Usable findings in major bushfire behaviour research in eucalypt forests – McArthur, Burrows, Vesta

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Abbreviations

FDI	Fire Danger Index from McArthur's Forest Meter, runs from 1 to 100	
FMC	Fuel moisture content	% of moisture by weight
HRR	Heat release rate	kW or kW / sq m
MLR	Mass loss rate – in dry fuel, MLR measures fuel supply rate	kg / sq m / sec
ROS	Rate of spread	m / sec or kph

INTRODUCTION

As a bushfire manager, I need to know how to explain and teach bushfire fire behaviour with science and logic. I also need to be able to predict, to diagnose, to analyse it, and determine its effects. I need to be able to assess local opinions and beliefs against scientific truths. I need to be able to assign confidence level or accuracy level in a fire behaviour model. This means bushfire behaviour science must be traceable to first principles and rock solid foundations. I am also looking for a practical and simple rule of thumb for each fire spread or flame height mechanism. For example, because most fires are wind driven, my starting point for a wind driven spread mechanism in severe weather is that ROS in a sub canopy litter bed is around 10% of wind at fuel bed level or ROS in a grass fire is around 45% of wind speed at fuel bed.

There have been three significant bushfire behaviour studies in eucalypt forests in Australia – McArthur, Burrows, Vesta. Coincidentally, most of the fire trials have been done in similar West Australian forests. This Paper reinvestigates them to identify usable useful findings that the bushfire manager can apply in day to day management and planning.

The major focus on bushfire research in eucalypt forests in Australia has been on rate of spread. Flame height observations were sometimes included, but have rarely been the focus of specific study. For this reason I begin analysis of bushfire research with rate of spread and then proceed to flame height.

This paper continues the back to basics series of papers. It examines the findings of major research works in eucalypt forests against the framework of bushfire behaviour mechanisms. I am taking this approach because Australian bushfire researchers have successfully muddied the waters. For example, Vesta has condemned the McArthur prediction model and wants to replace it altogether, yet Australia's bushfire weather forecast system is based on the McArthur Meter, which is highly respected and understood. The prediction model and the Meter were derived by the same author and are closely interconnected. Project Vesta did some good work but has produced its own prediction model that has unknowingly amalgamated three distinct mechanisms, and therefore has not advanced the cause or practice of science.

Paper 1 of this series has identified specific combinations of the factors that define unique mechanisms of bushfire behaviour - flame spread mechanisms, firebrand spread mechanisms and flame height mechanisms. They are all identifiable and user friendly. They have their own algorithms that are not transferrable. The mechanism concept is a safeguard for scientific legitimacy, because it prevents practitioners and researchers from invalid extrapolations and amalgamations.

Back to basics series:
Some core underpinning theory is incorporated into the first Paper:
1 Manual of bushfire behaviour mechanisms in Australian vegetation
Some more basic theory about spot fire behaviour introduces the second paper:
2 Spot fire direction and spread in severe bushfire attack - Australian vegetation
Together they provide a useful scientific background for the following papers:

3 Flame spread and flame height in eucalypt forests and grassland in severe bushfire
4 How the East Kilmore Black Saturday fire got away
The foregoing papers become the basis for analysing the findings in major research works on bushfire behaviour in Australian forests:
5 Back to basics approach for bushfire behaviour research
6 Usable findings in major bushfire behaviour research in eucalypt forests – McArthur, Burrows, Vesta
The wide range of published correlations between FMC and ROS led to the next paper, which takes a back to basics approach to FMC and flammability
7 Effect of FMC on flammability of forest fuels

Rate of spread (ROS)

In this section, I examine four significant research projects in eucalypt forest fire behaviour, beginning with McArthur, then Project Aquarius, then Burrows and finally Project Vesta. Aquarius provided data for other purposes, but the other three conducted research and used it as a basis for modelling severe fire behaviour. I analyse their work for rate of spread knowledge that can be traced back to core bushfire behaviour foundations and that is useable by the bushfire manager. I check their findings against first principles by firstly identifying which flame spread mechanism they are dealing with.

The research of the modellers was typically concerned with how fast a line of fire runs in zero wind and with increasing wind. Thus they were investigating the radiation spread mechanism and the wind driven mechanism, and in particular, the two fundamental influential variables of fire behaviour in a given fuel bed – air speed at fuel bed level and moisture content of the dead fine fuel that burns to create the tall flame. The modellers were also aware that spot fires contributed to fire spread. The following chapters show that instead of recognising spot fires as a different mechanism, they extrapolated and amalgamated their good data based on wind driven mechanism with data from severe bushfires caused by diverse mechanisms. The following chapters will allow the reader to assess the quality of their findings and their models.

As a bushfire manager, I am looking for a practical and simple rule of thumb for each spread mechanism. For example, Can the models answer this question? What ROS is expected in a eucalypt forest in severe bushfire weather?

Chapter 1 McArthur - rate of spread

2.1 Potted History

McArthur's data (McArthur, 1967) is predominantly based on field studies, ie, experimental burns in forests in mild weather. The forests were mainly in West Australia and in the ACT. He supplemented these studies with many observations and detailed post mortems about major bushfires.

In the 1962 leaflet, McArthur reports having done 400 experimental fires, mostly in WA and ACT. He included reference to data from three large bushfires - the 1952 Mangoplah fire in NSW, the 1959 Kongorong fire in SA and the 1961 Dwellingup bushfire in WA. By 1967, he says he has burnt over 800 experimental fires. They were allowed to run for 15 to 60 minutes and closely studied. He said this data has been reinforced by the study of a large number of high intensity bushfires. In 1967, he presented the Forest Fire Danger Meter, which determines fire danger index from weather data and allows prediction of fire behaviour for all weather conditions.

2.2 McArthur's theories

His work is guided by several theories:
ROS is positively correlated to fine fuel load. It is also positively correlated to decreasing fuel particle size, fuel bed dryness, wind speed, up slope angle, and increasing aeration of fuel bed
ROS is negatively correlated to increasing fuel particle size, fuel moisture content, and time since recent rain and down slope angle.

2.3 McArthur's original and later data

Unlike US researchers, McArthur rarely published his data or his analyses of data. He generally published his findings as smoothed charts. This makes his findings unverifiable. However, I have found one exception where over 40 records of rate of spread against fuel moisture content and wind speed at fuel bed have been recorded, dating from 1958. I copy them in Figure 1 and rearrange them in Figure 2 with metric units. They are significant because they are some of his actual research data, and they show him using the core influential variables of fire behaviour in a given fuel bed – air speed at fuel bed level and moisture content of the dead fine fuel.

