for compiling the fire danger rating was to select a suitable variable to express fire behaviour. This variable would reflect fire danger and, as such, it should be sensitive to changes in weather and fuel as well as providing a good basis for planning fire control.

Fire danger ratings with widespread use in U.S.A. Canada and Australia incorporate some expression of rate of fire spread as a variable of fire danger. The National Fire Danger Rating for the U.S.A. incorporates a spread index on a 0 to 100 scale, (U.S. Forest Service, 1966). The Canadian system incorporates a spread phase in calculating a forest fire-weather index, (Canadian Forest Service, 1970). In Australia, McArthur's forest fire danger meter uses a 0 to 100 scale on which changes in flame height, spotting distance and rate of spread are described.

Rate of forward spread of headfire has proved useful for planning fire suppression and controlled burning, (Peet, 1965 ,1967) and the evidence suggested it would be sufficiently sensitive to changes in weather and fuels to be a useful measure of fire danger. Means for predicting forward spread required detailed consideration.

The U.S.A., Canadian and Australian fire danger systems use weather variables to predict moisture content for litter fuels. The rapid fluctuations for fine fuels were expressed by weather variables such as air temperature, relative humidity and past rainfall. The slower seasonal drying of heavy fuels was approximated by drought indexes which show cumulative drying effects. For a fire danger rating these estimates of fuel moisture were joined with wind velocity to express fluctuations in spread index. The Australian system incorporated additional adjustments for changes in fuel quantity.

The treatment of weather and fuel variables was similar for all three fire danger systems. The variables were added to fire danger in a step by step process without evident allowance for interaction between them. Secondly, fairly complex predictions of fuel moisture were loaded with wind velocity for a fire danger rating. This format seemed a good pattern for the jarrah fire danger rating.

McArthur (1967) listed seven variables which affect rate of forward spread in eucalypt forests. These were: moisture content of the fuel, wind velocity, quantity of fuel, fuel size and arrangement, slope, atmospheric instability and spotting. Each had to be considered for inclusion in the fire danger rating. It was evident some would be useful; others would be rejected because of difficulties in measurement or in defining their effect in a jarrah forest environment.

Facilities for measuring weather at most forest centres in the jarrah forest were limited to third order weather stations, (Bureau of Meteorology, 1954). Atmospheric instability was rejected because it could not be measured easily. Fuel size and arrangement was thought to be unsuitable because of difficulties in measuring changes under forest conditions. Spotting potential was not understood well enough for prediction purposes.

The three variables remaining in McArthur's list were used to predict fire danger for the U.S.A., Canadian abd Australian systems. Moisture content, wind velocity and fuel quantity are generally well understood by foresters and simple systems for estimating them could be devised.

It was decided the jarrah rating would be constructed from the same three variables. This was considered a compromise between the number needed for accurate predictions of spread, the number that could be extracted from sparse data, and what could be measured each.day. Fire hazard would be joined with wind velocity to predict rates of spread in a standard three tons per acre litter. Afterwards adjustments to spread would be made for different litter quantities.

The general acceptance of fuel moisture, wind velocity and fuel quantity into fire danger systems suggested they should combine as overriding controls in most forest fire situations. It was accepted certain conditions could affect this control, such as intensive atmospheric instability or steep slopes.

Data for the jarrah fire danger rating was provided by 130 experimental fires lit in the spring and summer months of three fire seasons. A further 70 autumn fires were used for checking the prediction tables. They were all in jarrah forest near Dwellingup.

The range of weather and fuel conditions for the spring and summer fires were:

Air temperature	60 to 95 degrees F.
Relative humidity	10 to 75 per cent.
Litter quantity	0.5 to 5.5 tons per acre
Wind velocity at 4 feet	0.3 to 7.0 miles per hour.
Profile moisture content	6 to 50 per cent.

Litter quantity was the only variable controlled to any extent; through selection of the fire sites. The others depended on day to day changes so were not necessarily combined at the top or bottom extremes of the ranges. The range of spread rates measured during these fires, and associated fuel and weather, is shown in Table 16.

Table 16

Extremes of Forward Spread

Fuel and Weather for Experimental Fires

Rate of Forward Spread ft./min.	0.1 to 5.6
Litter Quantity tons/acre	2.0 to 3.0
Temp. degrees F.	69 to 87
Relative Humidity per cent	62 to 24
Profile Moisture Content per cent	50 to 5
Wind at 4 feet m.p.h.	0.5 to 3.0

Development of the Fire Danger Rating.

This section sets out the analyses and steps employed to put the fire danger rating together.

The method of analysis for the fire data was guided by the short-cut graphic method outlined by Ezekiel and Fox (1963). The main reasons for adopting this approach were a lack of computer facilities at the time of the study, in 1964, and the need to start with basic concepts for function of each variable. The graphic approach proved useful for determining the best function for each variable in this data.

Some of the graphs used in these analyses lie in the appendix, others are in the text. To maintain continuity of presentation each relationship will be described by formulae which approximate the curves shown in the graphs. These formulae are approximations because in most cases, the curves were eye-fitted. Formulae were fitted to the curves using the successive approximation method outlined by Jensen (1964).

The graphic approach used here basically followed these steps. All rates of spread were plotted against one of the variables, wind velocity for example. Thereafter a section of the graph was extracted where fuel quantity remained reasonably constant between individual fires. This section was used to test the effect of fire hazard on the wind-spread relationship.

This procedure aimed to test the effect of an independent variable on rate of spread by keeping the other two variables as constant as was feasible. In the stratum of data created this way graphic analysis was employed to discover the function of the tested variable.

The limited amount of data usually meant a paucity of observations in an individual stratum. Relationships were eye-fitted for this reason and to ensure sensible curves were used. The form of the curve was biased by the findings of other researchers especially where the scatter of points meant several different types of curve could be eye-fitted equally well.

Fire Hazard and Rate of Spread

Controls were imposed over wind velocity and fuel quantity in the fire data in order to extract a number of spread rates revealing the influence of fire hazard.

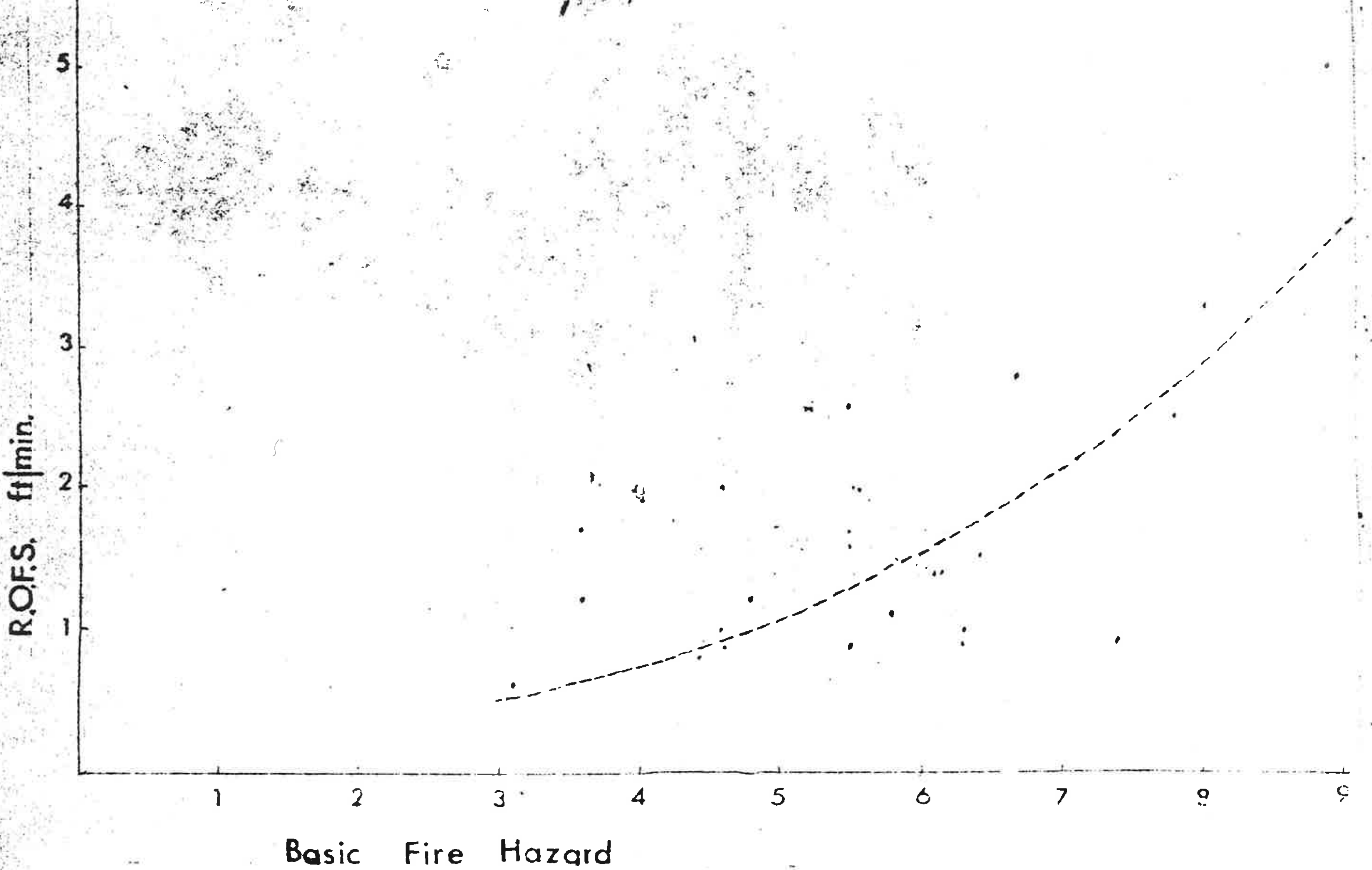
A group of fire data was extracted by imposing these controls: wind velocity at four-feet was restricted to 2.0 to 2.5 miles per hour and litter quantities to 2.0 to 3.5 tons per acre. One additional control was used, profile moisture contents had to be less than 16 per cent.

The additional moisture control was imposed because the main discrepancies between fire haxard and moisture content took place when rainfall corrections were made, i.e. the lower litter layer was damp. Rain-affected data was rejected by limiting the range of profile moisture content.

There were 25 fires in the stratum of data created by these controls. For each fire, basic fire hazard was calculated from daily maximum temperature and minimum relative humidity recorded at Dwellingup. Graph 9 shows basic fire hazard for each fire plotted with its average rate of forward spread.

Graph 19

Rate of Forward Spread and Basic Fire Hazard



There was no clear-cut relationship between fire hazard and forward spread, but a curved one was fitted to the rising trend of points after consulting the findings of other researchers, principally Fons (1946). This curve was approximated by the formula:

$$y = 0 + 0.043x^2 \qquad (9)$$

Where y = Rate of forward spread in feet per minute

x = Basic fire hazard.

Wind Velocity and Rate of Spread

A similar method was used to study the effect of wind velocity on forward spread. For the variable a number of strata were graphed to establish the form of the relationship with forward spread and, secondly, one of these graphs was selected to represent wind effects in the fire danger rating.

A group of 60 fires was extracted by specifying a profile moisture content less than 16 per cent. This was done to avoid rain effects for the reasons previously mentioned.

Litter quantity was used to divide these 60 fires into three strata, fires where quantity was limited to 1.0 to 1.5 tons per acre, those between 1.5 and 2.0 and another stratum with quantities between 4.0 and 4.5 tons per acre.

Within each stratum the fires were divided into wind classes of 0.5 miles per hour to reduce the scatter of points. Rates of spread were plotted in each wind class and curved relationships were eye-fitted, (Graphs 10, 11 and 12, Appendix 5).

For each graph the curve seemed similar, a function of x^3 or x^4 for wind, e.g. Graph 12 could be approximated by the formula $y = 0.800 + 0.021x^4$ This type of curve was accepted after studying the wind-spread relationships put forward by Fons (1946) and McArthur (1962).

For the fire danger rating, a wind-spread relationship was derived by extracting another 30 fires from the data, all with fuel quantities between 3.0 and 3.5 tons per acre. The data was treated the same way, fires were divided into wind classes of 0.5 miles per hour. Rates of forward spread in each class were averaged and a curve eye-fitted to the points (Graph 13). It was decided this curve would be expressed with an x^4 function for wind even though the calculated values rose rather steeper than the eye-fitted ones for velocities above 4.5 miles per hour. Since these were extrapolated on the graph anyway the discrepancy was accepted for this descriptive purpose. The formula was:

$$y = 0.80000 + 0.00317x^4 \qquad (10)$$

Where y = Rate of forward spread in feet per minute

x = Mid-point of wind class in miles per hour.

Graph 13 was used to express a wind-spread relationship for the fire danger rating. It represented wind effects in

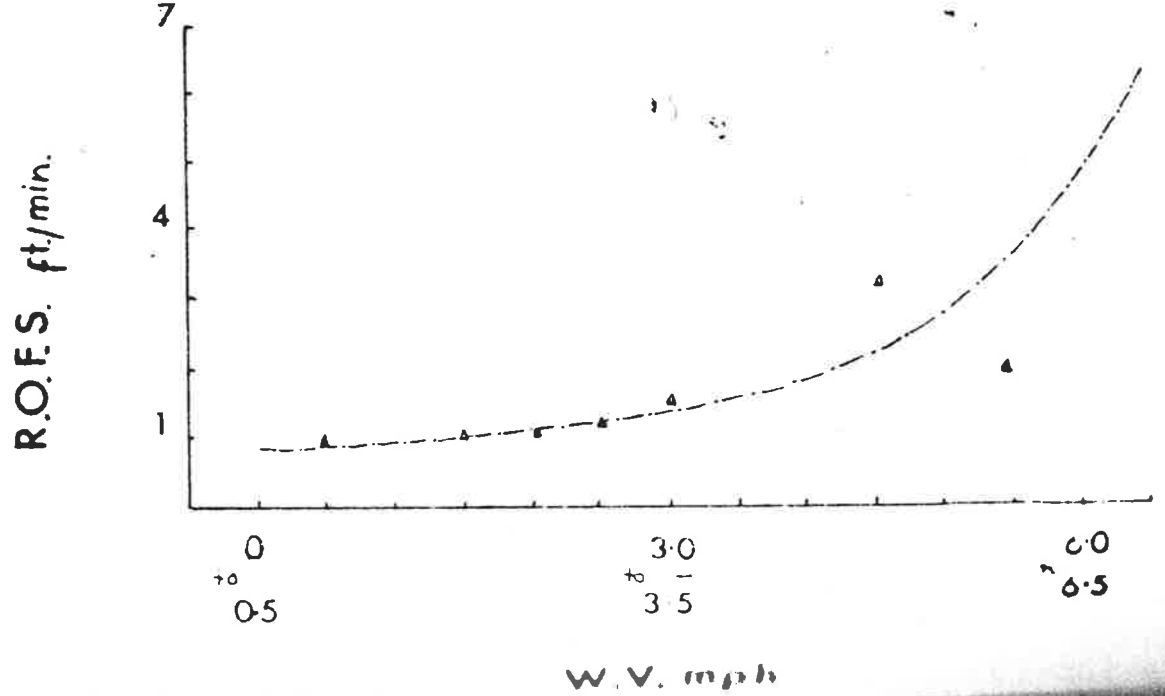
Graph 13

Wind Velocity and Rate of Forward Spread

F.Q. 3·0 to 3·5

Av. F.H. 5·3

Key Graph for F.D. Rating



a 3.0 to 3.5 tons per acre litter, the standard weight selected for the danger rating. Since this curve was similar to those expressing wind effects in the other three litter quantities tested here it seemed reasonable to extrapolate this wind-spread function to them without the risk of incurring major errors in prediction.

Fire Hazard and Wind Velocity

In the fire data contributing to Graph 13 the range of basic fire hazard was quite small, i.e. 5.1 to 5.7. The average of 5.3 was used to link this wind-spread relationship with fire hazard.

Graph 9, showing the relationship between fire hazard and spread, was used to draw a nest of curves around Graph 13. These curves represented wind-spread relationships for each hazard class between Nil and Dangerous. The spacing of the curves was worked out from Graph 9, each space representing the difference in spread rate between a hazard of 5.3 and hazard at the start of each class, e.g. Average Summer 6.1. These hazard spacings were shown in Table 17 which lists distances in terms of forward spread for curves above and below the standard one in Graph 13.

Table 17

Adjustments to Rate of Spread for Basic Fire Hazards Above and Below 5.3

Fire Hazard	Hazard Class	Forward Spread from Graph 9 ft./min.	Difference from Fire Hazard 5.3 ft./min.
1.1	Low	0.2	-1.0
4.1	Moderate	0.8	-0.4
5.3		1.2	0
6.1	Average S	1.6	+0.4
7.1	High S	2.2	+1.0
8.1	Severe S	3.0	+1.8
9.1	Dangerous	4.0	+2.8

Graph 14 shows the nest of wind-spread curves used for calculating the fire danger rating. To aid in calculation of the rating these curves were expressed in a table as progressive multipliers of forward spread (Table 18).

This example, from the curve for Average Summer, shows how the multipliers were used. Referring to Table 18, forward spread in 0.01 to 0.50 wind class is multiplied by 1.09 for spread in the 0.51 to 1.00 miles per hour class and that is multiplied by 1.10 for forward spread in the 1.01 to 1.50 class and so on up to the 6.51 to 7.00 class.