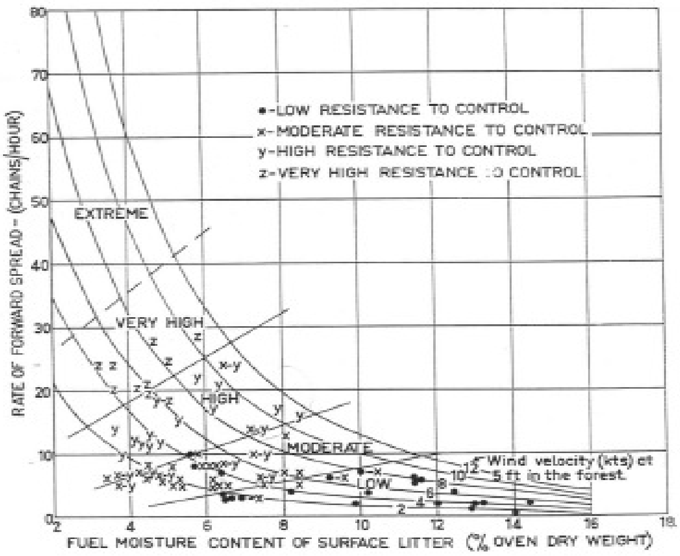
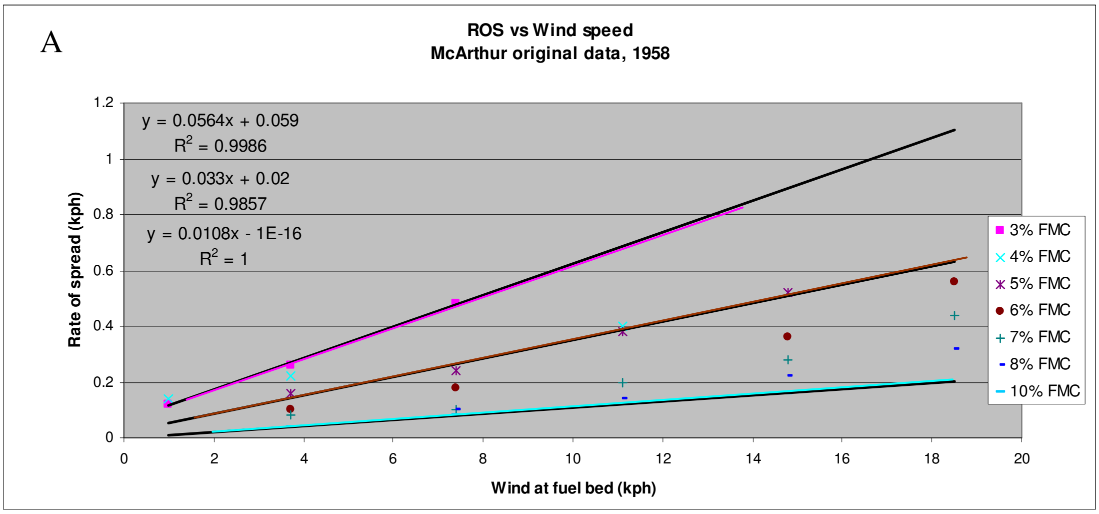


Figure 1
Each letter or dot on this chart is a data point showing steady state rate of spread against FMC and wind speed at 1.5m, which I call wind at fuel bed level. The data is in forest with fuel load of approx 12 t/ha. McArthur's fires are point sources, he allows them to run for approx 40 minutes before suppressing them. Figure reproduced in **Tolhurst (2010)** from McArthur's 1958 reference



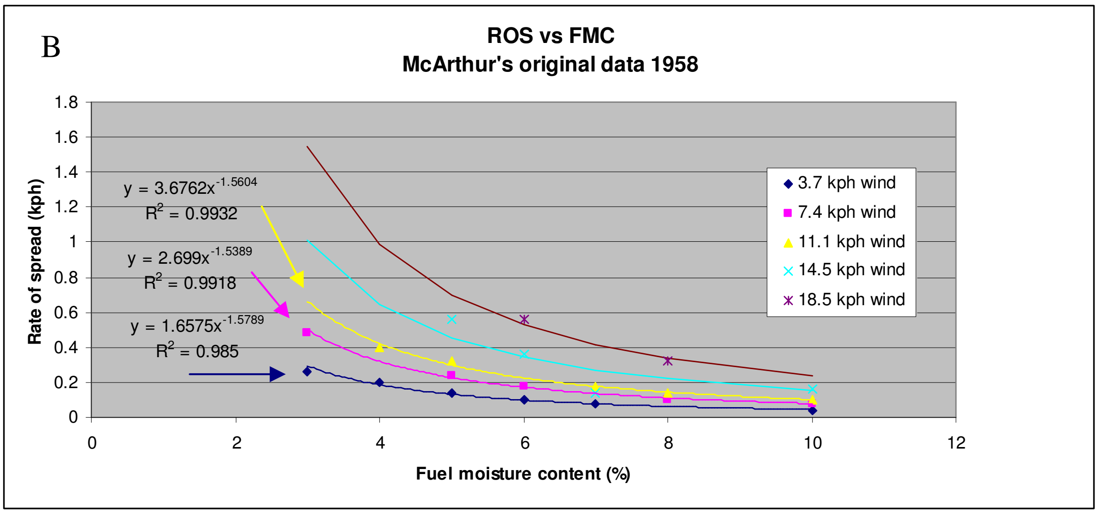


Figure 2 McArthur's original 1958 data range re-presented in metric units
2A shows linear ROS trend lines for 3%, 5%, and 10% FMC, very highly correlated.
2B shows ROS is very highly correlated with FMC to the power -1.55. I regard his data points of 18.5 kph wind speeds below tall forest canopy as dubious, because they suggest open wind speed is around 80 kph.

ROS vs Wind speed

Figure 2A shows that the correlation between ROS and wind speed is linear with high correlation coefficient. Eg,
For the driest fuel (3.5% FMC) ROS = 5.6% of wind at fuel bed level
For 5% FMC, ROS = 3.3% of wind at fuel bed level
For 10% FMC, ROS = 1% of wind at fuel bed level

This 1958 data sits comfortably within the wind spread mechanism.

ROS vs FMC

Figure 2A shows that for all wind speeds, the correlation between ROS and FMC is inversely exponential to the power -1.56.

Over the years, there have been at least three versions of McArthur's rate of spread charts (Figure 3). For simplicity, McArthur's charts are shown here as linear, even though he presented them as exponential. I have ignored McArthur's nominated fuel loads on these charts, and assume they apply to all fuel loads. This is based on findings by Burrows (1999a) that only the top 1.5 cm or so of the litter bed is consumed by the moving flame (**see below**).

Figure 3 shows three versions, and the first thing to notice is that they are all different. The 1978 version has the highest rates of spread for a given wind speed and a given FMC, and 1958 has the lowest. The 1967 version is in between. It also shows that the ROS on the 1978 chart is 50% greater than the 1967 charts. Overall, there has been a tripling of the rate of spread for a given wind speed over a 20 year period, since 1958. Why so? (See below)

Figure 3 also includes the outcome of my 2005 analysis for ROS in litter bed forest in severe weather (worse than 40^{0}C and 10% RH and 40 kph wind in open). My analysis included a comparison of my chart with published eucalypt forest fires and almost all fell within 20% tolerance band (O'Bryan, 2005). I find that ROS averages approx 10 - 12% of wind speed at fuel bed in worst case weather. This is approx 3 – 4% of wind speed in the open.

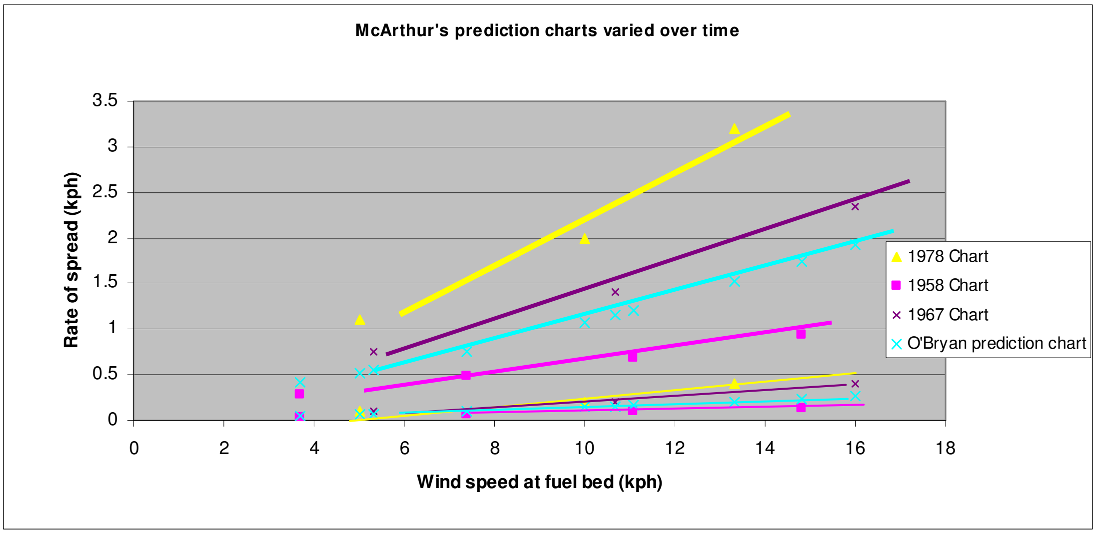


Figure 3
Each data group shows two lines. The top one (in bold) is 3% FMC and the lower one is 10% FMC.
The 1958 chart derives from Tolhurst (2010), uses 12t/ ha
The 1967 chart derives from McArthur (1967), uses 20t/ ha
The 1978 chart derives from Luke and McArthur (1978), uses 20t/ ha
The O'Bryan (2005) prediction chart is a best fit estimate, verified against line of fire spread mechanism bushfire data within 20% error range

Other McArthur versions: The McArthur Meter Mark V incorporates a prediction chart. It is closest to the 1967 chart. McArthur's 1962 chart (McArthur 1962) focuses on low intensity control burns, and therefore presents charts between 6 and 10+% FMC. For 6 and 8% FMC, the rates of spread are 150 to 180% times the 1958 figures for wind speed 6 – 9 kph (4 - 6 mph).

I am working with the hypothesis that McArthur's earlier charts are some of his authentic initial research findings for an advancing line of flame in a predominantly litter fuel bed. I therefore postulate that the tripling was his attempt to extrapolate to account for observed rate of spread in later studies with higher proportion of shrub cover or in severe bushfires due to leap frog spotting, or both. This conclusion is supported in Luke and McArthur (1978), who use the 1972 Mt Buffalo fire (p 107 and also Fig 6.15) to explain the basis of the FDI system on the McArthur Meter. "Remembering that this is an index representing the behaviour of a fire on level ground in a 12.5 t/ha fuel type, the necessary corrections for slope and fuel quantity are …"

Figure 4 is my best estimate of McArthur's view of litter bed fire behaviour by the 1960's. Using the 12.5 t / ha fuel load, the McArthur Meter calculates ROS as 0.014 x FDI. This can be converted to plot ROS against wind speed at fuel bed and FMC. I used the Luke and McArthur (1978 Table 4.2) equilibrium moisture content table and the Vesta conversion for in-forest wind speed (3 to 1).

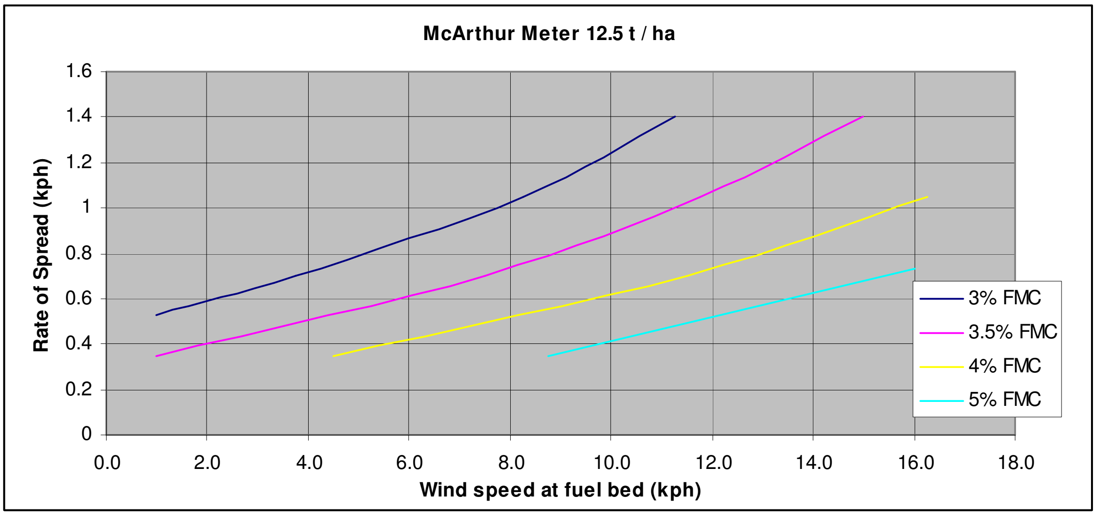


Figure 4 Derived ROS from McArthur Mark V Meter, using estimated air speed at fuel bed level.

Figure 4 shows a ratio of ROS to wind speed at higher wind speeds is up to 12% for 10 kph at 3% FMC. Furthermore, at lower wind speeds, the ROS to wind speed ratio reaches absurdly high levels, eg, 30% for 2 kph winds at 3% FMC, and 17% for 4 kph winds at 3% FMC. Figure 4 is therefore between 2 to 3 times the ROS to wind speed ratio of McArthur's original 3% FMC data (see Figure 2). At zero or low wind speeds the radiation spread mechanism is dominant, and it is the slowest of all the spread mechanisms. It is therefore not helpful to include it on a wind driven chart.

How much of McArthur's data is usable by the bushfire manager?

Apart from the 1958 data, which seems to be original (except for in-forest wind speeds greater than 14 kph or so), McArthur's charts cannot be regarded as accurate because they are smoothed or contrived to account for the boost due to spot fires.

The 1958 charts (Figure 2) are useful benchmarks because they apply to the "McArthur forest" (tall eucalypt forest with approx 12.5 t/ha litter bed and scattered shrubs) and are associated with a line of flame in a litter bed that runs according to the wind driven mechanism.

It is useful to have a benchmark for ROS of a line of flame in a dry litter bed forest (3% FMC). Eg, Daylesford bushfire data (see below) is usable. A line of flame ran at 1 kph when wind was 48 kph. This was 2% of wind speed in the open (= approx 8% of wind at fuel bed), and therefore similar to his 1958 data. It is also useful for McArthur's note that leap frog spotting has three times the spread rate of the mother fire. Unfortunately, his subsequent modelling neglected to incorporate this observation.

The Longford and Wandilo fire data for line of flame is also usable, but for another reason, ie, for first round identification of the spread mechanism or fuel bed type. Eg, Wandilo bushfire records two ROS examples of line of flame in a shrubby stunted eucalypt forest at 5% and 4.7% of wind in open, eg, ROS = 2 kph in 42 kph wind. Longford data includes examples of spread rate in similar shrubby stunted eucalypt forest. Eg, 1.4 kph ROS in 50 kph winds = 3% of wind in open, and 1.6 kph in 32 kph wind = 5% of wind in open.

These observations show that a wind driven fire in shrubby or open forests runs around double that ratio of a wind driven surface fire in a tall forest with light shrub cover. , eg, a benchmark of 4 – 5% of wind speed in open compared to 2% or less Thus, if a fire record significantly exceeds the 5% ratio, the bushfire manager and researcher should be alert to investigate if another spread mechanism is involved.

A further example: Figs 1 and 3 in McArthur (1967), which apply to 25 t/ha jarrah forest with a "loosely compacted fuel bed carrying a percentage of shrub species", have ROS ranging up to 2.4 kph when wind is 48 kph at 10m in the open. Thus, he is reporting ROS is up to 5% of wind speed in the open, which equates to 20% of wind speed at fuel bed level. Although this ratio was well in excess of the benchmark ratio for the in forest wind spread mechanism, it remained undiagnosed. It is a similar ratio to many of Vesta's findings (see below), and it is suggested the appropriate mechanism is tall flame / piloted ignition.

The following notes articulate and examine other McArthur's findings that I have deduced from his body of reports. It also tries to document why there is a tripling of ROS for a given wind speed over a 20 year period, since 1958.

2.4 McArthur's findings

His main focus is rate of spread, spotting and concern for fire suppression at the controller level. His influential input variables in lower intensity fires are wind speed, fuel bed dryness, fine fuel load and slope, and in higher intensity fires, spotting. His benchmark workplace is the tall eucalypt forest with predominantly litter bed and little understorey. We can deduce that he believes his findings for low intensity fires can be extrapolated to high intensity bushfires via the McArthur Meter. We will also discover that his prediction system has increased observed ROS to account for the turbo effect of the short distance spotting process in high intensity fires, but he does not describe his process or provide quantification. Apart from fuel dryness and air speed, McArthur's trademark fuel bed indicator for rate of spread prediction is fuel load. He perhaps believed fuel load was a user friendly proxy for other indicators. Whatever the reason, its usage effectively dumbed down the understanding of bushfire behaviour principles in bushfire managers and researchers for decades.