Graph 14

Wind Velocity Fire Hazard and Forward Spread

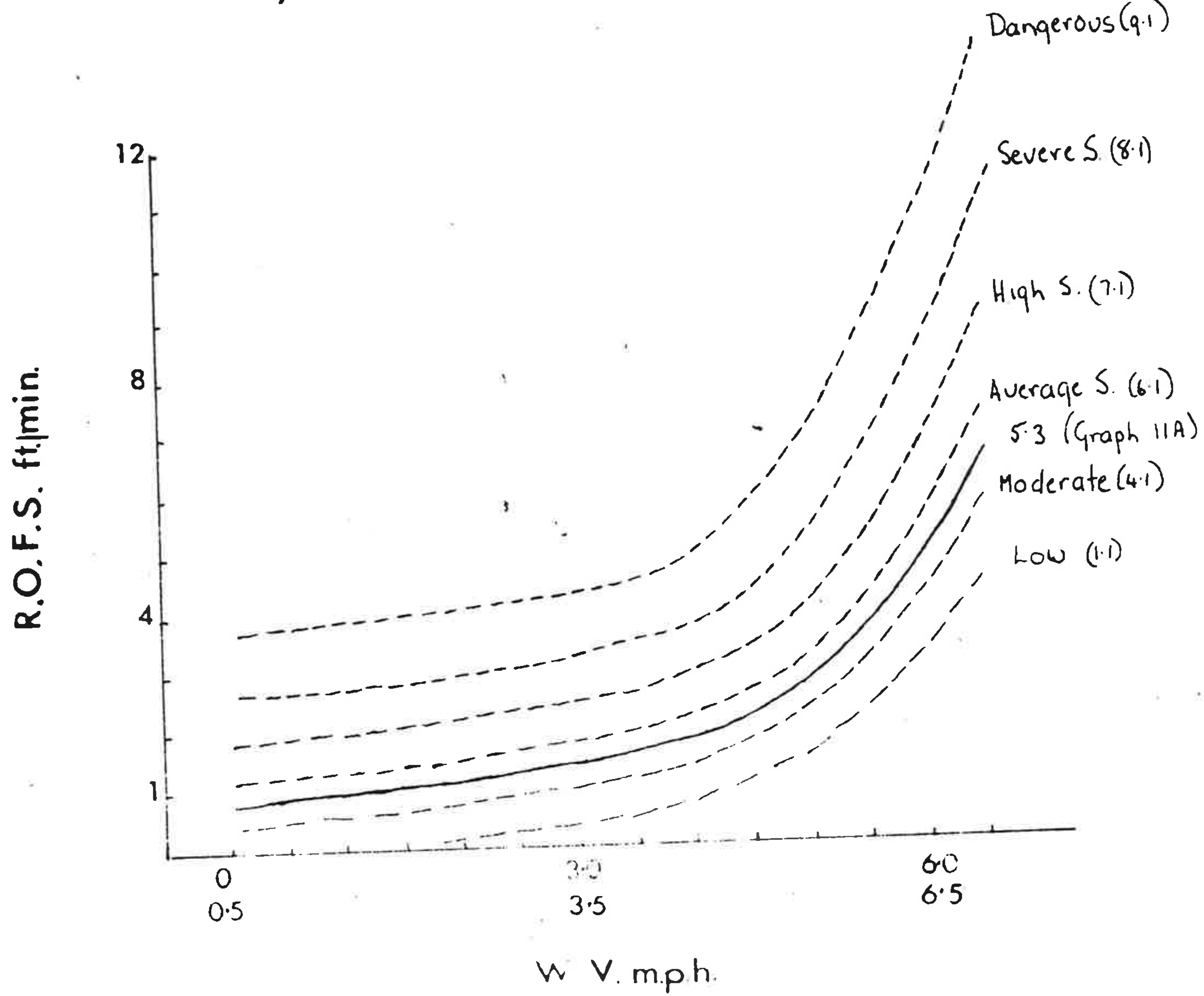


Table 18

Progressive Multipliers for Wind Velocity Classes

Fire Hazard	0.0 to 0.5	0.5 to 1.0	1.01 to 1.50	1.51 to 2.00	2.01 to 2.50	2.51 to 3.00	3.01 to 3.50	3.51 to 4.00	4.01 to 4.50	4.51 to 5.00	5.01 to 5.50	5.51 to 6.00	6.01 to 6.50	6.51 to 7.00
Nil		1.15	1.16	1.17	1.18	1.19	1.20	1.23	1.25	1.28	1.31	1.34	1.35	1.35
Low		1.15	1.16	1.17	1.18	1.19	1.20	1.23	1.25	1.28	1.31	1.34	1.35	1.35
Moderate		1.12	1.13	1.14	1.15	1.16	1.17	1.18	1.20	1.25	1.30	1.32	1.35	1.35
Average S		1.09	1.10	1.12	1.13	1.14	1.15	1.17	1.20	1.25	1.28	1.30	1.32	1.35
High S		1.08	1.09	1.10	1.11	1.12	1.14	1.16	1.18	1.22	1.28	1.31	1.34	1.37
Severe S		1.04	1.06	1.08	1.10	1.12	1.14	1.17	1.20	1.25	1.30	1.32	1.36	1.40
Dangerous		1.03	1.05	1.07	1.09	1.11	1.14	1.17	1.20	1.26	1.30	1.32	1.36	1.40

Litter Weight and Rate of Spread.

Fires with profile moisture contents less than 16 per cent were used again, this time to study the effect of increasing litter weight on rate of fire spread. From this group a stratum of 26 fires was extracted, all with wind velocities between 1.5 and 2.0 miles per hour.

One more subdivision of data was employed in this stratum, fires which burnt under low and Moderate fire hazards were separated from those which burnt under Severe Summer and Dangerous. This control was imposed to separate out fire hazard effects from those due to fuel weight.

The fires in each hazard group were divided into half-ton litter classes and rates of spread were plotted. The relationship between increasing litter weight and increasing spread was not clear-cut (Graphs 15 and 16).

The fuel weight-spread relationships developed by Fons (1946) and McArthur (1962) provided the basis for fitting linear relationships to these two graphs. These relationships were:

Low and Moderate Fire Hazard (Graph 15)

$$y = 1.100 + 0.046x \qquad (11)$$

Severe Summer and Dangerous Hazard (Graph 16)

$$y = 0.500 + 0.550x \qquad (12)$$

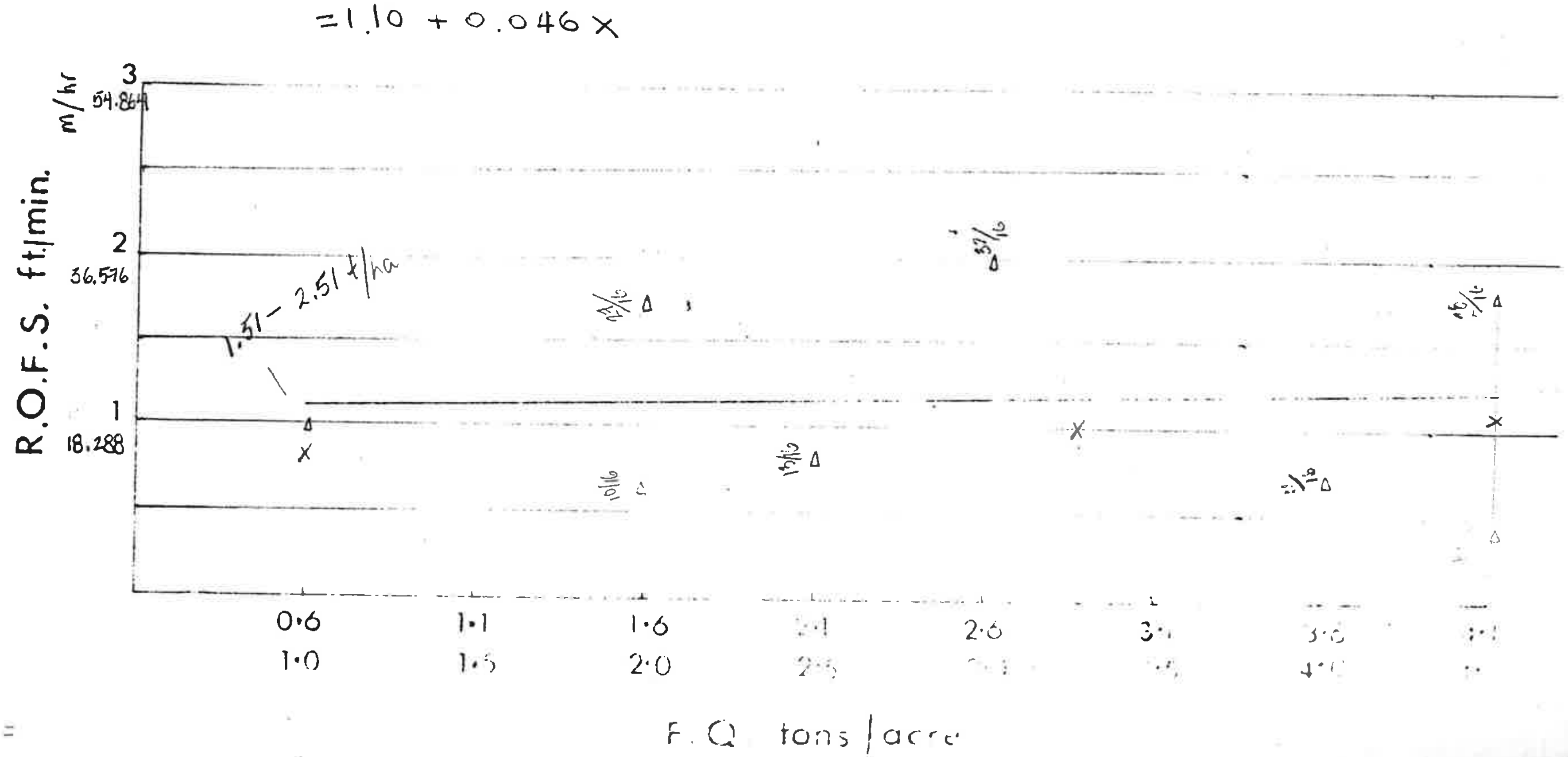
Where y = Rate of forward spread in feet per minute.

x = Mid-point of fuel class in tons per acre.

Graph 15

Fuel Quantity and Rate of Forward Spread

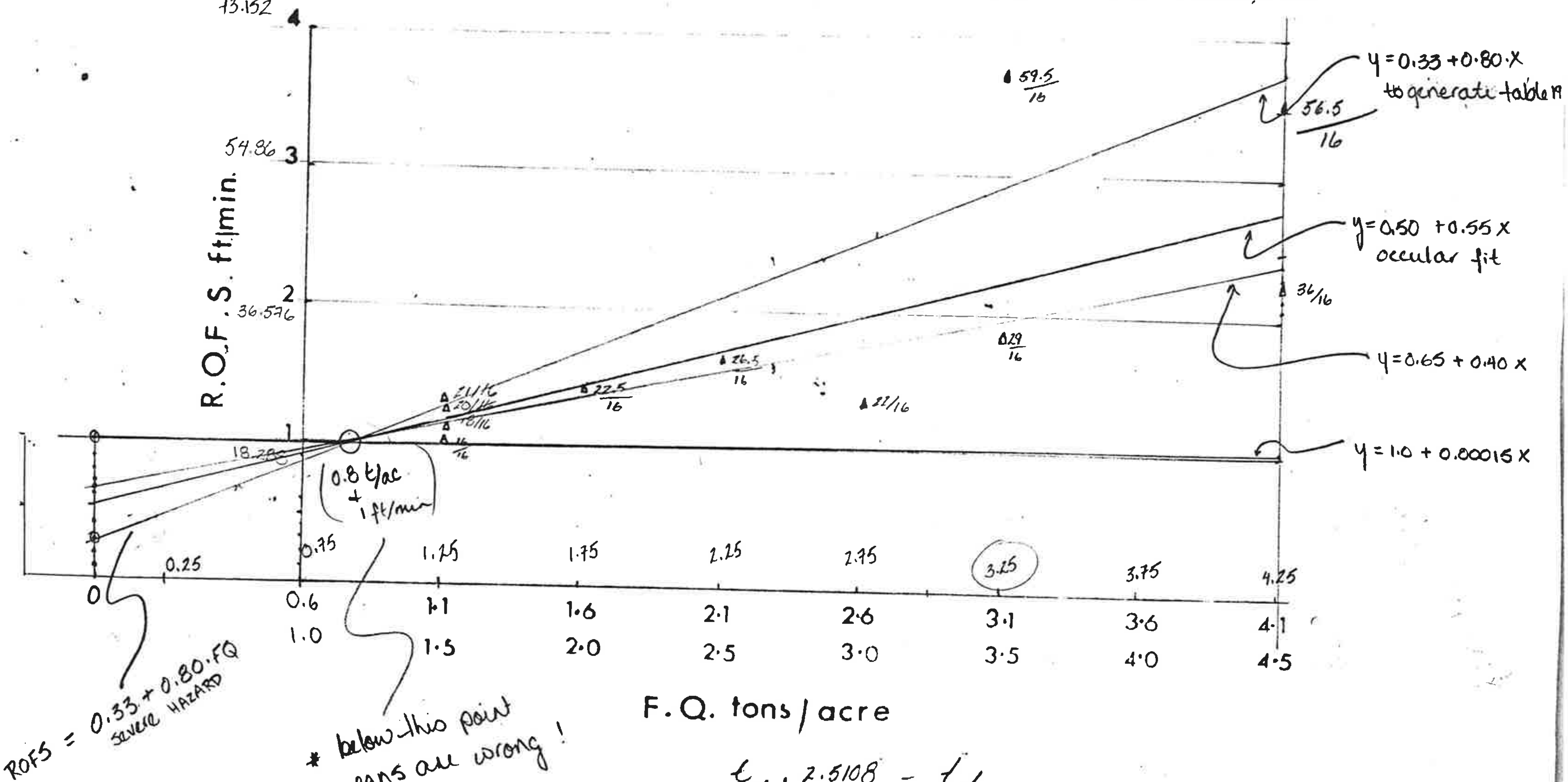
MODERATE and LOW HAZARD



Graph 16

Fuel Quantity and Rate of Forward Spread

DANG. and SEV. HAZARD



$\frac{t}{ac} \cdot 2.5108 = t/ha$

Separate "tray" experiments were used to test the linear relationship for fuel weight. Various weights of jarrah litter were burnt in metal trays and the rate of fire spread was measured from one end of the tray to the other.

The trays were 10 feet long and 1.5 feet wide. They were fixed three-feet above ground level and evenly spaced in a compound with ten-feet high walls. The purpose of the compound was to minimize wind effects without impairing the escape of smoke. Fuel weights were rotated between trays after each burn to avoid bias from wind eddies. Wind was measured but never exceeded 0.5 miles per hour.

This experiment included six different litter weights ranging from 650 to 3,200 grammes per tray. The burning was replicated 20 times before spread rates were compared. Graph 17 (Appendix 5) shows the relationship between rate of spread and increasing litter weight derived by this experiment. The relationship was:

$$y = 0.95000 + 0.00015x \qquad (14)$$

Where y = Rate of forward spread in feet per minute

x = Litter weight in grammes per tray.

There was significant correlation between spread rates and increasing litter (99 per cent level of confidence) but fairly massive increases in litter were necessary to produce really significant changes in spread. This was evident in the slope of the regression. Differences in spread were only statistically significant between 650 grammes and 2500 grammes or higher. In addition litter weight only accounted for 9.5 per cent of the variation in spread rates indicating it had not exerted a strong control.

Although fairly uniform weather was chosen for this experiment moisture contents of the litter ranged between three and 11 per cent. This range of moisture accounted for 15 per cent of the variation in spread rates suggesting is exerted a stronger influence than litter weight.

The same experiment provided additional evidence a linear relationship was suitable for litter spread relationships in jarrah and confirmed the necessity of separating out moisture effects.

The relationships shown in Graphs 15 and 16 were used for fuel corrections in the fire danger rating. Additional corrections for the Average and High summer hazards were taken as the mid-point between the two graphs. These corrections were multipliers which adjusted rate of spread in 3.0 to 3.5 tons per acre of litter to a range of other litter weights.

An example from Graph 16 shows the method for calculating fuel corrections. Rate of spread for 3.1 to 3.5 tons per acre was 2.3 (Standard) feet per minute rising to 3.0 feet per minute for 4.1 to 4.5 tons per acre. The fuel

2.9 - 2.84 rounding error

correction which adjusts 2.3 to 3.0 is 1.3. Corrections were worked out this way in the three hazard classes for fuels between 1.5 and 4.5 tons per acre, (Table 19).

Table 19

Rate of Spread Corrections (Multipliers) for Litter Weights other than 3.0 to 3.5 tons per acre.

Litter Quantity tons per acre	Fire Hazard Class: Low Moderate	Fire Hazard Class: Average S High S	Fire Hazard Class: Severe Dangerous
1.50 to 2.00	0.88	0.71	0.61
2.01 " 2.50	0.92	0.77	0.74
2.51 " 3.00	0.96	0.88	0.87
3.01 " 3.50	1.00	1.00	1.00
3.51 " 4.00	1.04	1.12	1.17
4.01 " 4.50	1.08	1.21	1.30

Construction of the Fire Danger Rating

These partial experiments had provided enough information to join fire hazard with wind velocity to predict forward spread in three tons per acre of litter. Further, spread rates could be adjusted for litter weights between 1.5 and 4.5 tons per acre. It remained to construct the fire danger rating by putting these experiments together.