His core explanatory document is McArthur (1967), supplemented by Luke and McArthur (1978). I now summarise these and other documents to glean additional background about assumptions, theories and rationale.

(1) Rate of spread (ROS)

McArthur's rate of spread is not clearly defined. Three different rates of spread are discernable in McArthur's text – (1) rate of spread of the fire front as a line of flame, (2) ROS of the leading fire front that has been boosted by mass short distance spotting and (3) ROS of the leading leap frog spot fire. They each apply to different spread mechanisms but he does not differentiate them as such. This suggests even though his original work made findings for the wind driven mechanism, his next works sought to extrapolate these findings to account for the spotting mechanism The Case Studies demonstrate his quest to account for or predict observed ROS may have overruled his commitment to fire behaviour science fundamentals.

Is this finding usable? Identification of different ROS is important

(2) Effect of fuel moisture content (FMC) on ROS

McArthur found ROS was inversely proportional to FMC to the power -1.56 in 1958, but by 1962, he proclaimed it to be -2 to -2.5. He compared this to the linear inverse correlation in ponderosa pine in USA used by Rothermel and Anderson (1966), explaining the difference in our forests was due to spotting. This suggests he was boosting his line of fire findings in trials to account for the higher spread rates in bushfires due to spotting. He was apparently unconcerned that wind spread and spotting spread were two different ROS mechanisms, like apples and oranges. Nevertheless, it gives a clear understanding in hindsight that his charts and Meter included an expedient but unscientific boost to account for the spotting factor.

He provides an equilibrium FMC chart derived from temperature and RH, and explains its diurnal nature. The fact that he never mentions weighing fuel particles for FMC suggests that he probably used this table to compute FMC. Cheney (1968) confirmed this. This EMC chart may have been copied from USA. I am not aware of a systematic Australian study.

Is this finding usable? His FMC vs ROS correlation is not reliable because it is extrapolated beyond original data to account for spotting process in an undocumented way.

(3) Effect of wind velocity on ROS

McArthur's 1958 data that show ROS and wind speed have a linear correlation was overturned by McArthur (1967), where ROS was proportional to square of wind speed. He explains that the effect of wind speed on ROS is greatest at low FMC because it is associated with the spotting process. This suggests confirmation for his choice of power function for wind speed.

Is finding usable? His wind speed vs ROS correlation is not reliable because it is extrapolated beyond original data (which used the wind spread mechanism) to account for spotting spread mechanism without documented explanation.

(4) Effect of shrub layer on ROS

McArthur says that of all the fuel components in a forest, litter bed has the slowest flame speed. He says a shrub layer on the forest floor, eg, tussock grass, bracken or blady grass, has a faster ROS than litter due to finer fuel particles and more aeration. He does not quantify the difference. This suggests he knows that better aeration and smaller particle size increases combustion rate and ROS. This implies an understanding that fuel load per se is an ineffective prediction tool in different fuel bed types, ie, that an extra 4 t/ha of shrub layer will generate a faster ROS than an extra 4 t/ha of litter bed fuel.

This means McArthur's concept of shrub layer fuel was therefore a substantial scientific and logical error. He accounted for the extra fuel beds by fuel load alone. Thus, if litter load is 10 t / ha, and we add 5 t/ha of shrub fuel load, his theory says ROS increases by 50% of the litter flame speed. But McArthur clearly says flame in shrub travels faster than litter bed. Therefore McArthur's logic will always under predict shrub layer ROS, and the degree of under prediction increases as shrub fuel load increases.

I have watched in horror as researchers added dense heath fuel loads (up to 3m tall in treeless areas) and bark fuel loads to the McArthur Meter mix (via "elevated fuel hazard" and "bark hazard" in the government's "Overall Fuel Hazard Guide" (DNRE, 1999) with impunity, and recoiled in even more horror as other researchers cited and emulated it. It suggests that, like McArthur, they do not know that adding an extra few t / ha of shrub layer to the McArthur Meter results in under-prediction, and that spread in shrub layer has a different mechanism to spread in litter bed. Nor do they realise that bark has no role in the wind driven spread mechanism of a forest fire. But I have now carefully re-read McArthur (1967), and I am disappointed to acknowledge that these researchers were blindly following the lead of the master into error.

Is finding usable? McArthur's habit of adding the shrub fuel load to the Meter was inaccurate, misleading and confusing and a poor example for impressionable researchers. There is no research to show that wind driven ROS of the flame in the surface / near surface layers is influenced by taller flame in the elevated shrub layer.

(5) Effect of fuel quantity on ROS

McArthur stated dogmatically that ROS is proportional to fuel load available for combustion. He does not define available fuel. However, his discussion about burnout time suggests he is referring to total combustion, ie, flame phase and smoulder phase. This means total fine fuel. He does not distinguish live from dead fine fuel. He does not distinguish flaming phase from smoulder phase. He assumes all the fine fuel present on site contributes to ROS. In contrast to Byram (1959) who defines available fuel as fuel consumed in the flame phase, the McArthur Meter defines fine fuel as "combustible material less than 6 mm".

McArthur's (1967) examples show that ROS is proportional to fuel load, but they are very mild fires in very light wind and ROS is very low. He assumes all the fuel load is consumed by the fire front. Eg, his Fig 5 is for jarrah forest up to 10 t / ha fuel load, where ROS is 70m / hr. His Table 2 applies to an 8 t/ha forest where ROS is 30m / hr and 0.3 m flame height, and a 16 t/ha forest where ROS is 60 m / hr and 1m flame height. He assumes this correlation applies to high intensity fires. Strangely, he does not show fuel load examples for higher ROS. This is a serious omission. If he had acknowledged that these examples applied to the radiation spread mechanism, he would have realised he could not transfer their findings to the wind spread mechanism. It shows disregard for good work by contemporary US researchers, who clearly reported that the faster the wind speed, the more fuel was left unburnt in the litter bed (eg, Rothermel and Anderson, 1966). This was confirmed later by Burrows and Vesta (see below)

He presents fuel accumulation curves for karri and jarrah that rise to around 25 t/ha after 25 years, but he does not explain that in those days, WA measured fine fuel load up to 12mm thickness. (WA changed its definition to fine fuel 10mm in 1976 – Cheney (1981). Therefore when he quotes 25 t/ ha in Jarrah forest, fuel load could well be double what a 6 mm definition would measure. Yet he jumps from western state graph to eastern state graph without clarification. By comparison, Vesta found jarrah litter (using 6 mm definition) levelled off around 14 t/ha after a dozen or so years.

When we read McArthur's fire post mortems (see below), we see how he adds all the dead fine fuel on site to try to match the observed ROS and apparently prove his model, akin to a salesman. He laments in the Longford fire (see below) that observed ROS in bracken is inexplicably greater than his prediction, despite loading it up with high shrub fuel load.

Is finding usable? Rather than throw the baby out with the bath water, I ask - what fuel load on the McArthur Meter is the most useful to use for prediction? I recommend using 12.5 t / ha data for ROS because it is probably closest to McArthur's original work and focus, and therefore most accurate. It means it can only be applied to a predominant litter bed forest and it must not be loaded it up with shrub fuel load because different spread mechanisms apply to the shrub flame spread scenario.

(6) Effect of slope

McArthur says slope has an effect on line fires according to his equation, but over long distance fire runs or when the spotting process takes over, slope becomes irrelevant. His equation has been accepted by a generation of researchers, but may not have been tested. It is significantly different to Byram et al (1964)

Is this finding usable? Yes, but its accuracy needs to be tested.

(7) Effect of spotting on ROS

McArthur and colleagues refer confusingly to the true fire front, pseudo fire fronts, the apparent ROS and the true fire front.

McArthur (1967) describes short distance spotting as 1 - 3 km, but says the impact of short distance spotting within 400 – 800m on ROS is substantial. It can cause a mass ignition effect, which can lead to mass spotting downwind. He says "the apparent rate of spread can be very high, but does not represent the movement of a true front". Luke and McArthur (1978) define long distance spotting as > 7-8 km, and say it has little effect on the main fire. They regard it as a separate fire.

They define short and medium spotting as up to 8 km. Bark pieces up to 10 – 20cm long are torn off fibrous trunks of stringybarks and peppermints, but they are not very buoyant and seldom travel more than 3-4 km ahead. They can produce mass spotting (p 104). The multiple spotting pattern can produce a mass fire effect and form "pseudo flame fronts", which "take the form of an intense stationary fire with huge convection and inflow winds. Once the burn-out completes and the inflow circulation ceases, a new fire front progresses as a normal fire front". They also say most embers fall within the first 100m and decline to 1-2 spot fires at 2-3 km.

This raises the question – what ROS is his Meter predicting – the apparent rate or the true front? We ask this question of his Daylesford example: The Meter's ROS prediction for FDI 35 and 25 t/ha is 1 kph and spotting distance is 3km. McArthur (1967) finds ROS in the first hour is 0.75 kph, which is just less than the Meter prediction, but after describing the spotting processes, he says the average ROS of the fire is 3 kph, "three times the rate of spread expected from a moving flame front where spotting is not the predominant spread mechanism". He is clearly referring to leap frog spotting rate of spread. Cheney (1968) calls it the apparent rate of spread. Thus, both McArthur and Cheney clearly affirm that the Meter refers to the mother fire front.

INSET
Bizarre curiosities: Cheney (1968) discussed the same fire but with different data. His paper was published after McArthur's (1967), but was submitted to the publisher before it.
Cheney: 35^{0}C, 10-15%, 40-48 kph, FDI 60 Fuel 10 t/ha predicted ROS = 0.8kph
McArthur: 35^{0}C, 34%, 48 kph, FDI 35 Fuel 25 t/ha predicted ROS = 1 kph

Who was correct? Was 16 January 1962 a Total Fire Ban day (TFB)? Yes, 15, 16, 17 and 19 January were TFB's, which are declared when FDI exceeds 50. Therefore, chances are that Cheney's weather is more accurate.

Is the finding usable? It is helpful to understand the three types of spotting – short, medium and long distance. He provides useful observations about the potential impact of spotting on ROS. He provides no quantified correlations about influence of spotting on either line of flame ROS or leap frog spot fire ROS.

(8) Fire acceleration effect

McArthur explains the acceleration effect in concept. Under severe conditions, fire burns in litter for 17 minutes reaching 0.14 kph, then it ignites shrub layer and jumps to 0.36 kph after 10 min, then it ignites crown and 10 min later is 0.5 kph. I have observed in a multi-layer fuel bed with connecting ladder fuel that this can occur instantaneously, within seconds.

Is he indicating that in forest, speed through the shrub layer can be 2.5 times the litter bed speed, and if it crowns, can be 4.5 times the litter bed ROS? We know that whilst crown fires can consume the canopy from the fire below, ie, as a passive crown fire, it is rare for an active crown fire to progress through an open eucalypt canopy, as it does through much denser pine plantations or ti-tree thickets.

Is the finding useful? No, it is too arbitrary and therefore bizarre and confusing

(9) McArthur's prediction system

The current McArthur Forest Meter dates from 1967 and is based on 12.5 t/ha of litter bed and a high forest (eg, 20 – 30+m). The significance of tall forest relates to reduced wind speed at fuel bed (Cheney, 1968). McArthur's Fig 4 shows that high forest (= tall commercial forest) reduces wind speed to 20 – 25% of open station, moderate stocking and shorter forest to 30% and open short forest to 40%. The Meter states that fires in lower quality forest (meaning shorter forests with less canopy cover) tend to run faster with the same open station wind speed.

The McArthur Meter can be a little confusing, until we realise it is actually three tools in one. - - - Firstly, it calculates a fire danger index (FDI) from weather inputs – chiefly temperature, RH and wind speed. FDI is a scale of 1 to 100. Technically, FDI is limiting as a prediction tool. Better accuracy would be delivered if air dryness and air movement were applied as separate independent variables. For most of the FDI scale, a windy day with mild temperature can have the same FDI as a calm day with high temperature, and the fire behaviour on each day will be very different, but the Meter predicts them as the same. This confusion can be overcome if FDI and wind speed are provided jointly.

- Secondly, it divides this scale into five classes of difficulty of suppression in the standard "McArthur forest", ie, 12.5 t/ha eucalypt forest – predominantly litter bed. His suppression difficulty scale is directly related to Fire Danger Index, which is directly related to rate of spread (Luke and McArthur, 1978, see below). I remind readers that McArthur (1967) states that the McArthur forest litter bed has the slowest fire rate of spread speed, due to its thicker particles and compaction. He also says that a pure litter forest cannot generate a crown fire because of the large gap between litter flame and canopy. Thus the Meter's suppression difficulty scale derives from a slow forest flame that cannot crown.

- Thirdly, it has a fire behaviour prediction table that shows rate of spread, flame height and spotting distance for the tall "McArthur forest" but also shows how additional fine fuel load increases rate of spread, etc. Technically, the prediction table is only related to fire suppression difficulty at the 12 t/ ha fuel load. Therefore, theoretically, suppression difficulty in a 12.5 t / ha forest at FDI 50 is equal to that of a 25 t/ha forest at FDI 50. The bushfire manager knows this is not the reality.

Luke and McArthur (1978) state that Australia's fire danger rating system serves two purposes:

- To provide the basis for Bureau of Meteorology fire weather forecasts
- To provide fire control managers "with reliable daily or even hourly information on which to base their assessment of fire risk, likely fire behaviour, … detection services, location of initial attack crews"

They say the Fire Danger Index scale 1 – 100 is "directly related to rate of spread" and FDI 100 applies to the Australia's worst possible weather conditions – 40^0C / 15% RH / 55 kph (p114). But, they quote worse weather than this in their text (eg, Black Friday 13 Jan 1939 was 46^0C, 8% and 30 - 60kph), 14 January 1944 was 40^0C, 10%, 35 – 55 kph, and 8 January 1968 was 40^0C, low RH, 90 kph. Stranger still, it is different weather to McArthur (1967) worst case day. But this is but the first of the frustrating ambiguities of the fire danger meter.

INSET

What is FDI 100? Not even our top researchers can agree

McArthur (1967) says of the FDI scale that “100 represents worst possible conditions”, 100 – 105^{0}F, RH 10% wind 36 mph. This converts to 37- 40^{0}C, RH 10%, and 58 kph wind speed. On the Mark V McArthur Meter, 37^{0}C plots at FDI 110 approx and 40^{0}C plots over FDI 120. Thus even McArthur’s worst ever 100 is actually 110 or 120.

McArthur clearly meant FDI to be approximate, like a guide. He says of the Fire Danger Meter - “estimates of rate of spread are complicated by the tremendous spotting potential of most eucalypt species but are generally of an order of accuracy to satisfy operational field users whilst at the same time provide a satisfactory basis for generalised fire danger forecasts”. McArthur’s colleague Cheney (1983) says that at high FDI, the ROS of the fire front is directly influenced by short distance spotting.

Luke and McArthur (1978, p114) says that FDI 100 weather is 40^{0}C, 15% RH and 55 kph. On the Mark V McArthur Meter, this plots at FDI 100

Cheney (1983) says the FDI 100 is based on 45^{0}C, 8% and 36 kph which occurred on Black Friday, 13 Jan 1939 at 1400 hrs at Melbourne weather station. This plots to FDI 100. He also says that FDI nudged above 100 three days earlier in 1939. Tolhurst (2009) also reported these conditions for Black Friday.

So far, we have three descriptions of worst possible conditions from the same researcher group:
37-40^{0}C, RH 10%, and 58 kph
40^{0}C, 15% RH and 55 kph
45^{0}C, 8% and 36 kph

In the meantime, Noble et al (1982) have converted McArthur Meter into equations. His equations accurately represent the Meter’s FDI scale and the prediction scale. Unfortunately, they did not define the limits of their equations, and subsequent researchers have not bothered to do so either. The equations are only valid for FDI 1 to 100 and for prediction to fuel load 25 t/ha and 3 kph rate of spread because these are the limits of the McArthur Meter. Since then, however an ever growing convoy of researchers and authorities have invalidly used the equations to calculate FDI of around 200 and rates of spread over 10 kph. But this invalidity has now been sanctified in many peer reviewed papers.