Five steps were used to put the fire danger rating together:

Step 1. Rates of spread at the start-point of each hazard class were taken directly from Graph 14. Changes between these points were smoothed.

Step 2. The progressive multipliers listed in Table 18 were used between the start and mid-point of each hazard class, e.g. Average Summer 6.1 to 6.5.

Step 3. The progressive multipliers change with rising fire hazard. Rates of spread between the mid-point and top of each hazard class were smoothed. Each hazard between 0.6 and 10.0 was allocated a range of forward spreads which increased with wind velocity. These spread rates formed Table C of the fire danger rating (Appendix 6).

Step 4. Table C was subdivided into nine fire danger classes designated by a colour code (Table 20). The nature of this subdivision was based on range of data and on requirements for controlled burning.
For Table C spread rates above 5.6 feet per minute were extrapolated. Since the prediction of higher spreads would be prone to error these danger classes were wide. The lower danger classes were narrow because the data was concentrated there, and because spread differences were important for

planning controlled burning.

Step 5. Corrections for fuel were added so that rates of spread from Table C could be adjusted above and below 3.1 to 3.5 tons per acre. These were shown in Table 19 which now became Table D of the fire danger rating (Appendix 6).

Table 20

Fire Danger Classes

Rate of Spread feet per minute	Fire Danger Class
Greater than 20.1	Red
16.1 to 20.0	Pink
12.1 to 16.0	Orange
7.1 to 12.0	Yellow
3.1 to 7.0	Brown
2.1 to 3.0	Blue
1.1 to 2.0	Green
0.6 to 1.0	Purple
Less than 0.6	White

Day to Day Estimates of Fire Danger.

When the fire danger tables were first presented for field use there were quite wide variations in estimates, depending on interpretation of weather and fuel variables by individual observers.

It was necessary to undertake further research to standardize measurement techniques for weather, and to provide guides on litter accumulation. These experiments are explained here, together with recommendations for using the fire danger tables.

Fire Hazard

An estimate of the day's fire hazard is provided each morning during the fire season as part of the fire-weather forecast.

These forecasts cover large areas, i.e. the jarrah and karri regions, so adjustments are often necessary for particular forests. Adjustments may be necessary for a forest division or even the smaller district (W.A. Forests Dept. 1964) depending on the variability of past and present weather.

Variability in hazard occurs quite often after rain, e.g. in the Dwellingup division. Rainfall in the forest near Dwellingup can exceed twice the amount in the eastern forest (refer Table 1). In the days which follow, controlled burning can be successful in the eastern forest while the western area is too damp. This difference was important in planning day to day fire operations.

Daily forecasts of maximum temperature and minimum relative humidity are provided for two centres, Dwellingup and Pemberton. For calculations of local basic fire hazards these may need adjustment. Unfortunately there is little quantitative information on which to make day to day adjustments, although monthly averages for individual centres, (Bureau of Meteorology, 1954) provide a rough guide. Conversely, when fuels are dry and weather patterns for the day are uniform, local adjustments to the forecast may be unnecessary. The basis for adjustment is experience of local conditions supported by measurements of day to day differences with the forecast centre.

Each morning, a local estimate of basic fire hazard is made from forecasted temperature and relative humidity, adjusted if necessary. The calculation comes from Table A of the fire danger rating (Appendix 6) where maximum temperature lies on the vertical axis and minimum relative humidity on the horizontal one. Basic fire hazard is at the junction of the two axes.

After rain, basic fire hazard is adjusted with correction factors from Table B of the fire danger rating. The derivation of this factor has been the main source of discrepancies in estimating fire danger. These discrepancies can be minimized by keeping standard weather records. A suggested form of recording is given in Table 21, showing a list of measurements required from the weather station.

Table 21

Weather Records for Rainfall Correction Factors

Date	Screen Temperatures Degrees F.				Average Daily Temp.degrees F.	Rainfall to 9.a.m. Points
	10 a.m.	12 noon	2 p.m.	4 p.m.		

The three variables necessary for rainfall correction factors were shown in Table 21.

Average daily temperature is the mean of screen temperatures at 10 a.m., 12 noon, 2 p.m. and 4 p.m. The temperature class in Table B is selected with the mean of average daily temperature for all drying days since rain.

The number of drying days since rain includes all days when no rain fell after 9 a.m. and with average daily temperature exceeding 60°F.

The rainfall class is selected by totalling amounts of rain which fell on successive days. Where falls were divided by drying days, separate correction factors are calculated for each, and the lowest one is used.

Wind Velocity

The measurement of wind velocity needed more research before spread rates could be predicted with reasonable confidence.

The most convenient source for regular wind readings in jarrah forest were the fire detection towers. These were manned continuously on dry summer days and are usually well placed to measure wind flow over the forest.

Wind measurements at four feet in the forest were not so easily obtained over a range of forest sites, especially early in the morning when they were needed for planning of operations like controlled burning.

This was the reason for an experiment to measure ratios between wind velocity on a tower, and velocity at four feet in the forest. Eight sites were picked in forest around a tower ranging from one to five miles from it. The tower was 1600 feet above sea level, and the sites 400 to 600 feet below on flat or upper slope topography.

Wind velocities at the site was compared with the tower every two minutes for a 30 minute period. The anemometer at the site was four feet above ground level, and the one at the tower was above the cabin so that wind flow over it was unimpeded.

The average velocity for each two-minute period in the forest was multiplied by the appropriate factor to equate it with the average tower velocity at the same time. A plot of these adjustments, for two sites, is shown in Graph 18 (Appendix 5). The multiplier for forest wind fluctuated with velocity and site characteristics such as distance from the tower and topography. However, an average for the eight sites was accepted, i.e. velocity on the tower was assumed to be five times greater than velocity at four feet in the forest.

For convenience in planning, both tower velocity and four feet velocity were shown in the fire danger rating (Table C). When using the tables it must be remembered the tower velocity is an interpretation of the four feet one, hence prone to errors. Each tower should be checked to ensure wind velocities are approximately five times greater than within the surrounding forest.

Most of the fire detection towers in the jarrah forest region are equipped with Dwyer mantel model wind meters. Unlike the sensitive cup anemometer these do not measure wind run but an instantaneous measurement of velocity. This meant testing the Dwyer meters so that a suitable system of measuring average velocities could be formed. It was found several spaced readings were necessary before the meter approximated the velocity for the anemometer. Maximum and minimum gust strengths were recorded for five minutes. The average for five minutes usually gave a reasonably close approximation to the average velocity for the anemometer, measured over the same period.

Estimates of fire danger may use either a forecasted or measured wind velocity, depending on the purpose of the estimate. Forecasts are necessary for the early morning planning of operations like controlled burning. Since forecasts are prone to error, fire danger terminology should specify what winds were used, forecast or actual ones.

Litter Accumulation

A knowledge of rate of litter accumulation is a necessary prerequisite for planning of fire control in jarrah forest. It forms the basis for deciding controlled burning rotations and day to day decisions such as disposition of suppression forces (Peet, 1967).

It was necessary to conduct a separate experiment in order to provide a reliable guide on litter accumulation in jarrah forest. Since this work was necessary before the fire danger rating was of much practical worth, it is pertinent to explain the work here.

The principles of litter accumulation in jarrah forest were already established. Leaf fall occurs each year in summer (Loneragan 1962), and for this study January was used to separate one fall from the next. Rate of accumulation was influenced by number of annual leaf falls since the last burn, and by canopy cover (Hatch, 1955).

This work gave insufficient detail on litter accumulation between one and five leaf falls, nor were the canopy ranges wide enough. It was decided to concentrate on one to five leaf falls because this range was important to planning of rotational controlled burning (Peet, 1967). Canopy cover was extended to four classes, 20, 40, 60 and 80 per cent crown cover over the forest floor.

Each age between one and five leaf falls was sampled in the four canopy classes. Two forest areas were selected for each age-canopy stratum. Age of each sampling area was determined from records of past controlled burning and canopy from aerial photo interpretation plans (A.P.I).

The A.P.I plans showed canopy cover of the forest as a percentage cover over the forest floor. These percentages were checked at each sampling point with a spherical densiometer to ensure they approximated the mapped one.

It was required the past controlled burn be clean and of good quality. Where patchiness or heavy scorch were evident the area was rejected.

Each stratum (e.g. three annual leaf falls and 20 per cent canopy, or three annual leaf falls and 40 per cent canopy) were sampled in two forest areas to avoid bias from particular site characteristics such as topography or past fire history.

Five sampling sites were randomly selected in each forest area. At each site five quadrat samples were collected after ensuring canopy cover and fuel accumulation were as forecast.

Each sample of litter included all leaves and twigs up to half an inch in diameter, from four-square-feet of forest floor. Weights at each site were averaged and expressed in tons per acre equivalent oven dry weight. These average weights expressed litter accumulation for that stratum.

The relationship of litter weight with age and canopy cover was established with multiple regression analysis. This was done with the computer at the University of

Western Australia, (Type P.D.P. -6) using the Fortnan programme M.R.-40-T.

In the first part of this analysis an attempt was made to show the function of best fit for each variable. Litter quantity, age and canopy were assigned four transformations, linear, squared, square-root and logarithm. This covered the range suggested by Hatch's earlier work, and by general observations of the data. Then the transformations were rejected one by one in stepwise regressions. Changes in the coefficients of determination and correlation were used to choose the regression of best fit. It was:

$$y = (0.1932x_1 + 0.8067 \log x_2 - 0.6245)^2 \qquad (13)$$

Where y = litter quantity in tons per acre equivalent oven dry weight.

x_1 = number of annual leaf falls.

x_2 = canopy cover per cent.

This expression for litter accumulation was statistically significant at the 99 per cent level of confidence. It covered 80 per cent of the variation in litter quantity.

For use in planning controlled burning rotations and fire suppression the regression was transformed into a table of litter accumulation (Table 22). Providing age and canopy are known this table gives the means for calculating litter accumulation.

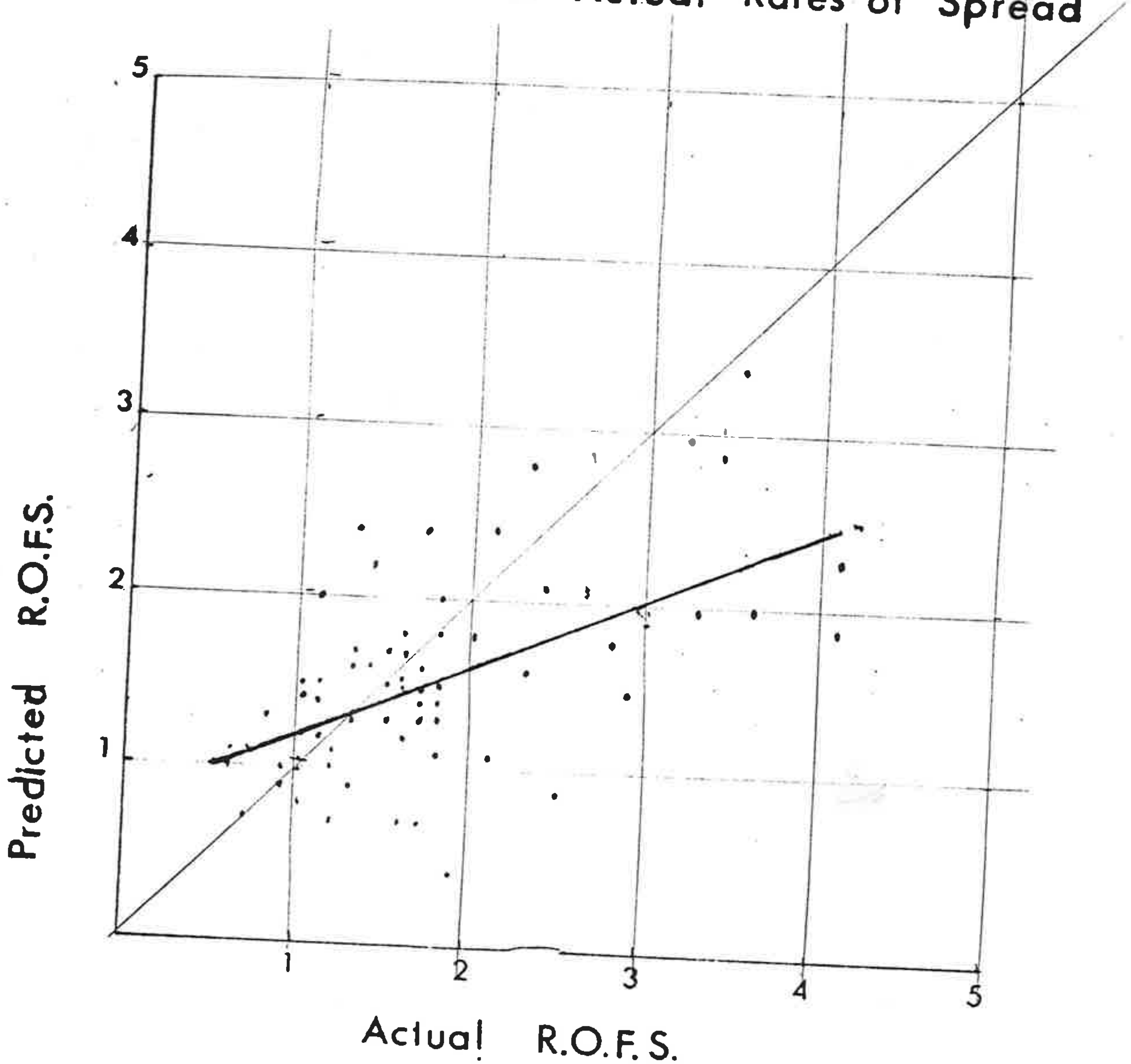
Table 22

Rate of Litter Accumulation in Jarrah Forest in Tons Per Acre Equivalent over Dry Weight

	Canopy Cover Per Cent			
Number of Annual Leaf Falls	20	40	60	80
1	0.4	0.7	1.0	1.2
2	0.7	1.1	1.4	1.7
3	1.0	1.6	1.9	2.2
4	1.4	2.1	2.5	2.8
5	1.9	2.7	3.2	3.5

Graph 19

Predicted and Actual Rates of Spread



The equation for this regression was:

$$y = 0.780 + 0.420x \qquad (14)$$

Where y = Predicted forward spread in feet per minute

x = Actual forward spread in feet per minute

The correlation coefficient for Regression 14 was 0.59 (significant at the 99 per cent level of confidence) and the standard error of estimate was 0.38 feet per minute.

Graph 19 shows predictions from the jarrah tables tend to overestimate spread rates up to 1.4 feet per minute, and to underestimate between 1.5 and 4.0 feet per minute.

From a fire operations viewpoint the errors in predicting spreads up to four feet per minute were not likely to impede planning. Of greater concern was the prediction accuracy for more intense fires. These faster rates of spread had been extrapolated in the tables so considerable errors could result.

Table 23 lists observed rates of spread for three wildfires in the southern forests of Western Australia and predictions of spread rates from the jarrah tables, made at the same time. The most noticable discrepancies occurred during the Harvey fire and the peak of the Boorara fire. In both cases spot-fires were thrown considerable distances in front of the advancing headfire. It was apparent the throwing ahead of spot-fires by intense wildfires would create considerable errors in prediction.

Table 23

Predicted and Actual Rates of Forward Spread for Three Wildfires

Fire	Date Burnt	Actual Rate of Forward Spread ft./min.	Predicted Forward Spread ft./min.	Difference ft./min
Farrs Fire	7/12/1966	7.0	4.0	3.0
Harvey Fire	15/2/1967	88.0	21.0	67.0
Boorara Fire	7/3/1969 to 9/3/1969	40 8 26 60 117	48 5 40 62 62	8 2 14 2 55

While these tests suggested the danger rating should predict slower spread rates with sufficient accuracy for general planning of fire control, they told little about the treatment of individual variables in the tables. A standard error of estimate of 0.38 feet per minute, for example, covers quite a wide range of fire hazard.

Further Analysis

The short-cut graphic analysis used for the fire danger rating failed to prove wind, fuel amount and fire hazard could combine into overriding controls throughout the range of spread in the tables. Could other variables such as slope be ignored? This question seemed best answered by testing the three variables with others recorded at the experimental fires; in stepwise mutliple regressions which showed the relative influence of each one on spread rate. These regressions were calculated with the Fortran programme M.R.40-T using the University of Western Australia's computer, (type P.D.P.-6).

Experimental Method

The multiple regression analyses had two objectives:

(i) To show the best function, or transformation for each of 13 independent variables expressing rate of spread.

(ii) To use the selected transformations in stepwise multiple regressions for rate of spread. The sequence of rejection for the individual variables would provide a measure of their influence on spread rate.

For the first objective five transformations were tried on each variable. These were: linear, square-root, logarithm, squared and cubed. This range of function aimed to cover the likely approximations to the handdrawn graphs.