But wait, there is more …
Cheney (1983) says Tullamarine weather is different to Melbourne weather, specifically that air flow is less obstructed that Melbourne’s. For example, He says Ash Wednesday weather was recorded at Tullamarine airport as 43^{0}C, 5% and 45 kph (FDI 130) and the SW squall had winds at 70 kph (FDI 190). He converts the observations to Melbourne weather station equivalent. The revised weather is as follows - 43^{0}C, 5%, 28 kph (= FDI 86) and the SW squall at 20.45 hrs was 43^{0}C, 5% and 37 kph (= FDI 106). Thus, he concludes, Ash Wednesday and Black Friday weather are similar. The Ash Wednesday extreme conditions persisted 15 hours compared with 7.5 hours on Black Friday

But the plot thickens…
Another two researchers quote different Ash Wednesday weather:
Tolhurst (2009) reports 41^{0}C, 14% RH and 60 kph (= FDI 120) for Ash Wednesday
Douglas (2011) said that according to a CFA report, weather conditions of Ash Wednesday, were FDI = 120. (41^{0}C, RH = 5%, and average wind speed 45kph at 10m in the open).

Perhaps, what really matters is the FDI at the fire ground when the fire started. Rawson et al (1983) quote Trentham afternoon FDI as 40 – 60 (38^{0}C, 18% RH and 20-40 kph, and Otway afternoon FDI as 100, (40^{0}C, 11% RH and approx 50 kph).

The next ambiguity is the meaning of the FDI. An Index of 100 means fires burn so rapidly that control is virtually impossible (Luke and McArthur (1978), p 115). On p 28, they state that “difficulty is usually experienced in bringing fires under control when their intensity exceeds 4000kw/m”. This refers to Byram’s equation for fireline intensity – I = H x W x ROS. Remembering the Index applies to a forest that carries 12.5 t / ha, the Meter’s ROS prediction multiplies to 4000 kW/m at FDI 60 (using

Luke and McArthur's value for H = 16,000). On the Meter, FDI 100 and 12.5 t / ha calculates to 7000 kW / m intensity. Thus at FDI 60, control is difficult and at FDI 100, control is virtually impossible.

The third ambiguity is that the concept of suppression difficulty is misleading, vague and not defined. Tolhurst (2010) quotes from McArthur's 1958 reference that describes how his fires were point ignitions that he let run for 40 minutes before extinguishing them. The difficulty of suppression scale arose from this. Difficulty of suppression in a 12.5 t/ha eucalypt forest with predominantly litter bed is relevant in such a forest, but it does not apply to a forest with a heavy shrub layer. But in the end, the concept is meaningless. McArthur (1967) virtually declares the suppression difficulty concept irrelevant if the fire is not stopped by rapid first attack. He says suppression is impossible in heavy fuel on a severe day unless they arrive in 15 – 30 minutes. He says suppression is impossible once fire attains high intensity and the spotting process is full flight.

Next ambiguity is the concept of predicted ROS. It is mysterious, because "the forest fire danger meter takes into account the spotting process in eucalypt forest types" (Luke and McArthur (1978), p 115). Thus, it tends to "overestimate in forest types containing a high percentage of gum barked species which have a lower spotting potential than fibrous barked species" (p 115). McArthur (1967) notes that the prediction table incorporates the booster effect of short distance spotting, especially ignitions within 400 – 800m ahead, which have "an immediate effect on rate of spread". Unfortunately, he does not describe his method or theories. We are left to assume it was inspired McArthur intuition.

But, Luke and McArthur (1978) also say that once the spotting process starts, each successive surge may be a little greater than the last, and the fire appears to accelerate in a series of jumps or surges. "The apparent rate of spread can be very high but does not represent the movement of the true flame front" (P 106).

This raises the question again – what ROS is his Meter predicting – the apparent rate or the true front? Which surge effect does the Meter predict? Is it the true flame front or the slightly boosted flame front or the apparent rate of spread? They do not specify their surge calculation method.

Final ambiguity is that potential adjustments are confusing and arbitrary. Cheney (1968) describes how to change fire behaviour prediction to match an observed ROS by changing FDI. He says the tables and the meter are designed to estimate fire behaviour for the McArthur forest with 12.5 t/ha fuel load. If the forest type is different, the corrections must be made to FDI.
His example is a severe fire in a pine plantation. Weather conditions are 25^0C, 58% RH and 22 kph winds. This calculates to FDI = 7. The tables for the "McArthur forest" predict ROS = 0.1 kph.
Because FDI and rate of spread are proportional to fuel load, he says the following adjustment can be made.
The estimated fuel load fuel load for the plantation is 56 t/ha.
The correction factor is 56 / 12.5 = 4.5
Therefore actual FDI is 7 x 4.5 = 32.

FDI 32 calculates ROS of 0.45 kph in a 12.5 t/ha forest, which equates to the observed ROS.

McArthur's (1965) adjustments in the Longford fire report (see below) are also confusing and arbitrary:

- Add shrub fuel load to litter load. This doubles rate of spread
- Low quality eucalypt forest doubles wind speed at ground level, therefore doubles FDI and doubles rate of spread.
- Wind change acting on a long flank fire causes rate of spread to double for a given FDI.

Adjustments in the Wandilo and Longford fire post mortems (see below), allow McArthur to match observed rate of spread after the wind change through the heathy woodland by declaring that the open canopy allows him to double wind speed at fuel bed and therefore double FDI for application in the prediction table. He also adds in the dead elevated fuel loads. While these adjustments make the predicted speed eventually agree with observed speed, it smacks of a hindsight application of the prediction table rather than a reliable structured prediction model.

Luke and McArthur (1978) also include some puzzling do's and do not's.

- ROS "and other characteristics are typical of single fires under commercial forests and should not be used to predict behaviour of multiple fires burning in close proximity" (p 116)
- The Meter is designed for wind speed at fuel bed level created by the cover of a 20m tall well stocked dry sclerophyll forest. In shorter open forests, ROS is therefore greater than predicted on the Meter. If it is grassy understorey, they say use the grass fire meter with reduced wind speed. But they do not elaborate on methodology.

Comments:

The McArthur Meter concept commenced in the 1960's by investigating a moving line of flame in a litter bed. It may well have been accurate then. Since then, researchers have organically expanded its reach into different fuel types, and increased its ROS estimates to try to account for the booster effect of ROS due to spotting. This was why McArthur made the ROS / wind speed correlation a power function, and why he added shrub fuel load. In doing so, he has extrapolated his own model beyond its design capacity, and loyal followers have extended it further, well supported by ample peer reviewed research.

Fire authorities and some researchers have followed McArthur's lead, discovering that they can account for high rates of spread simply by adding fuel load to the prediction chart. This takes the Meter well away from its design criteria. It is not only lazy and invalid science, but is not identifying the true mechanism of increased rate of spread. It is therefore preventing growth of scientific knowledge.

McArthur may not have put enough thought into FDI as a prediction input. FDI derives from the two recognised input variables of fire behaviour of a line of flame – air dryness (which determines fine fuel dryness) and air movement. But, its flaw as a prediction input is that it combines two variables into one, and therefore denatures their predictive power. For example FDI 50 can be a very hot dry day with light wind or a milder day with a powerful wind. Both will affect fire behaviour differently.

The bushfire case study section below identifies four types of rate of spread. The Meter was designed for one, ie, the line of flame of the mother fire front, but it is now being incorrectly applied to the others.