The 13 independent variables tested with these transformations were: Day Number (representing differences between spring and autumn), scrub cover (per cent), cloud cover (eights), wind velocity (miles per hour at four feet), litter quantity (tons per acre), litter cover (per cent), litter depth (incles), duff depth (inches), moisture content of the surface litter (per cent), profile moisture content (per cent), slope (degrees), air temperature (degrees F.) and relative humidity (per cent).

The response of each variable to these transformations was shown in Table 24. Correlation coefficients demonstrated whether improved correlation had been achieved by changing the function. Table 24 also lists the selected transformations and the significance of its correlation coefficient.

The second objective for this analysis was reached by using the selected transformations in multiple regressions for rate of spread. The 13 variables were rejected one by one, in successive regressions, on the basis of lowest Student t value for b coefficients. This ensured the variables least correlated to rate of spread were rejected first. The sequence of rejection was shown in Table 25.

It is quite possible the sequence of rejection may have been influenced by interaction between variables, in some cases one cannibalising another. A list was made of all independent variables correlated with wind velocity, fuel

Table 24

Regression Analysis of Experimental Fire Data

Correlation Coefficients for Five Transformations of Independent Variables

Variable	Transformation					Selected	Signi-
	Linear	Sq.Root	Squared	Log.	Cube	Transform	ficance %
Day	-0.029	-0.030	-0.025	-0.032	-0.021	log.	N.S.
Scrub Cover	0.215	0.236	0.129	0.214	0.106	Sq. root	99.9
Air Temperature	0.198	0.201	0.191	0.202	0.184	log.	99
Relative Humidity	-0.102	-0.056	-0.140	0	-0.156	cube	95
Cloud Cover	-0.138	-0.094	-0.163	0	-0.166	cube	95
Wind Velocity	0.458	0.461	0.340	0.423	0.190	Sq. root	99.9
Litter Quantity	0.038	0.068	0.010	0.092	-0.025	log.	N.S.
Litter Cover	0.160	0.156	0.161	0	0.162	cube	95
Litter Depth	0.181	0.187	0.182	0	0.180	Sq. root	99
Duff Depth	0.089	0.089	0.089	0	0.089	linear	N.S.
Surface Litter M.C.%	-0.185	-0.155	-0.178	0	-0.148	linear	99
Profile M.C.%	-0.082	-0.087	-0.037	0	0.003	Sq. root	N.S.
Slope	0.125	0.154	0.177	0	0.127	squared	99

Table 25

Step-wise Regression Analysis

Rejection Points for Each Independent Variable

Regression No.	Duff Depth	Surface Leaf M.C.%	Day No. (log.)	Scrub Cover. Sq.Rt.	Air Temp. (log.)	Relative Humid. (Cubed)	Cloud Cover	Wind Vel. Sq. Rt.	Litter Quantity	Litter Cover (Cubed)	Litter Depth (Sq. rt.)	Profile M.C.% (Sq.rt.)	Slope (Squared)	Coefficient of Correlation	Coefficient of Determination
1	x	x	x	x	x	x	x	x	x	x	x	x	x	0.627	0.354
2	x	x	x	x	x		x	x	x	x	x	x	x	0.627	0.357
3	x	x	x	x	x		x	x		x	x	x	x	0.627	0.360
4	x	x		x	x		x	x		x	x	x	x	0.627	0.362
5	x	x		x	x			x		x	x	x	x	0.625	0.363
6		x		x	x			x		x	x	x	x	0.623	0.364
7		x		x				x		x	x	x	x	0.620	0.363
8		x		x				x		x	x		x	0.613	0.358
9		x		x				x			x		x	0.592	0.335
10		x		x				x			x			0.568	0.310
11				x				x			x			0.550	0.293
12								x			x			0.506	0.249
13								x						0.450	0.199

x Variable retained

Variance ratios for all regressions were significant at 99 per cent confidence limit.

Table 26

Multiple Regression Analysis

Significant Correlations Between Independent Variables

Variable	Correlated Variables
Litter Quantity	Litter Cover Litter Depth Duff Depth Profile Moisture Content
Wind Velocity	Profile Moisture Content Moisture Content of Surface Litter
Profile Moisture Content	Day No. Air Temperature Relative Humidity Cloud Surface leaf moisture content Litter Cover Duff Depth
Surface Leaf Moisture Content	Day No. Air Temperature Relative Humidity Cloud Cover Litter Cover

quantity and moisture content of the litter (Table 26).

Experimental Results

The regression analysis suggested both litter quantity and profile moisture content were weak influences on rate of spread. Winds on the other hand, and surface moisture content, (representing basic fire hazard), were well correlated with rate of spread. These influences were illustrated in the step-wise regression (Table 25) where wind alone explained 20 per cent of the variation in the data and surface moisture content about 3 per cent. Since all 13 variables only accounted for 36 per cent of the variation in spread rates these contributions were important.

It seemed logical litter quantity and profile moisture content should influence spread rates since a range for both was evident in the data. This led to the suspicion measurement and sampling techniques were at fault. The correlations listed in Table 26 supported these suspicions. Fuel depth and cover were well correlated with rate of spread, yet they represent another expression of quantity. For fire spread, fuel disposition may have greater meaning then weight or quantity. Profile moisture content may not have been an effective variable, due to sampling errors. This supported the use of non rain-affected fuel for determining a function for fire hazard in the fire danger tables.

Scrub and slope both proved important influences over rate of spread. It seemed unlikely either could be ignored for predicting fire behaviour on a particular site.

Further comment on these regressions is best woven into the following sections of this chapter, which review the fire danger rating and how it was put together.

Discussion of Results

The Fire Danger Concept

The jarrah fire danger rating relied on average rate of forward spread being a reliable measure of differences between fires. Further experimental work left doubt whether this assumption was entirely true.

Table 27 lists the area burnt by 12 fires, all with average rates of forward spread either 1.1 or 1.2 feet per minute. Area spread for the 1.1 fires ranged from 665 square feet to 3200 square feet after 40 minutes, and for 1.2 the range was 1552 to 4964 square feet. These fires, with similar forward spread; were quite dissimilar in area burnt at 40 minutes after lighting.

Table 27

Average Rate of Forward Spread and Area Burnt at 40 Minutes

Rate of Forward Spread ft/min	Area Spread at 40 mins.sq.ft.
1.1	665
1.1	1400
1.1	1850
1.1	2065
1.1	2410
1.1	3200
1.2	1552
1.2	2396
1.2	2536
1.2	3141
1.2	3296
1.2	4964

These discrepancies in area indicated that average forward spread might not have been a good expression of differences in intensity between fires. Its use assumed that fires reached a steady state of spread quite quickly and thereafter spread uniformly. This assumption was tested by 15 fires in four forward-spread classes, 0 to 1, 1 to 2, 2 to 3, and 3 to 4 feet per minute. Average rates of spread for each two-minute period were plotted up to 32 minutes, (Graph 20, Appendix 7).

This study showed that fires with headfire spreads up to two feet per minute reached equilibrium fairly quickly, but faster-spreading ones tended to surge and accelerate up to 32 minutes. On this evidence an average for forward spread through the whole 32-minute measurement period would only provide valid comparisons between very mild fires. The acceleration of faster-spreading fires required some other means of comparison.

The acceleration of forward spread was illustrated by dividing spread rates for 343 experimental fires into two periods, 0 to 20 minutes after lighting and 20 to 28 minutes after lighting. The average rates in each period were compared with analysis of variance (*McCormick, pers. comm. 1970). In addition, average headfire flame heights for the two periods were compared, also wind velocity (Table 28).

Wind velocity, the main contributor to spread rates, showed no significant increase between 0 and 20, and 20 and 28 minutes. Both forward spread and flame height did increase, providing further confirmation that acceleration of the headfire takes place as the fire develops.

+Ward (pers. comm. 1970) suggested using rate of area spread as an alternative to rate of forward spread. The data was divided in the same way, 15 fires in one-foot spread classes up to five feet per minute. The area burnt over every four minutes was measured from fire plans and

* Fire Research, Forests Dept. Dwellingup.
\+ Fire Research, Forests Dept. Manjimup.

Table 28

Average Rates of Forward Spread, Flame Height and Wind Velocity for 343 Experimental Fires

Variable	Average 0 to 20 mins.	Average 20 to 28 mins.	Difference	Significance of Difference per cent (Variance Ratio)
Rate of Forward Spread ft./min	1.58	2.02	0.44	99
Headfire flame height, feet	1.49	1.88	0.39	99
Wind velocity M.P.H.	2.21	2.26	0.05	N.S.

averaged for the 15 fires. There was no statistical difference between these areas and those arrived at by dividing the final area by time.

The relationship of area increase with time was a curved one which converted to linear by squaring the time axis, (Graph 21, Appendix 7). The reason for constant area increase irrespective of headfire surges lay in changing fire shape, which elongated as headfire spread increased.

This change illustrated in Graph 22 (Appendix 7) which shows headfire spread and averages for four axes of the fire at the same time. The axes were headfire, two flankfires and backfire. Despite a fairly regular acceleration for the headfire, the average for four axes did not change much, indicating that area spread was increasing at a constant rate. The acceleration of the headfire was compensated by a changing fire shape which became more ovoid, with proportional decreases in flank and backfire spreads. These results supported earlier evidence of a changing fire shape as headfires accelerate, (Peet 1967).

An area factor was suggested, to compare individual fires, i.e.

$$K = \frac{A}{T}$$

Where K = Area factor for each fire

A = Area burnt in time T.

T = Time since lighting.

Table 29

Predicted (P) and Actual (A) Fire Areas at 8, 16, 24, and 32 Minutes after Lighting. (Square feet)

Fire	8 minutes		16 minutes		24 minutes		32 minutes	
No.	A	P	A	P	A	P	A	P
1	243	243	972	972	2430	2190	3889	3890
2	70	58	223	232	512	519	907	922
3	139	135	650	537	1321	1210	2120	2150
4	138	135	460	537	1120	1210	1940	2150
5	68	64	267	256	569	576	1031	1024
6	40	32	230	128	390	288	505	512
7	310	282	1103	1126	2520	2534	4520	4510
8	137	102	454	410	899	922	1575	1638
9	182	122	540	486	1125	1094	1694	1946
10	143	102	587	410	1110	922	1650	1638
11	50	58	218	232	509	519	882	922
12	105	128	335	512	1049	1152	2145	2048
13	316	256	1050	1024	2109	2304	3715	4096
14	200	320	1100	1280	2480	2880	5210	5120
15	440	441	2136	1765	3792	3970	6828	7060
Total	2581	2478	10325	9907	21935	22290	38611	39626

This factor was suggested rather than an actual area, so that fires which burnt for different periods could be included in the analyses. Unfortunately, the area factor has not yet been tested with re-worked data, so its uses are still open to question. Table 29 provides some indication, however, by showing calculated values of K alongside the very similar measured ones. For each of the four periods there were no significant differences between the predicted or actual fire areas. The fires were different ones from those in the original analysis.

Fire Hazard

The regression analyses provided further evidence profile moisture content was not reliable for predicting rate of forward spread. Its influence was clouded, probably due to high measurement errors.

Profile moisture content formed the basis for deriving rainfall correction factors. While the use of profile moisture content in this way can be decried, it is obvious rainfall effects cannot be disassociated from the fire danger scale. In retrospect surface moisture content may have been a better variable for calculating rainfall factors. The effect of profile moisture content could not be ignored since rainfall effects take a considerable time to disappear, but perhaps it would have been better to treat it in terms of fuel availability for burning.

Surface moisture content was well correlated with rate of spread and with four independent variables, i.e. cloud cover, day number, temperature and relative humidity. Day number represented the march of the seasons from spring to summer hence it could not contribute much to prediction of day to day changes in surface moisture content or basic fire hazard. Cloud cover, on the other hand, can change from day to day and could well add to the predictions.

The correlations of instantaneous air temperature and relative humidity with surface moisture content were of interest for fire hazard. It was shown that for all practical purposes a homogeneous relationship could be assumed between basic fire hazard and surface moisture content. This leads to the possibility of instantaneous checks of fire hazard during the day as well as estimating peak hazard from maximum temperature and minimum relative humidity.

In normal summer weather for the jarrah forest there is generally a good correlation between air temperature and relative humidity. Hatch found that maximum temperature alone accounted for 74 per cent of the variability in hazard whilst the addition of relative humidity only increased this percentage to 81. The work of other researchers, e.g. King and Linton, 1962; Simand, 1969; Pompe and Vines, 1967; all point to relative humidity as the direct variable influencing moisture content. Temperature was used in the danger rating as a proxy for relative humidity because it was generally easier to handle for measurement of day averages as well as daily peak values. This use of a proxy would not be valid in climates where poor correlation with relative humidity exists.

Wind Velocity

Providing the litter was dry enough to sustain a fire, wind velocity proved to be the most important variable affecting forward spread. This result from the regression analysis lent support to the strong function allocated to wind velocity in the fire danger rating.

The curved wind-spread relationship used for the danger rating may be improved by reshaping it into a linear or square-root type (refer Table 23), since these were the best of the four transformations.

Wind velocity influenced both moisture content of the surface leaves and the litter profile. Drying theory (Perry et al. 1963) suggests wind effects on drying to lie principally in very damp fuels. Wind measurements may be a useful addition to the drying trial, especially in the early stages after rain.

One of the most obvious weaknesses in the treatment of wind for the fire danger rating was the assumption of a constant ratio between tower and ground velocities. Subsequent work has shown this ratio changes with height of the tower above canopy, aspect and canopy cover at the point of ground measurement, and with distance from the tower. Considerable research is needed to fix tower to ground wind ratios more closely for a number of forest situations.

Litter Quantity

Litter weight, by itself, was not satisfactory for describing changes in forward spread. It was surprising the inaccurate visual observations of depth and cover were better correlated with spread rate than were measurements of weight.

For future work a more accurate means of measuring depth was devised. A special gauge is used which presses down on the litter bed with a fixed pressure. Depth to weight relationships were expressed in this formula, (Sneeuwjagt, pers. comm. 1971):

$$y = 0.510 + 5.080x \qquad (15)$$

Where y = litter quantity in tons per acre

x = litter depth in inches.

The correlation coefficient for this regression was significant at the 99 per cent level of confidence but the error of estimate for the 50 observations was quite high, 2.06 tons per acre. However, the purpose of the exercise was filled, to provide a more accurate means for measuring litter depth in future experimental fire work.

The value of litter quantity in the spread relationships was undoubtedly obscured by the high sampling errors associated with average weights from three of four-square-feet quadrats, (refer Chapter 4). More intensive sampling of the fire areas is warranted to test this point.

Type of litter has been proved to be important for regulating rates of forward spread (Peet, unpublished data, 1965). Under uniform conditions jarrah, banksia and pine litter burnt at quite different rates, depending on leaf characteristics. Since banksia and she-oak are common understorey species in the jarrah forest, spread variations due to litter type must have occurred during the experimental fires.

The spring data was divided for litter type, fires in jarrah-marri forest being separated from fires in jarrah-banksia or she-oak forest. The multiple regression analysis was run on both sets of data and showed improved correlation between litter weight, depth and cover, with spread. It appears that fairly detailed mapping of litter on fire site would be necessary to explain its full relationship with spread.

The lack of homogeneity for litter weight in jarrah forest makes it a difficult variable to use for describing spread differences. A doubling of litter weight is unlikely to act on spread proportionally, because disposition changes in the litter bed. As weight increases the lower litter layers become compacted and duff develops. This compacted and partly decomposed litter burns at a slower rate than the aerated surface, usually smouldering away behind the main flame front. In this study weight included all litter to ground level including duff. Some alternative sampling was needed to avoid introducing weight bias from duff.

Past fire history plays a part in composition of litter beds. Five years after the Dwellingup fires litter in the fire-damaged forest was about one ton heavier per acre than in the surrounding control-burnt forest of the same age. The difference was in the weight of moribund epicormic shoots which added to litter in the fire area. Those under half-inch diameter were included in normal litter sampling, and undoubtedly biased the weights.

The regression analyses showed that litter alone was an inadequate description for fuel. The area of forest covered by scrub was well correlated with rate of forward spread. On this evidence, scrub fuels warranted more detailed measurements than were provided by this experimental fire technique.

A basis for describing scrub fuels by species and cover over the forest floor was laid during assessments through the experimental area, (Chapter 3). Further work required the development of a concept to rate differences in the inflammability of foliage between species.

Changes in burning rates for foliage were described by McCormick (pers. comm. 1968), who related differences between species to moisture content and density of the foliage. More work of this type could provide a basis for grouping scrub types into classes of inflammability on a quantitative basis.

Sneeuwjagt (1971) added vertical disposition to the description of scrub foliage as fuel.

A point sampling method described the density of scrub types in one-foot height classes. Foliage was divided into size classes and into dead or green, so that fuel components could be added as fire intensity increased.

This measurement of scrub foliage was introduced because green foliage requires a certain intensity of fire before it preheats sufficiently to ignite. More intense flames result in the fine twigs being consumed, and so on to a higher intensity which consumes the whole plant. With further work this approach could provide an adequate fuel classification for scrub.

Interactions

None of the fire danger systems make an obvious allowance for interactions between variables. Wind, for instance, was loaded into fire danger at a rate regulated by a constant relationship with spread rather than a changing relationship depending on interaction with another variable, e.g. moisture content.

There was a strong interaction between litter quantity and its moisture content in their affect on rate of spread. This suggests that extrapolation of rainfall factors from three-ton fuel to other fuel quantities may not have been a valid procedure for compiling the fire danger rating. The correlation did support changing the fuel multipliers to spread (Table D) for changes in fire hazard.