Is the finding useful? The Meter is useful if its range is limited to FDI 1-100, where 100 is worst case. An FDI above worst case is logically nonsensical.
FDI combines wind speed and fuel dryness indicators such that it is proportional to ROS of the wind driven spread mechanism. ROS was probably chosen as an indicator because it is related to perimeter spread, and suppression is achieved when perimeter spread is contained. ROS thus indicates the amount of work and effort in suppressing a runaway bushfire, but does not necessarily indicate danger to communities. Being based on the wind driven mechanism, it is therefore not designed for and may not be useful to predict or explain other spread mechanisms. The difficulty of suppression concept is vague and therefore not usable

(10) Byram's Fireline intensity

What is McArthur's understanding of Byram's fire intensity? Luke and McArthur (1978) quote extremes of 60,000 kW / m for forest fires and 30,000 for grass fires. To obtain forest fire intensities of 50,000, they quote forest ROS of 2.5 kph and fuel load up to 40 t / ha. To obtain grass fire intensities of 55,000, they quote grass ROS up to 16 kph, and fuel loads up to 7.5 t / ha.

They then say flame height and depth are related to fire intensity, but do not explain how. For example, they quote a medium intensity fire as ROS 13.7 m / min (= 0.23 m / sec = 0.82 kph) in 17.5 t/ha (1.75 kg / sq m) and a flame depth of 27m and flame height of 15m. They do not quote BFI, but it calculates to 6500 kW / m (= 16,000 x 1.75 x 0.23). They quote a fully developed crown fire as ROS 30 m / min (= 0.5 m/sec = 1.8 kph) in 25 t/ha (= 2.5 kg/sq m) and a flame depth of 60m and flame height of crown fire. They do not quote BFI, but it calculates to 20,000 kW / m (= 16,000 x 2.5 x 0.5). They also quote a low intensity fire as 450 kW / sq m, which has 1.2m flame height and 2.7m depth.

I can build on these figures to discover more about their understanding of fire behaviour:

(a) Residence time: These figures allow us to calculate residence time as 120 sec as follows: **Tr = depth / ROS** = 27 / 0.23 and 60 / 0.5.
We now know this is burnout time, not residence time.

(b) Heat release rate (HRR) BFI is average combustion rate of the entire depth of the flame front. This allows us to calculate average HRR as follows:
HRR = BFI / depth
Low intensity fire HRR = 166 kW / sq m (= 450 / 2.7)
Medium intensity fire HRR = 240 kW / sq m (= 6500 / 27),
High intensity fire HRR = 333 kW / sq m (= 20,000 / 60)

(c) Mass loss rate
HRR = H x mass loss rate

Using Luke and McArthur's H = 16,000 kJ / kg, we can calculate:

Low intensity fire	mass loss rate = 10 gm / sq m / sec	(= 166/16000)
Medium intensity fire	mass loss rate = 15 gm / sq m / sec	(= 240/16000)
High intensity fire	mass loss rate = 21 gm / sq m / sec	(= 333/16000)

I can verify that this is the average combustion rate, as follows:
Average mass loss rate = total fine fuel load / residence time
Medium intensity fire Average mass loss rate = 14.6 gm / sq m / sec (1.75 / 120)
High intensity fire Average mass loss rate = 21 gm / sq m / sec (2.5 / 120)

But these figures are in total disagreement with McArthur (1967). He reports how HRR is inversely proportional to fuel moisture content (FMC). At 3% FMC, which corresponds with a high intensity fire, a litter bed has a mass loss rate of 56 gm / sq m / sec and HRR is 1000 kW / sq m. Even at 5% FMC, the relevant figures are 33 and 600. I deduce McArthur's figures are average HRR because he calculates them from burnout time, rather than flaming time.

Is the finding useable? No. the fire intensity concept is not meaningful because it is based on average heat release rate per unit area whereas fire behaviour variables like flame height and rate of spread are caused by peak heat release rate.
Because these figures are at the core of flame behaviour science, and because they are in total disagreement with McArthur (1967), I conclude that Luke and McArthur may not have quality checked their documentation

2.5 Summary so far

McArthur's Meter is an ingenious presentation of weather related data that generates a Fire Danger Index. Its primary ingredients are wind speed and air dryness.

His bushfire behaviour prediction model uses FDI and fuel load to calculate ROS, flame height and spotting distance. It is also simple and ingenious. But it is inaccurate because he uses fuel load, yet has not shown a causal link to rate of spread. It is inaccurate when it extrapolates beyond the original design criteria – continuous line of fire in a tall forest with predominantly litter fuel bed under influence of the wind spread mechanism. It is inaccurate because it includes booster factors to account for short distance spotting. They are neither explained nor quantified. For example, we can deduce from his original data that ROS for the driest litter fuel bed (12.5 t/ha fuel) is 5.6% of wind speed at fuel bed (approx 2% of wind in open). We can deduce that the McArthur Mark V Meter for the driest litter bed fuel (12.5 t/ha fuel) predicts 10 - 12% of wind speed at fuel bed (approx 4% of wind speed in open).

McArthur allowed contradictions to creep into his own system. He acknowledged that if shrubs occur on site, ROS is higher than litter bed, but does not specify a ratio. But then he adds their fuel load to the litter fuel load and uses the total to calculate rate of spread, forgetting that this process assumes their rate of spread is the same, weight for weight. In bushfire post mortems, he applies the Meter beyond its litter bed design capability to shrub fuel beds by adding in the shrub fuel loads and increasing the wind speed.
We then ask this question - How can ROS in a litter bed forest be logically extrapolated to predict ROS in a dense shrubby forest, when we know the fuel bed structures are different? Alas it cannot be done with scientific credibility.

HOWEVER, despite all the foregoing issues, the FDI scale remains useful as a fire danger indicator, but not as a measure of suppression difficulty. Furthermore, the prediction table is usable as an initial guideline, provided the user understands that it predicts ROS of a line of fire by a wind spread mechanism in a "McArthur" forest.

Figure 5 shows how the Meter can remain a useful prediction tool. It shows two of McArthur's lower fuel loads to indicate a likely range of ROS prediction possibilities. Eg, if FDI is 60, a continuous forest fire front should run between 0.7 and 1.3 kph. If the fire spreads at a greater rate than this, it is probable that another spread mechanism is controlling spread rate. If spread is at a slower rate, some local fuel or weather or terrain factor is causing a slow down.

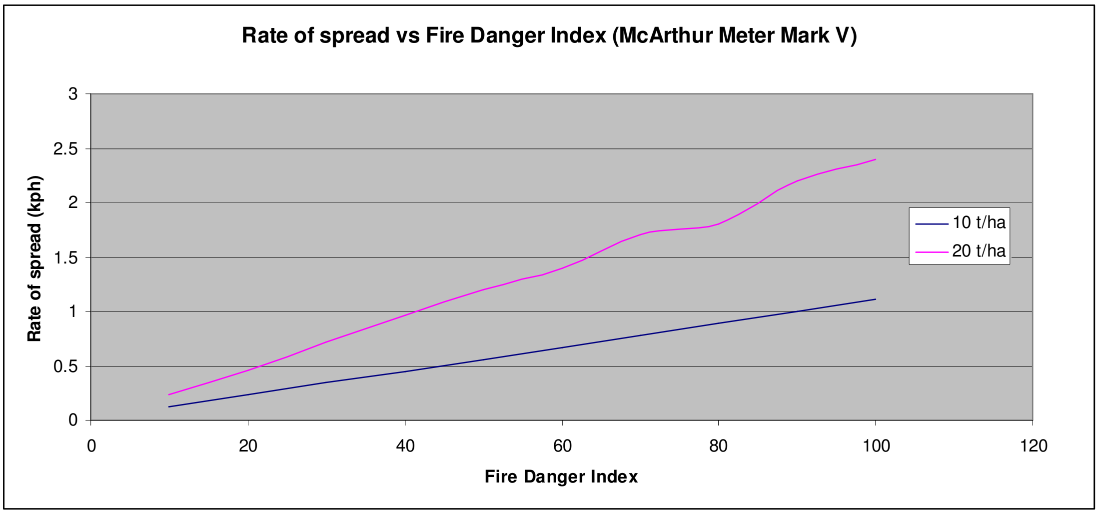


Figure 5 The predicted rate of spread for two fuel loads using Fire Danger Index. (The kinks are from the Meter). Technically, the spread rate applies to a continuous running mother fire front in a "McArthur" forest under the control of the wind driven spread mechanism, adjusted higher to account for short distance spotting.