If strong interactions exist, such as the quantity-moisture one for litter, it seems unlikely that any one of the variables will have a constant relationship with rate of spread.

When the data was divided into forest types the transformation of best fit for wind changed from linear to square-root to a squared function. Similarly, surface leaf moisture content changed from linear to logarithm to square root. In these cases fuel disposition and type has played a part in regulating the effect of wind and moisture content on spread rates. Future work should include closer studies of interaction between variables, especially in defining where one becomes limiting on another. Considerable investigation is needed into the best measure or sampling method to use for variables such as litter quantity before further modelling of fire danger rating is likely to prove productive.

Chapter 8

PLANNING OF FIRE CONTROL IN JARRAH FOREST

Introduction

Foresters facing problems in fire control need a basis for planning long-term and day-to-day objectives. Various systems have been used, such as subjective estimates of daily risks, hazard systems expressing inflammability, and fire danger ratings incorporating a number of fuel and weather variables. In both Australia and the U.S.A. the trend in recent years has turned towards fire danger ratings.

Fire danger ratings have been used for determining the strength and speed of attack on a running fire, and for deciding when to carry out controlled burning. But these uses are not in themselves a management system.

Nelson (1967) extended concepts for the use of fire danger to pre-planning. The number of fires and their acreage was related to fire danger, and on this basis plans could be made for placing suppression forces each day during the fire season, depending on current danger.

Systems which relate states of preparedness to current fire danger are used with varying degrees of refinement by most fire control organizations in Australia. Fire danger estimates the potential of a fire and, as such, is only one consideration in daily planning. Factors such as risk, accessibility, and values within the forest all play a part in day-to-day decisions.

Up to 1960 several different fire danger ratings were used in various parts of the U.S.A., each rating having been developed for a particular forest or fuel type.

Following an introductory period, a national fire danger rating was introduced in the U.S.A. in 1965. This rating provides for a uniform warning system throughout the U.S.A.

In Australia, McArthur (1964 to 1966) developed and then improved two fire danger ratings, one for eucalypt forests and another for grasslands. These are in common use in all States except Western Australia, where fire hazard has remained the standard system for warning the public.

In Western Australia, different and successive developments took place in the adoption of fire danger. The W.A. Bushfire Act (1954 to 1964) prescribes that fire hazard will be used for all fire weather forecasting by the Bureau of Meteorology. This system has been used since 1934, and there seems to be little public support for any changes in the Act which would permit forecasts of fire danger to be used instead.

Uniform systems, whether fire danger or fire hazard, offer advantages in public relations by presenting a single scale which is generally understood by the public as well as by fire control organizations. These forecasts however, cannot make accurate predictions for localized forest areas. There are, for instance, major differences in litter types, amounts, rates of drying and scrub cover between the jarrah and karri (Euc. diversicolor F. Muell) forests in the south-west of Western Australia. These differences are not allowed for in a standard fire danger system; yet they have a major effect on fire behaviour.

Even within a small area of reasonably uniform jarrah forest fluctuations in fire danger are evident. Graph 23 shows day-to-day differences between Dwellingup and Mt. Wells, a station 20 miles to the east. Fire danger at the two stations was calculated from fire hazard and wind at 2 p.m., fuel amount was assumed to be the same. Although both stations followed similar day-to-day rises and falls, there were notable differences between them, and these differences would be important for planning day-to-day operations.

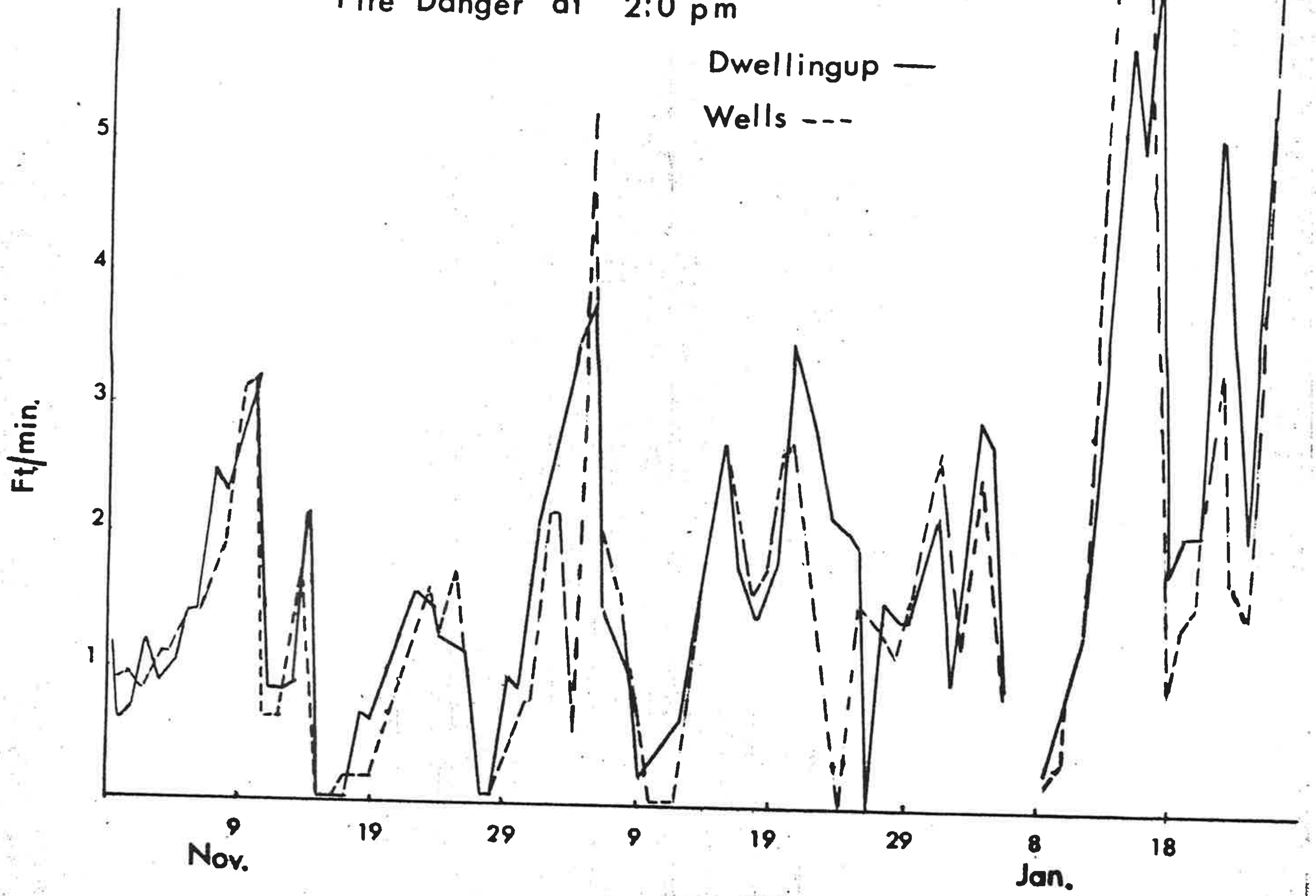
Since most operations such as controlled burning require reasonably accurate forecasts of fire behaviour, predictions of fire danger must be restricted to small areas of forest where the fuel and weather variables are known with reasonable certainty. This type of planning for internal departmental use should be separated from the broader requirements of a system for public warnings.

Controlled Burning Guide

Further developments were necessary before the fire

Graph 23

Fire Danger at 2:0 pm



danger rating for jarrah forest proved adequate for the planning of controlled burning. Part of the danger rating was developed into a controlled burning guide to meet the specific requirements of this operation.

The fire danger rating covered the range of weather conditions expected during a fire season, but the guide was limited to three of the lower fire danger classes: Purple, Green and Blue (refer Table 20). These classes represent the range of forward spread (0.6 to 3.0 feet per minute) normally accepted for controlled burning in jarrah forest.

The guide was designed for preliminary and daily planning of controlled burning, and to assist with decisions on methods of lighting.

Context and Calculations

The controlled burning guide is made up of five tables. These are Tables A and B of the fire danger rating and three other tables, (refer Appendix 6).

Adjusted fire hazard is calculated from Tables A and B in the same manner as outlined for the fire danger rating.

Table 1. This is an extract from Table C and predicts rate of forward spread in 3.0 to 3.5 tons per acre of litter fuel. Fire hazard is shown on the vertical axis and wind velocity on the horizontal axis. Rate of forward spread is shown at the junction of the two axes.

Table 2. This table represents a modification of Table D, i.e. the fuel corrections are already multiplied. It corrects rate of forward spread in five-year-old fuel to a range of fuel ages, according to their representative fuel quantities as shown on Table D.

The corrections are made in fire hazard classes; and the adjustment is made from the column which includes the adjusted fire hazard. This table shows additional information in autumn and spring scorch height specifications for the Purple, Green and Blue fire danger classes.

Table 3. This table combines the adjusted rate of forward spread, from Table 2, with hours of burning time to predict a strip width to be used for lighting. Hours of burning time are an estimate of the time the fire will run on that day.

Analyses for the Controlled Burning Guide

Two additional analyses were made for the controlled burning guide. These were: The expected maximum scorch heights in each of the three fire danger classes, and secondly, a definition of the likely number of hours of burning time each day.

The scorch height specifications came from experimental fire data. After each fire the scorch height was estimated for tree crowns burnt under by the headfire. These estimates, for 200 fires, were plotted against rate of forward spread.

There was poor correlation between rate of spread and scorch height, but the plot of points did indicate the probable maximum height for each of the three fire danger classes. These heights are listed in Table 30.

Table 30

Probable Maximum Scorch Height for Purple, Green and Blue Fire Danger Classes

Rate of Forward Spread ft/min.	Fire Danger Class	Scorch height feet Spring	Autumn
0.6 to 1.0	Purple	15	27
1.1 to 2.0	Green	20	35
2.1 to 3.0	Blue	30	45

High scorch heights in early autumn are probably associated with the inflammability of the outer, rough bark and heavy ground-wood at this time. Autumn scorch heights generally approach those in spring after the first soaking winter rains.

The second analysis was an attempt to define hours of burning time each day. Thermograph traces were examined to determine the hours each day when temperature exceeded 60 degrees F. These hours were found to be related to the maximum temperatures for that day.

The relationships shown in Table 31 are averages from several hundred observations taken from thermograph traces: recorded between 1962 and 1967 at Dwellingup. The table shows:

The daily maximum temperature.

The time when temperature normally rises above 60 degrees F., for spring and autumn seasons.

The hours thereafter when temperature remains above 60 degrees F.

Table 31

Daily Maximum Temperature degrees F.	Spring		Autumn	
	Time	Hours	Time	Hours
61 to 65	1200 hrs	3	1130 hrs	4
66 to 70	1030 "	7	1000 "	8
71 to 75	1000 "	8	0900 "	10
76 to 80	0930 "	10	0800 "	12
81 to 85	0900 "	12	0700 "	14
86 to 90	0800 "	14	0600 "	18

The definition of an hour of burning time as one when air temperature exceeded 60 degrees F. came after considering fuel samples from the litter drying trial. Here very little drying occurred when temperatures were less than 60 degrees F. This lack of drying, and the associated high moisture content equilibriums affects both the inflammability of the fuel and the ability of a fire to sustain a rate of spread once ignition has been successful. While wind velocity and fuel quantity are also important, it was considered that temperature would provide a rough guide for hours of burning time and one that could be easily assessed.

Controlled Burning

The term "controlled burning" is generally synonymous with "prescribed burning", and implies that fire is applied to the forest at an intensity which minimizes damage to the forest. This objective relies on standards for preliminary planning, and selecting suitable weather and lighting patterns.

In Western Australia the controlled burning guide described here is used for these standards. In addition, it has been adapted for use in karri and pine plantations, while awaiting further data on these fuel types.

Each Forests Department division in the jarrah forest has an annual controlled burning programme of between 60,000 and 100,000 acres. The tendency has been for an increasing use of aircraft for lighting (Packham and Peet, 1967) resulting in much larger blocks being burnt. This has led to some revisions in planning, but general principles remain unaltered (Peet, 1967).

The three fire danger classes used for controlled burning in jarrah forest are the basis of a management system which includes pre-planning and job execution.

The scorch heights assigned to each fire danger class, ranging from 27 to 45 feet in autumn to 15 to 30 feet in spring, provide the standard for planning.

Five types of controlled burning are practised in the jarrah forest, and the guide is used for planning the first four, (W.A. Forests Dept. 1964). These five types are:

(i) Burning of buffer areas or firebreaks around areas of high risk
(ii) Burning of buffer strips or firebreaks around areas of high value.
(iii) Prescribed burning of large areas on a rotational pattern.
(iv) Advance burning prior to logging operations.
(v) Top disposal burning for regeneration and fuel reduction, following logging operations.

Top disposal burning requires estimates of fuel dryness additional to those given in this guide. Here the fires burn heavy ground-wood as well as litter, and flame height is usually controlled by burning when flash fuels are damp but when the heavier wood is dry enough to be consumed.

The planning of controlled burning in litter fuels follows three steps: Master Plan, Prior Inspection, and Daily Planning.

Master Plans

Each division is required to prepare a master plan of controlled burning showing proposed annual programmes for the next five years.

Recently suggestions have been made that these proposals be kept on aerial photo interpretation plans, which show forest type and canopy cover. Both these variables are important for determining the rate at which fuel quantity increases (Peet, 1971).

Whenever possible, controlled burning is done in long strips through the forest, rather than in a patchwork manner. These strips are about one mile wide when ground crews are used for lighting (Peet, 1965), and three to five miles wide for aircraft.

In preliminary planning the annual programme is broken into unit areas, each representing a day's work for a ground crew or aircraft, depending on which is to be used for lighting. These units are inspected separately to prescribe suitable estimates of fire danger for lighting the burn.

Prior Inspection

Prior inspection has three objectives: information on perimeter roads, edge burning for perimeter control, and suitable fire danger class for lighting the area.

Edge Burning.

Prior burning of perimeter edges around each job is prescribed where heavy fuels in adjacent forest may present problems in containing the fires.

Edge burning is done in early spring or late autumn when the duff and heavy ground-wood are damp. This minimizes chances of the edge re-lighting before the main burn is completed. Lighting of edges is usually done with a flame thrower on days when the local fire danger does not exceed Purple.

Fuel Classification.

Fuel in the jarrah forest is classified by weight of litter on the forest floor. The same tons per acre standard is used as was described for the fire danger rating.

Aids have been provided to assist with litter classification (Peet 1967, 1971), including tables of litter weights related to annual leaf falls and to canopy, and descriptions of depth - weight relationships.

Prescribed Fire Danger.

Scorch specifications for the Purple, Green, and Blue fire danger classes for lighting are the standard for prescribing an acceptable rate of spread.

The acceptable scorch height for jarrah forest depends on the lower crown height of the smallest potential crop trees. This height is determined by field inspections, also by aids such as aerial photos and records of past logging.

Regeneration in cut-over areas is protected until the crown height of the saplings is tall enough to avoid serious damage from scorching under Purple conditions, i.e. about 20 feet. All areas of saplings are burnt on days of

Purple, poles on Green days and mature forest on Green or Blue.

For the better-quality forest a 20-foot-square spacing of potential crop trees is accepted as full stocking for prescribing an acceptable fire danger. The crown heights of trees filling these spaces defines the acceptable scorch heights for the area. The acceptable scorch height is compared with specifications for the three fire danger classes and a class is prescribed.

Recording.

After prior inspections are completed, the job numbers of the unit areas, their acreage, fuel classification and prescribed fire danger are listed in an index table (Peet, 1967). This table is used with the weather forecasts and calculations of local fire danger to plan daily controlled burning programmes.

Daily Planning

Selection of a day's programme of controlled burning is based on the 7.45 a.m. fire-weather forecast from the Bureau of Meteorology. This forecast covers the jarrah forest region, and includes a statement of expected weather, maximum temperature, minimum relative humidity and fire hazard.

Fire hazard is adjusted with local measures of rainfall, period since rain and rates of drying. Fuel quantity and wind velocity are added to predict fire danger for particular forest areas.

Predictions of local fire danger are compared with the prescribed ones in the index table. The days programme is selected from areas where the two fire dangers match.

Predictions of fire danger are checked at regular intervals during the day, with actual weather conditions. This is done to ensure that fire danger is as predicted, and that fire intensity remains within acceptable limits.

Organization.

Fire danger thus provides the standard for the organization of controlled burning in the forests of Western Australia. This was an attempt to develop a management system which would operate with reasonable success for annual programmes totalling between 800,000 and 1,000,000 acres.

The main criticism lies in the standard: the fire danger rating is only a guide, and the number of variables and method of data analysis require improvement for more accurate predictions. Also this fire danger rating cannot be extrapolated into other forest types, e.g. karri or pine, without incurring some errors in prediction.

Fire Suppression

The most commonly used fire danger ratings were designed primarily as aids for fire suppression. The jarrah rating included a controlled burning guide which has advantages in maintaining continuity of concepts, calculations and terminology for both controlled burning and fire suppression.

The jarrah fire danger rating is used for organization of pre-suppression and as a guide for suppression. Its use in pre-suppression is outlined in fire action orders, described below.

Fire Action Orders

A fire action order specifies where fires can be attacked safely as fire danger rises, and the speed and strength of the attack, and suggests a method of attack. A fire action order thus covers most aspects of detection, states of preparedness and despatch.

Fire action orders are compiled from the following considerations, based on known performances of suppression forces.

In jarrah fuels, when local fire danger is Yellow or higher, there is little likelihood of successful direct attack on headfires. These fire dangers represent rates of forward spread exceeding seven feet per minute; headfire flames are generally higher than ten feet; and spot fires can be expected ahead of the main fire front.

Rate of spread of flank fire is assumed to approximate half the headfire rate, and back fire one third the headfire rate (Peet, 1967). Using the limit of seven feet per minute for direct attack, flank fires can be suppressed up to fire dangers of Orange and backfires up to Red.

In most fires some part of the perimeter can be attacked by direct method, and the fire action order should specify these parts.

For fire dangers up to Orange direct attack should be tried on all flanks except when fire danger is Yellow or higher, when the attack should concentrate on the flanks and backfire. The fire is kept narrow until fire danger drops below Yellow, when the headfire is cut off by direct attack.

For fire dangers above Orange headfire attack is unlikely to succeed with any method because of long throw distance for spot-fires. The flanks should be attacked by the parallel method, and the backfire with direct method. The same strategic principle is used: the fire is kept as narrow as possible until fire danger drops below Yellow, then the headfire is attacked.

Considerations of suppression, crew performance and safety are the basis of fire action orders. These orders form part of a fire control working plan for each forest division, which sets out the organizational aims for that protection unit.

Detection.

In the forests of Western Australia a network of look-out towers is the means of fire detection, although aircraft have been added in severe fire situations.

The time elapsing between ignition and detection, and then between detection and attack increases in importance as fire danger rises.

These times depend on fire danger: that is, the rapidity with with the fire diameter reaches 30 to 40 feet. This size usually produces a sufficiently dense column of smoke for detection by towers, although factors such as direct view, visability, height and density of the canopy may handicap tower watchers.

The time for a fire to reach a diameter of 30 to 40 feet varies from up to two hours in a White fire danger to a few minutes in a Red fire danger. Fires burning under White or Purple take a considerable time to be detected, and thereafter spread at a slow rate, with minimal forest damage except in young regrowth. Such fires do not suggest the need for a high detection commitment.

The detection commitment increases as fire danger rises and speed and strength of attack becomes increasingly important. For fire action orders the towers are continuously manned when fire danger is Green or higher. This stipulates both the length of day and the number of days when full detection will be maintained. When the peak fire danger for the day is Yellow, for example, it is likely to be Green at 6 a.m., and the towers would be manned from that time until the fire danger drops below Green in the evening.

State of Preparedness and Despatch

The size and composition of the minimum suppression force required to mount a successful attack on a forest fire depends on time elapsed since ignition and on fire danger, as well as on forest and fuel types. Fire danger provides an estimate of the fire's intensity and the rate at which it is increasing in size.

State of preparedness and levels of despatch can be planned ahead if performances of suppression crews are properly evaluated. For jarrah forest, one suppression crew will contain 15 chains of fire perimeter each hour as an average performance. This assumes that mechanical aids such as bulldozers will increase in numbers as fire danger rises.

For a Blue fire danger, rates of spread lie between two and three feet per minute, with perimeter increases about six times as fast. If such a fire is attacked within one hour of ignition one gang should suppress it in one and a half hours. If the same fire burnt for two hours before attack, two gangs would be required to suppress it in the same period.

Considerations such as these led to the development of despatcher tables for the jarrah forest (W.A. Forests Dept. 1968). These tables provide guides for states of preparedness and despatch. They list the number of crews and equipment to be sent to the fire immediately after it is detected.

The despatcher tables form part of the fire action order. They are especially important on holidays when sensible precautions must be equated with the cost of maintaining suppression crews on stand-by.

Holiday precautions are listed in the fire action order, and range from one crew on days of Green fire danger to four crews and two bulldozers on Orange days and all available forces on Red days.

The use of fire danger for planning states of preparedness and despatch is an attempt to integrate into the management system a sensible correlation between risks and the cost of covering those risks.

Suppression

Attack on a fire in jarrah forest follows this sequence.

As soon as the fire is detected, suppression forces are despatched at the strength suggested by the fire action orders. The strength of these forces depends on the current fire danger, fuel type and time for the force to reach the fire.

Once despatch has been initiated, with suggestions where the fire should be attacked, a fire behaviour plan is compiled. This is a rate-of-spread plan drawn from projected fire danger, which, in turn, depends on forecasts of weather and fuels in which the fire is burning or likely to burn into. These plans show the expected positions of the fire's perimeter at hourly intervals.

The fire behaviour plan and forecasts of weather, particularly wind direction and strength, are the basis for deciding attack strategy. This includes method of suppression, re-assessments of strength and composition of the forces employed, and allocation of priorities to sections of the fire's perimeter. These priorities are based on forecasts of weather changes and their effects on fire behaviour.

Weather observations at hourly intervals, or in some cases even more frequently, are maintained by divisional offices. These readings, in conjunction with the detailed fuel plans form the basis for calculating fire danger and drawing the fire behaviour plan.

On any day of Green fire danger or higher, two-hourly weather observations are maintained to ensure that forecasts are as predicted. Fire action orders are frequently changed during the day if the forecast proves inaccurate.

The system outlined here shows extensive uses for fire danger not only in planning for preparedness and despatch but also in determining attack strategy during a fire. Once established, this fire danger standard has proved valuable in maintaining continuity of concepts and action for the personnel involved in fire suppression.

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APPENDIX 1

APPENDIX 1

Table A

Climatic Averages in the Jarrah Forest Region

Number	Climatic Factor
1	Average daily maximum temperature ^{o}F
2	" " minimum "
3	" " mean
4	Average index of mean relative humidity
5	Average daily 3 p.m. relative humidity
6	Average monthly and yearly rainfall (points)

(a) Perth. Lat. 31° 57' S Long. 115° 51' E 197 ft. a.s.l.

Factor	No. of Years	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1	30	84.6	85.1	81.3	76.3	69.0	64.4	62.8	63.8	66.8	69.7	76.7	81.2	73.5
2	30	63.3	63.5	61.5	57.4	52.8	49.8	48	48.4	50.4	52.6	57.3	60.9	55.5
3	30	74.0	74.2	71.4	66.9	60.9	57.1	55.4	56.1	58.6	61.1	67.0	71.1	64.5
4	30	53	52	57	60	68	72	73	71	64	64	57	54	62
5	30	43	43	46	48	58	63	63	60	57	54	47	46	52
6	30	33	50	90	175	514	755	708	578	337	230	75	54	3599

(b) Dwellingup Lat. 32° 47'S Long. 116° 02' E 883 ft. a.s.l.

Factor	No. of Years	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Year
1	13	82.6	83.7	78.8	72.1	64.1	60.1	58.3	59.6	62.6	67.0	74.4	79.5	70.2
2	13	55.5	55.6	53.3	48.8	44.8	43.1	40.5	41.3	42.7	45.1	49.3	53.1	47.8
3	13	69.1	69.7	66.1	60.5	54.5	51.6	49.4	50.5	52.7	56.1	61.9	66.3	59.0
4	13	57	58	65	75	83	85	87	85	83	76	65	62	72
5	13	38	37	44	53	67	73	73	66	62	57	46	41	55
6	16	30	41	89	253	623	1017	1049	886	552	292	170	86	5088

(c) Donnybrook Lat. 33° 33' S Long. 115° 49' E 208 ft. a.s.l.

Factor	No. of Years	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Year
1	30	86.1	86.0	81.2	75.6	67.3	62.6	61.1	62.6	65.8	69.1	76.9	82.3	73.
2	30	56.0	56.0	53.8	49.7	45.9	43.3	41.6	42.3	44.7	46.7	50.4	53.8	48.
3	30	71.0	71.0	67.5	62.7	56.6	52.9	51.4	52.4	55.2	57.9	63.6	68.0	60.
4	10	44	45	51	56	62	67	67	68	68	68	51	48	56
5														
6	30	48	73	115	183	557	791	801	644	457	314	117	68	4168

(d) Manjimup. Lat. 34° 14' S Long. 116°99' E 917 ft. a.s.l.

Factor	No. of Years	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Year
1	13	78.3	79.4	74.8	69.5	62.8	59.3	57.4	58.7	61.4	64.7	71.0	75.3	67.7
2	13	53.7	54.0	53.0	50.5	46.5	44.5	42.5	43.0	43.7	46.2	49.3	51.8	48.2
3	13	66.0	66.7	63.9	60.0	54.7	51.9	49.9	50.9	52.5	55.5	60.1	63.5	58.0
4	11	60	58	65	71	80	82	84	81	79	73	68	63	71
5														
6	30	79	77	138	222	594	722	712	639	488	330	158	98	4257

APPENDIX 1

Table B

(a) Distribution of Annual Rainfall (inches) for Station East and West of Dwellingup.

Station	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Total
Mandurah	0.24	0.43	0.78	1.67	5.24	7.38	6.98	5.21	3.33	2.10	0.73	0.43	34.52
Pinjarra	0.34	0.48	0.81	1.66	5.29	7.33	7.51	5.82	3.64	2.47	0.84	0.55	36.74
Dwellingup	0.51	0.49	0.98	2.62	6.64	10.70	10.40	7.96	5.52	3.24	1.62	0.74	51.42
Duncan's Mill	0.50	0.47	0.75	1.75	3.62	5.56	6.30	6.04	3.93	1.98	0.70	0.36	31.96
Marradong	0.33	0.57	0.79	1.45	4.09	5.36	6.18	4.62	3.04	2.07	0.72	0.53	29.75
Wandering	0.50	0.61	0.98	1.36	3.47	4.67	5.22	4.11	2.69	2.05	0.68	0.61	26.95
Narrogin	0.48	0.66	0.97	1.18	2.72	3.44	3.96	2.91	1.94	1.51	0.59	0.54	20.93

Table C

(b) No direct evaporative data are available for the jarrah forest, but monthly values for Dwellingup have been calculated from Prescott's Formula. (Hatch, unpublished data, 1964).

$$E = 263 \text{ S.D.}$$

From the calculated P/E ratio it can be observed that effective rainfall in the average year occurs in the seven-month period between April and October. See table below.

Dwellingup

Factor	Jan.	Feb.	Mar.	Apl.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Total
Rain-fall (ins.)	0.51	0.49	0.98	2.62	6.64	10.70	10.40	7.93	5.52	3.24	1.62	0.74	51.42
S.D. (ins.)	0.283	0.253	0.206	0.121	0.050	0.033	0.025	0.049	0.123	0.148	0.231	0.252	
Evap. (ins.)	6.2	5.5	4.5	2.7	1.1	0.07	0.6	1.1	2.7	3.2	5.1	5.5	38.9
P/E	0.08	0.09	0.22	0.97	6.04	15.29	18.33	7.24	2.04	1.01	0.32	0.13	

APPENDIX 2

APPENDIX 2

Dwellingup Scrub Assessment - Results Strata, 1 2 and 3.

Family	Species	Stratum 1 N	Stratum 1 Total Area Sq. ft.	Stratum 2 N	Stratum 2 Total Area Sq. ft.	Stratum 3 N	Stratum 3 Total Area Sq. ft.
Rutaceae	Eriostemon spicatus A. Rich.	7	2.96				
	Boronia ovata Lindl.			1	0.36		
	" spathulata Lindl.	21	5.29	22	10.42	9	3.88
Orchidaceae	Spiculaea ciliata Lindl.			1	0.20		
Rhamnaceae	Trymalium ledifolium Fenzl.	9	7.14	16	24.89	17	22.89
Restionaceae	Loxocarya flexuousa (R.Br.) Benth.	20	25.91	29	22.64	17	20.70
Sterculiaceae	Lasiopetalum floribundum Benth.	18	13.68	29	32.80	10	10.72
	Thomasia glutinosa Lindl.			4	5.19	15	18.98
Santalaceae	Leptomeria axillaris R.Br.	1	0.09	10	4.61		
Stylidiaceae	Stylidium brumonianum Benth.	2	1.14			4	2.97
	" amoenum R.Br.					8	1.52
	" ciliatum Lindl.					9	1.44
Stackhousiaceae	Stackousia brunonis Benth.	2	0.41	1	0.15		
	" huegellii Endl.						
Thymelaeceae	Pimelia rosea R.Br.	27	15.13	9	4.61	24	6.41
	" suaveolens (Endl.) Meissn.	1	0.20	1	0.04	5	1.55
	" multiflora +					2	0.72
Tremandraceae	Tetratheca viminea Lindl.	6	2.85	22	11.34	20	8.23
Umbelliferae	Trachymene compressa +	12	13.67	12	33.40	5	3.58
	Xanthosia atkinsoniana F. Muell.	20	17.74	29	14.85	16	9.23
	" candida Benth.	3	0.96	12	7.44	16	2.88
	" peltigera Benth.	11	4.14	34	16.77	30	7.64

APPENDIX 3

... EXPERIMENTAL FIRE SHEET - BASIC DATA BEFORE LIGHTING.

No. 1.S. Date 16/12/1964

ality (map reference) Diamond Block. Corner S.W. Highway and Pie Rd.

ography 2°. Southerly Slope.

Age 5 Annual Leaf falls

Composition Jarrah - Marri.

% soil surface covered by litter. 100

Depth (1) Loose litter 2"

(2) Duff ½"

est Type Eucalypt species.

~~Type~~ distribution. Mature jarrah-marri forest of medium density.

nd vegetation - Scrub type. Acacia urophylla and bracken.

% ground covered. 50

Height. 4 feet.

Fire Behaviour

d Cover 4/8 Cu

1345	4	8	12	16	20	24	28	32	36	[illegible]
Fire Height	1.1	2.0	2.5	1.5	1.6	1.5	1.3	4.0		
kfire Height	0.5	0.9	0.9	0.9	0.9	0.9	0.3	1.0		
ire Height	0.2	0.5	0.5	0.5	0.5	0.5	0.3	0.5		
ur of smoke	White	W	W	W	W	W	W	W		
mc	Light	L	L	L	L	L	L	Med		
ire flame depth	1.0	1.0	1.6	1.0	1.0	1.0	0.8	2.0		
ire flame length	1.6	2.0	3.0	2.0	2.0	1.6	13	4.5		
ire flame angle	90°	+70	+60	+70	70	90	90	60		

[illegible] FIRE RECORD SHEET NO. [illegible]

Forest Type

Fire No....15...........   Date....16/12/64.........

Time	D.B.	W.B.	R.H.%	Litter	M.C.%	Profile	N.C. %
1345	78	63·5	45	70	9·4	117	17·8
1417	78	64	44·5	64	11·3	116	15·7

Time	Reading	Inc/min.	M.P.H.
0			
2	41	20·5	2·3
4	82	20·5	2·3
6	123	20·5	2·3
8	144	10·5	1·4
10	184	20·0	2·2
12	201	8·5	1·3
14	271	35·0	3·5
16	327	28·0	3·0
18	358	15·5	1·9
20	391	16·5	1·9
22	468	38·5	3·8
24	516	24·0	2·6
26	591	37·5	3·7
28	633	21·0	2·3
30	674	20·5	2·3
32	711	18·5	2·1
34			
36			
38			
40			
42			

Fuel Sample	Total Wt.	Bag Wt.	Net Wt.	F.M.R.	M.C. %	ROW	T.P.A.
1	355·0	82·0	273	61	16	235	5·03
2	390·0	82·0	308	68	16	265	5·67
3	395·0	82·0	313	73	16	269	5·7[illegible]

EXPERIMENTAL FIRE SURVEY SHEET NO3.

Fire No. 15 Date 17/12/64.

T	D feet	B degrees	T	D	B	T	D	B	T	D	B
2	1.3	228	18	17.7	283	34			50		
4	2.0	140°	20	7.0	110	36			52		
4	2.0	54	20	10.0	230	36			52		
4	2.5	211	20	17.3	278	36			52		
4	2.9	272	20	19.0	294	36			52		
6	5.4	254	20	12.1	334	36			52		
8	3.5	87	22	21.2	278	38			54		
8	3.5	197	24	8.0	125	40			56		
8	4.8	241	24	18.7	244	40			56		
8	5.0	337	24	20.7	299	40			56		
8			24	12.9	24	40			56		
10	1.4	302	24	12.2	338	40			56		
12	5.0	117	26	23.6	281	42			58		
12	5.9	220	28	10.0	132	44			60		
12	8.4	267	28	12.0	270	44			60		
12	9.7	204	28	25.5	281	44			60		
12	7.0	9	28	17.0	340	44			60		
14	12.9	302	28	16.4	22	44			60		
16	6.2	122	30	27.3	286	46					
16	7.0	219	32	10.9	128	48					
16	12.2	270	32	18.3	250	48					
16	17.5	294	32	28.2	285	48					
16	8.5	347	32	17	22	48					
			32			48					

Bearing	Slope
302	2°
175	0
85	0
5	0

Fire Effect on Forest

	Species	Mature 60" GBH	Poles	Saplings
Scorch Ht.	Jarrah	Nil	Nil	20

Fuel Bed Type

(A = totally consumed) B.

(B = partially consumed)

Tons per acre left 1.5.

Other Damage Nil

Ground Vegetation % remaining unburnt 10

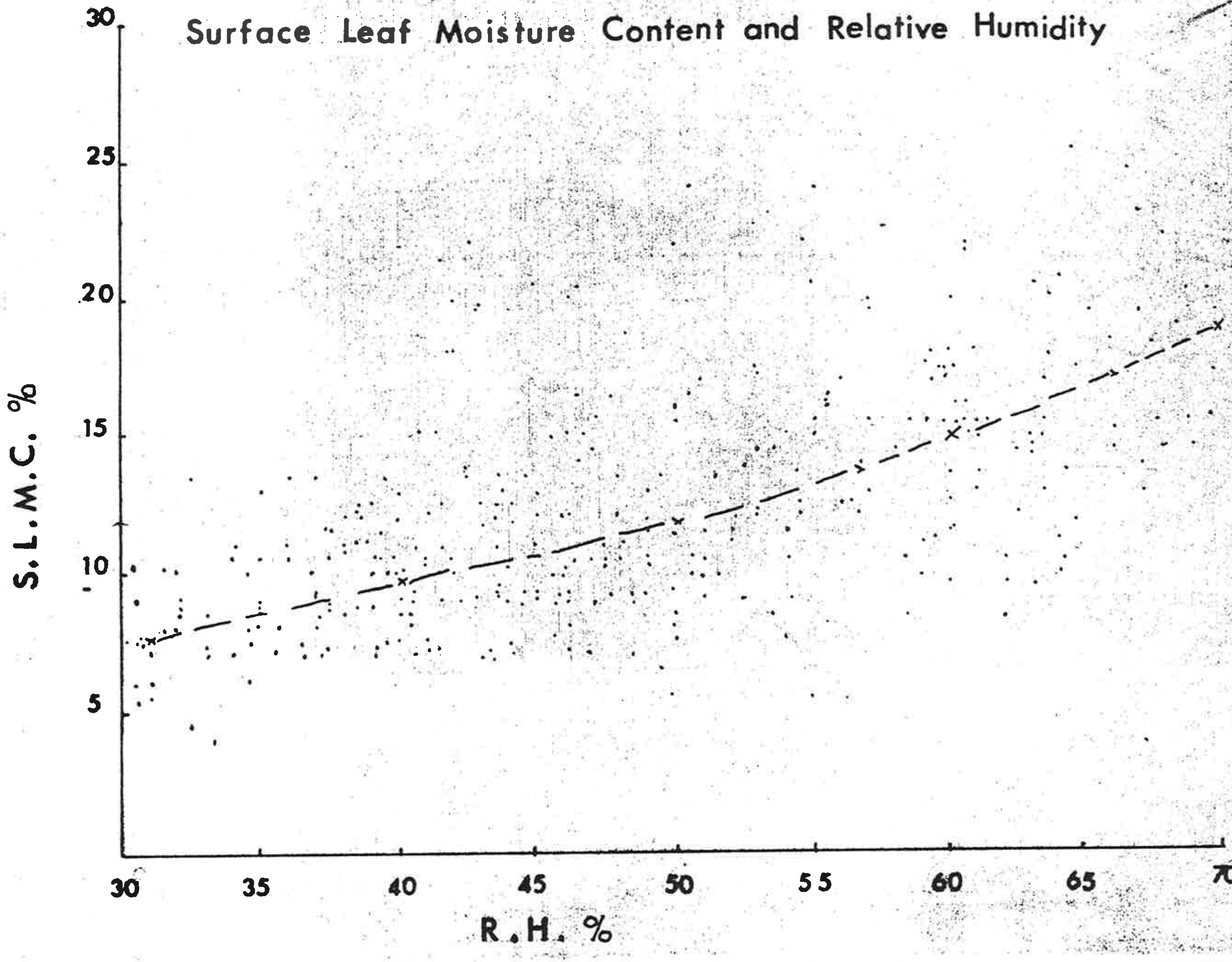
Fuel Sample	Total Wt.	Bag Wt.	Net Wt.	F.M.S.	M.C.%	E.W.	T.P.A.

Above for "after fire" litter weights which equalled 1.5 tons per acre

APPENDIX 4

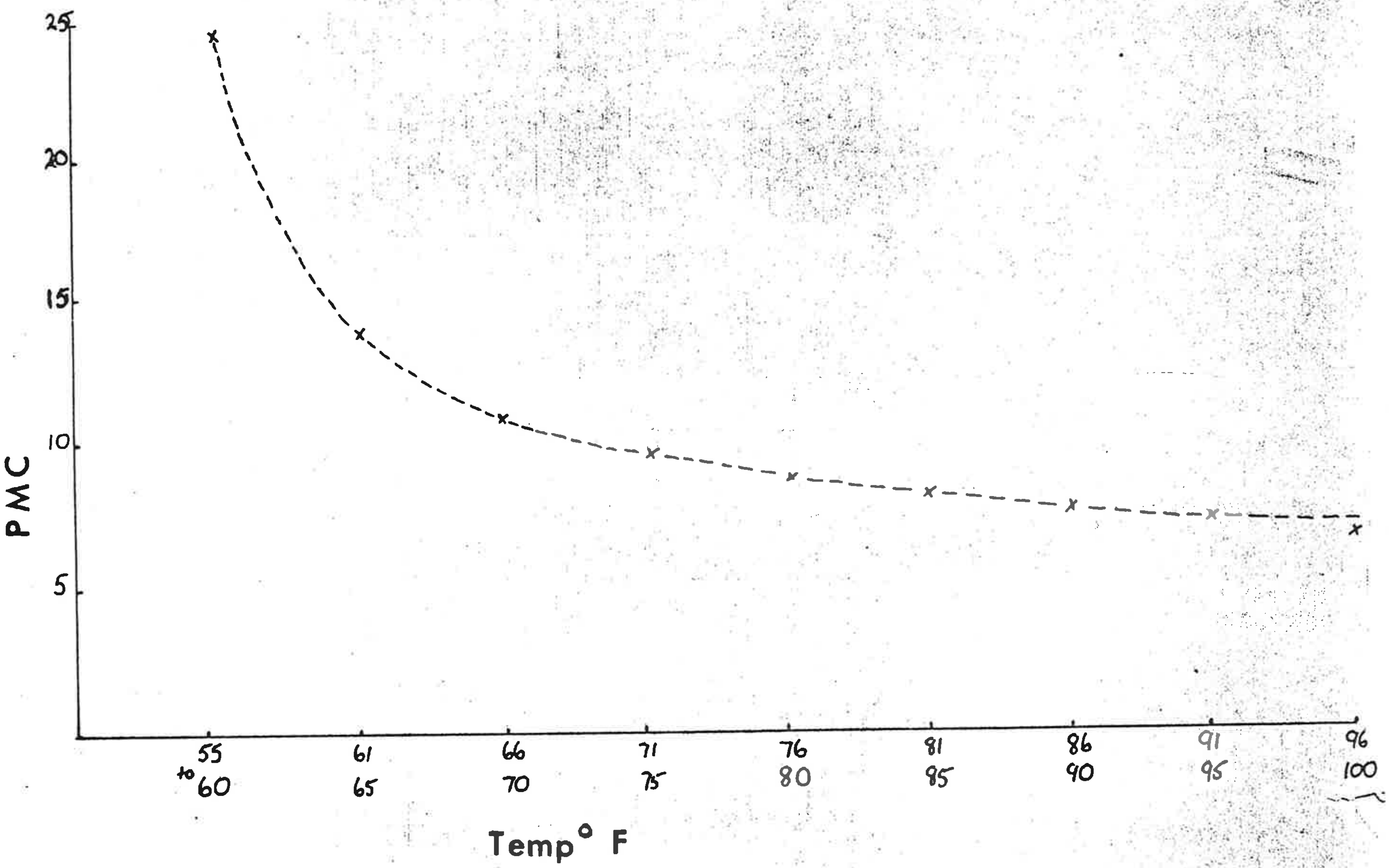
Graph 3

Surface Leaf Moisture Content and Relative Humidity



Graph 7

P.M.C. and Air Temperature



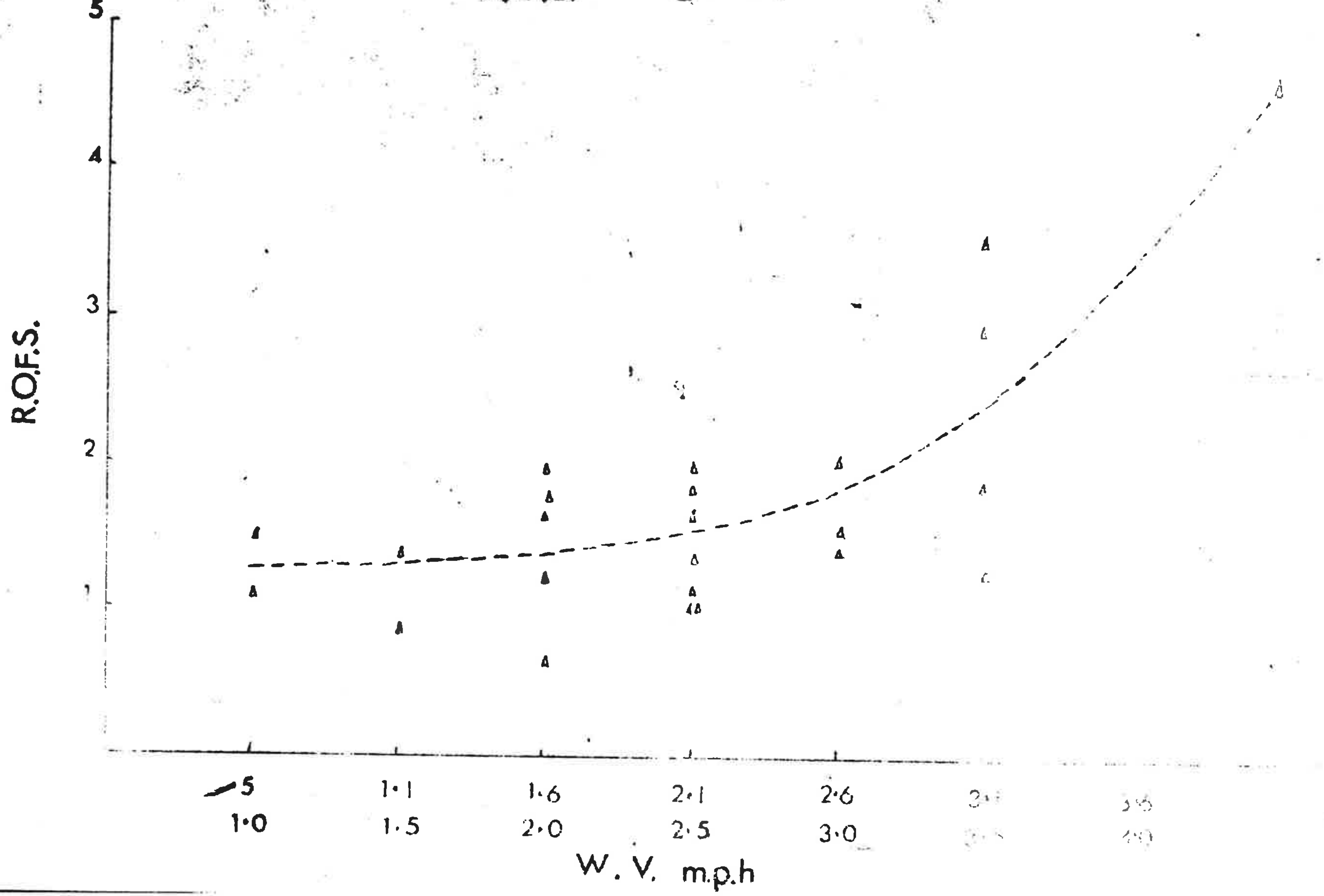
APPENDIX 5

Graph 10

Wind Velocity and Rate of Forward Spread

F.Q. 1·5 to 2·0

P.M.C. 5 [illegible] 15

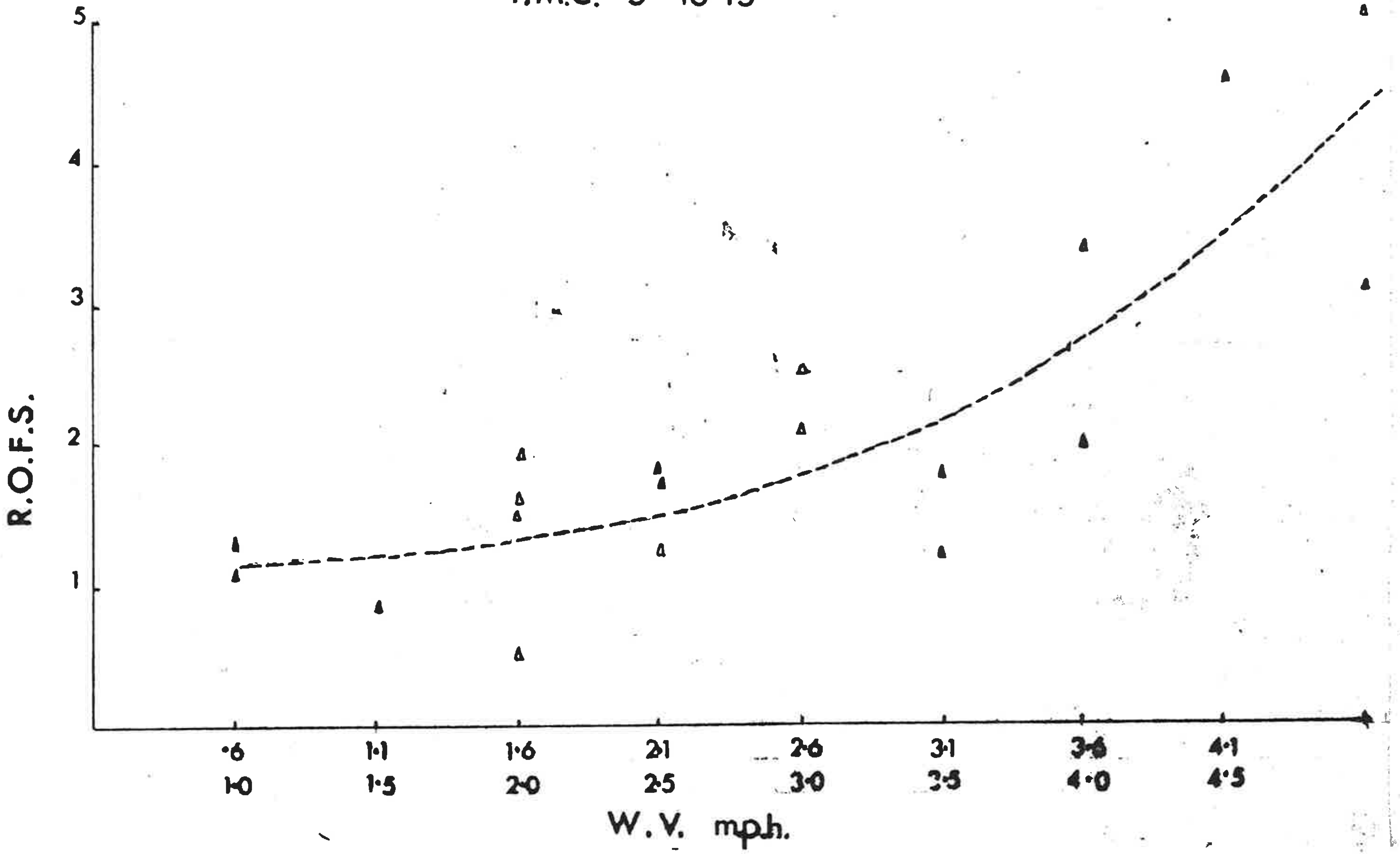


Graph 11

Wind Velocity and Rate of Forward Spread

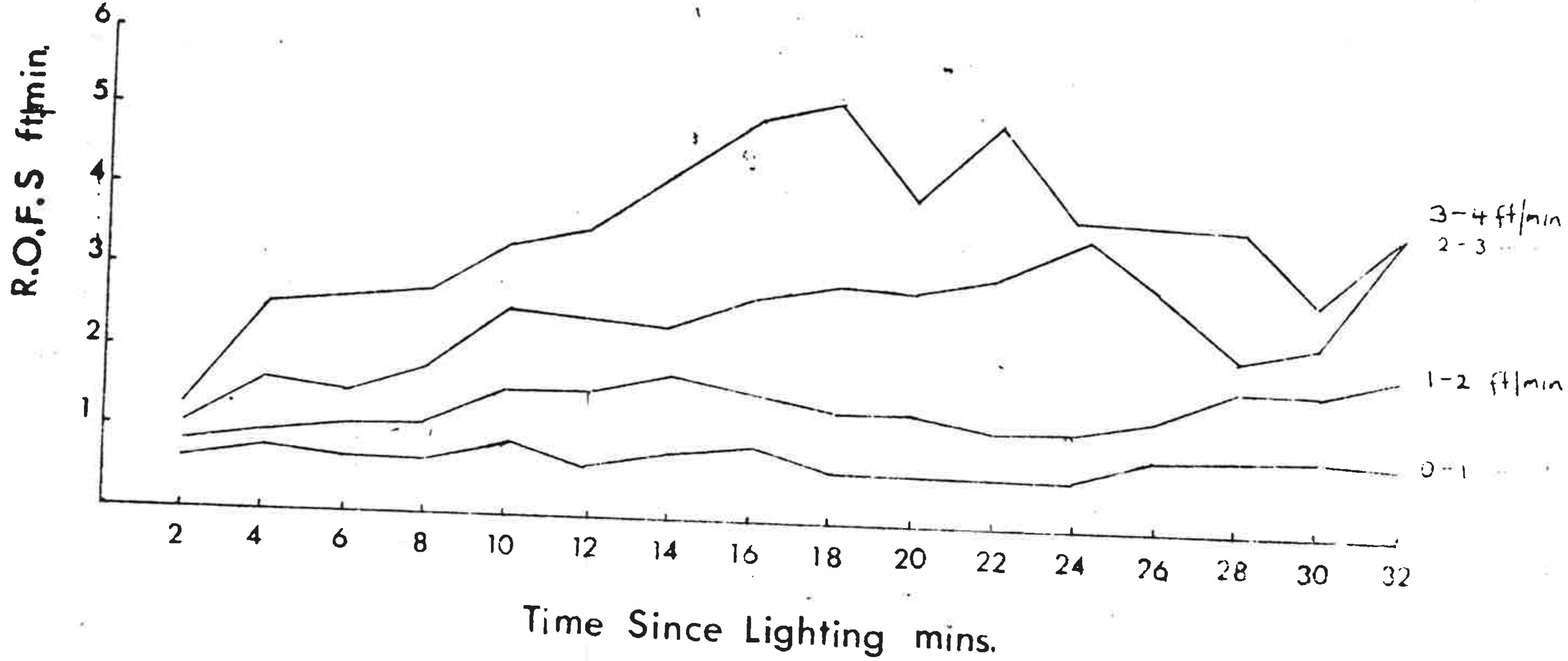
F.Q. 1·0 to 1·5

P.M.C. 5 to 15



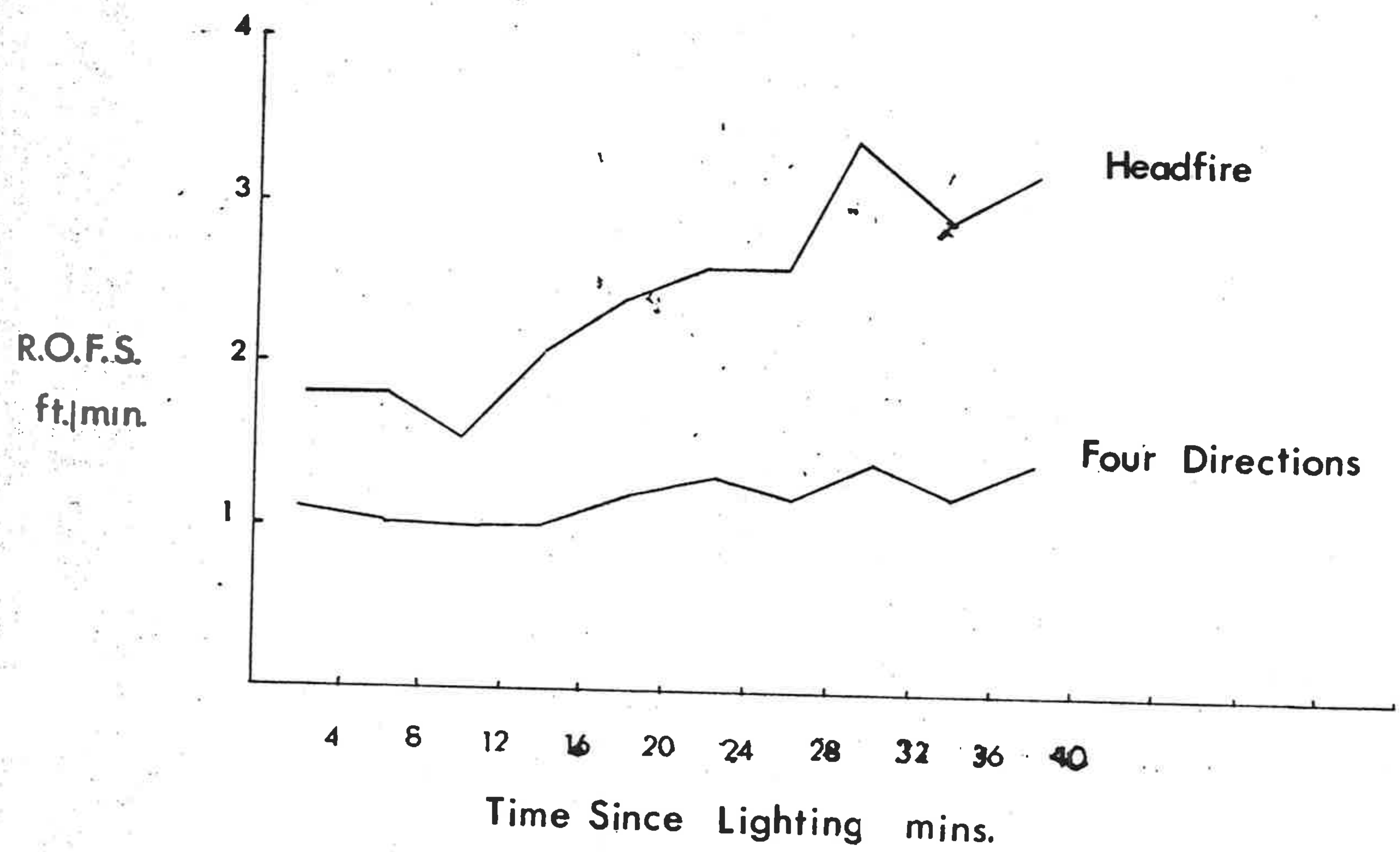
Graph 20

Rate of Forward Spread



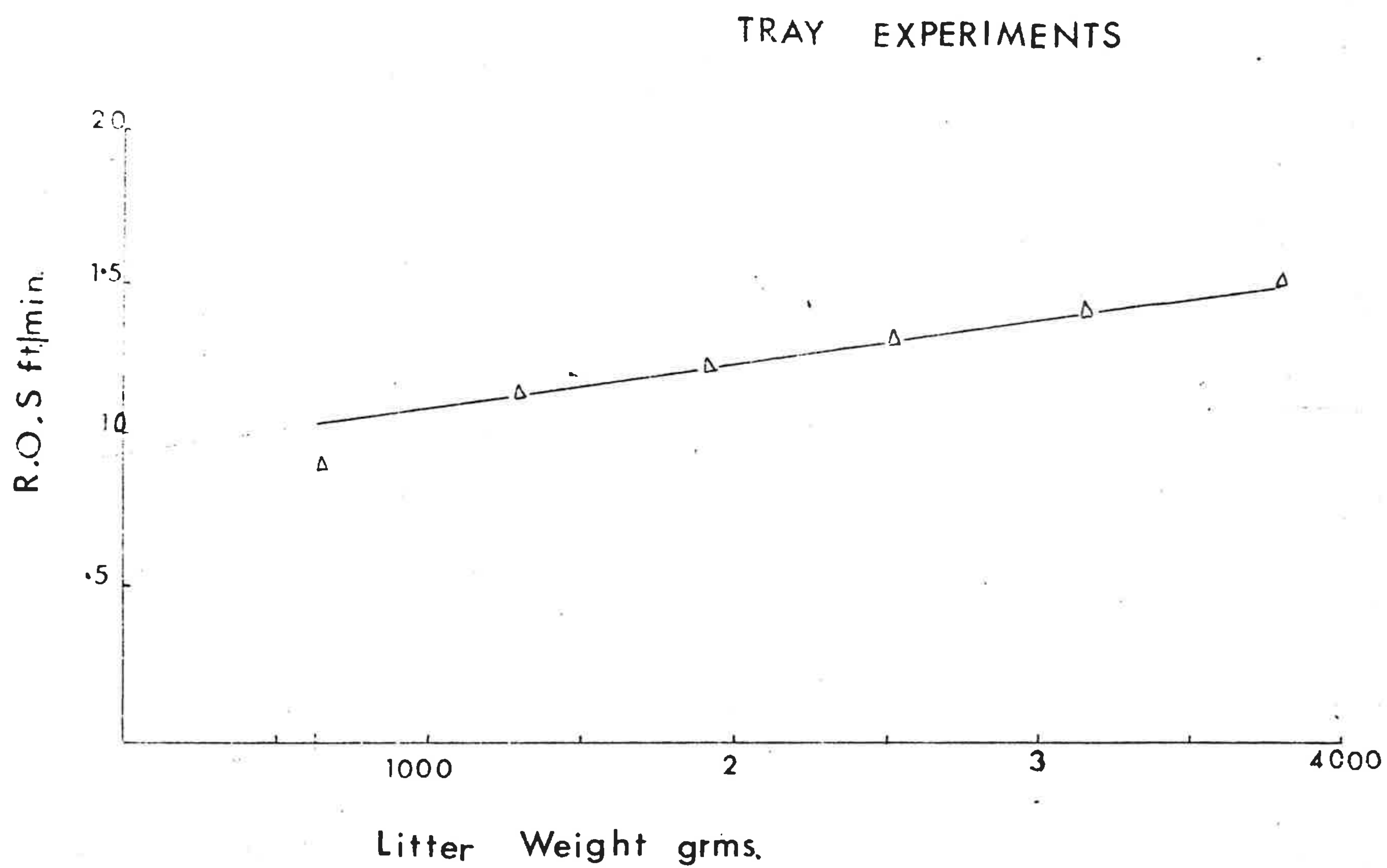
Graph 22

Headfire Spread With Average for Four Directions



Graph 17

Fuel Quantity and Rate of Spread

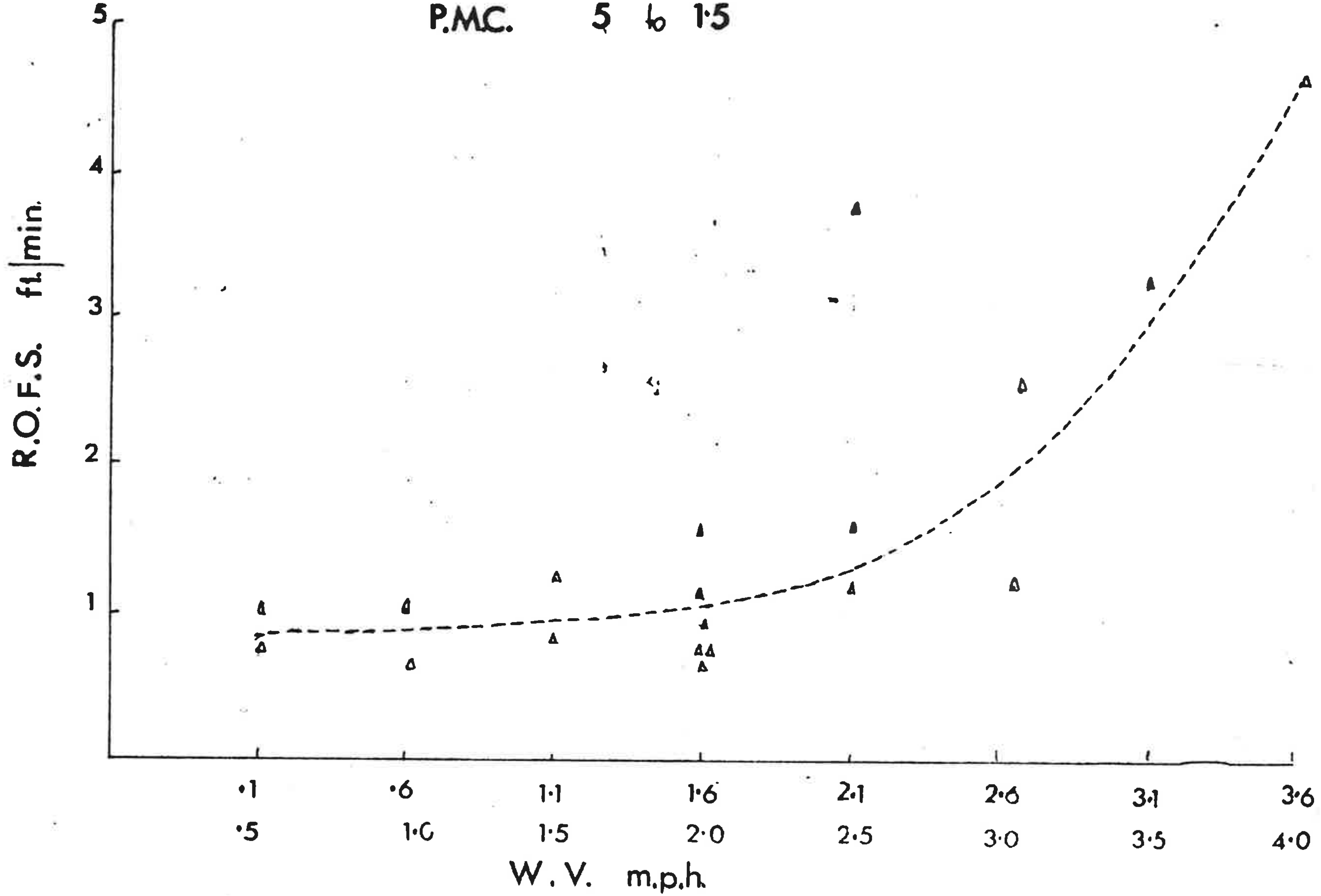


Graph 12

Wind Velocity and Rate of Farward Spread

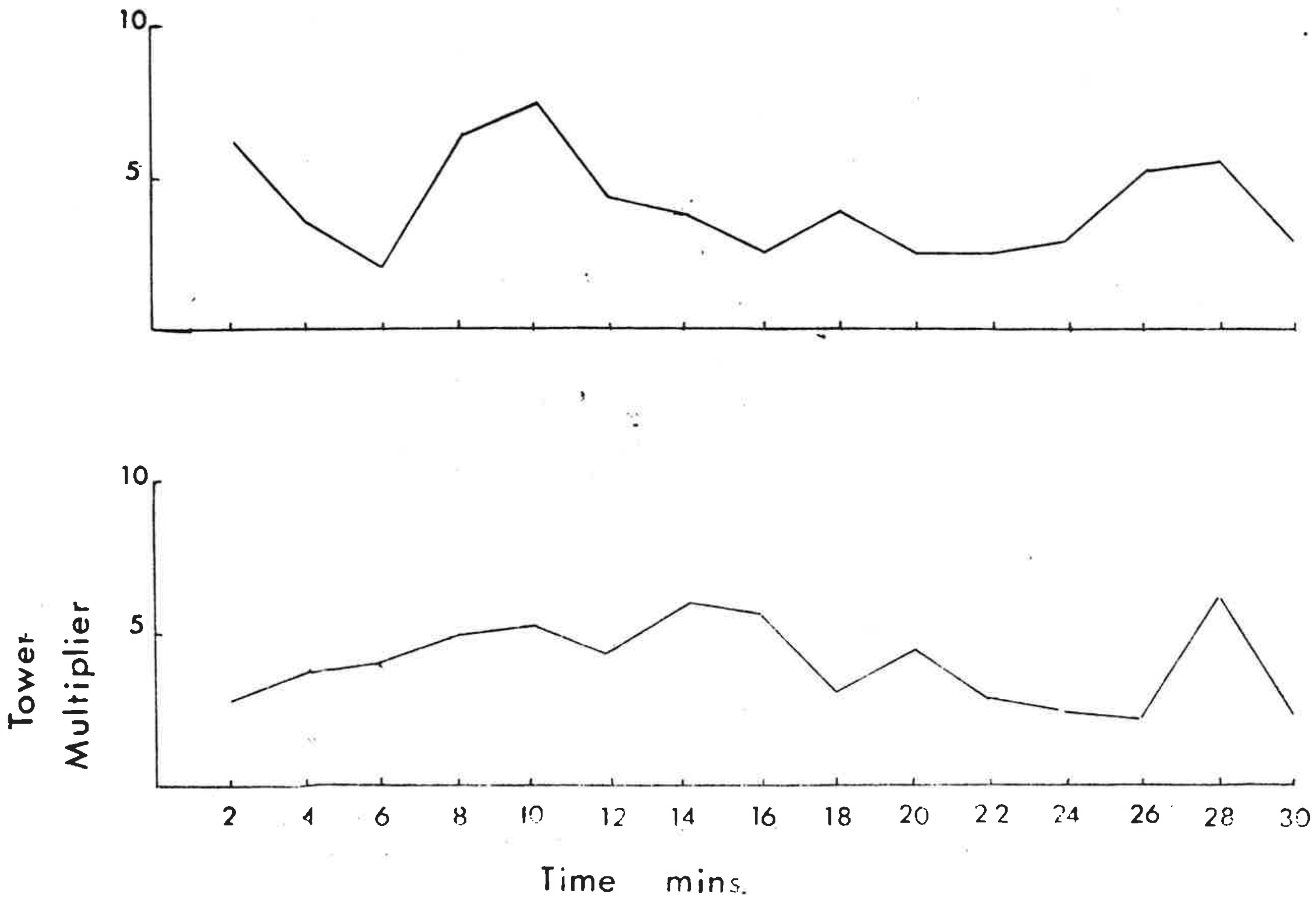
F.Q. 4·0 to 4·5

P.M.C. 5 to 1·5



Graph 18

Ratio of Tower to 4-Feet Wind Velocity



APPENDIX 6