2.6 Contemporary bushfire case studies by McArthur

I now examine other contemporary McArthur bushfire studies to look for clues in his understanding.

Bushfire Case Study 1 Daylesford bushfire 16 Jan 1962 (McArthur, 1967)

The 1967 report presents a detailed description of a bushfire at Daylesford which features rate of spread of two separate bushfire mechanisms – wind driven line of flame and the leap frog spotting.

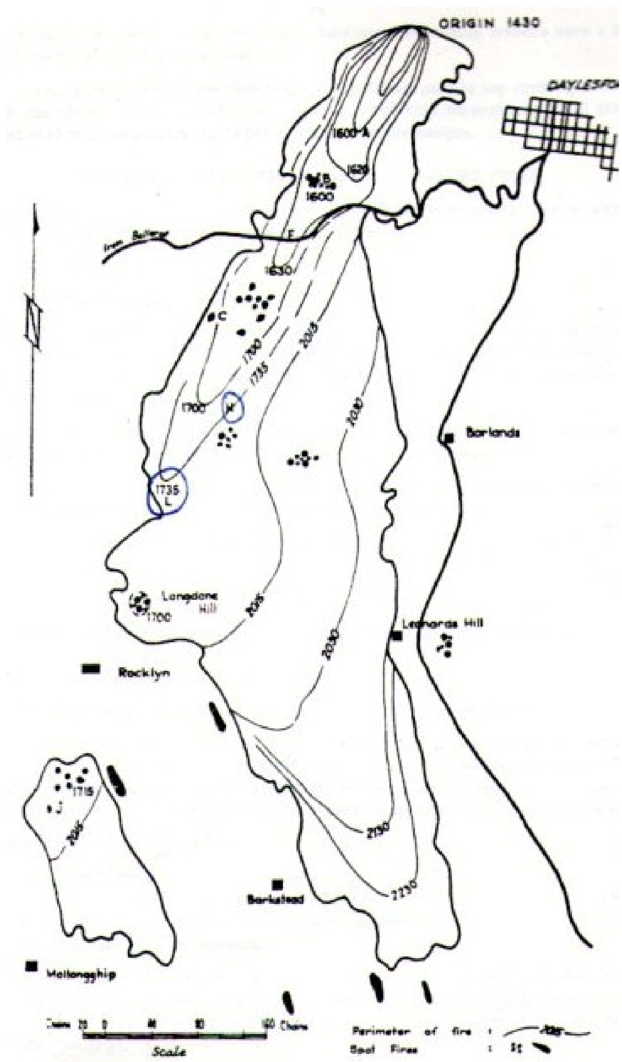
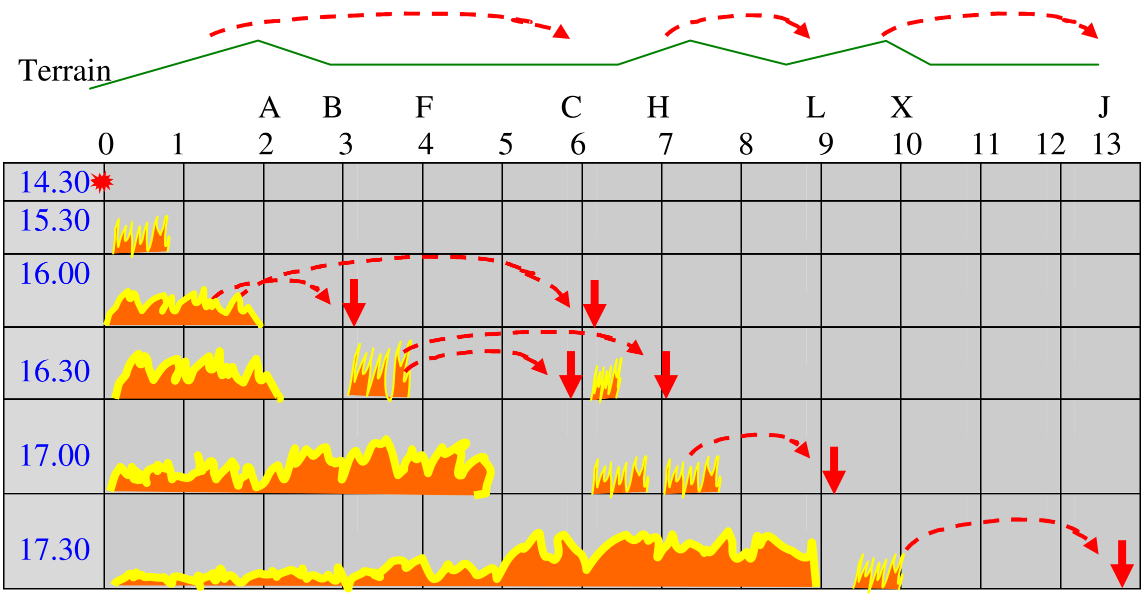


Figure 6 McArthur's map of Daylesford isochrones and spot fires (McArthur 1967)

Chart 1 describes the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 1 **Daylesford bushfire 16 Jan 1962**
(McArthur (1967) - FDI 35 or Cheney (1968) – FDI 70 – see below)



Notes: The two lines above this chart are as follows:
Green line is approx terrain diagram (the terrain diagram shows that longer distance spotting is associated with up slope runs). The letters correspond to McArthur's Fig 9 and descriptions
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread

I can distinguish four distinct rates of spread in Chart 1:

Rate of spread of original fire front
Original flame front travels at approx 1 kph.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front travels approx 1 kph

Rate of spread of leading fire front
At 16.30 leading fire front is 6 km from origin (= 3 kph), but there is an unburnt gap behind it.
At 17.30, leading fire front is at 10 km from origin (= 3.3 kph), but there is an unburnt gap behind it. The net leading fire front rate of spread depends on the leap frog distance of the leading spot fire. If jump distance is large, the gap between the main line of fire and the leading flame front is not burning. If the jump distance is small, the rear fire front quickly closes the gap and the net rate of spread can be double the original fire front, and if close flame fronts run in triple tandem, the net rate of spread can be triple.

Rate of spread of leading leap frog spot fire
At 16.30, leading spot fire is 7 km from start - ROS = 3.5 kph (= 7/2).

At 17.30 leading spot fire is 13km from start - ROS = 4.3 kph (= 13/3).

Weather / site details:
McArthur's data
Weather **35^0C / 34%, wind at 10m = 48 kph NNE FDI 35**
Tall eucalypt forest, litter bed and low shrub layer, Fuel load 25 t/ha,
Predicted ROS: McArthur Meter predicts 1kph and flame height 16m for FDI 35 and 25 t/ha

Cheney's data (1968) for the same fire differs slightly (also see 2.4 (7). (Because it was a TFB Day, Cheney's weather is probably correct)
Weather **35^0C, 10-15%, 40-48 kph, FDI 70**
Tall eucalypt forest, litter bed and low shrub layer, Fuel load 10 t/ha,
Predicted ROS: McArthur Meter predicts 0.8 kph and flame height 11m for FDI 70 and 10 t/ha

McArthur's observations
Initial ROS of line of flame = 1 kph,
Flame height 6m. Very little crowning occurs.
Spotting up to 200m.
ROS = 8% of wind speed at fuel bed
ROS = 2% of wind speed in open

He notes the discrepancy between his predicted line of flame speed and the speed of the leading fire front. He says: "The average rate of spread over the first 3 hours was just on 2 mph (3kph). This is three times the rate expected from a moving flame front where spotting is not the predominant spread mechanism"

My explanation:
McArthur's chart predictions refer to rate of spread of a continuous line of running flame. If leap frog spotting initiates other lines of running flame downwind, they each run at the McArthur rate of spread. The net or effective rate of spread of a leading fire front in an ember driven bushfire cannot be predicted by the McArthur Meter, although it can help explain it.

Bushfire Case Study 2 Hobart bushfire 7 Feb 1967
(McArthur, 1968; Cheney, 1976)

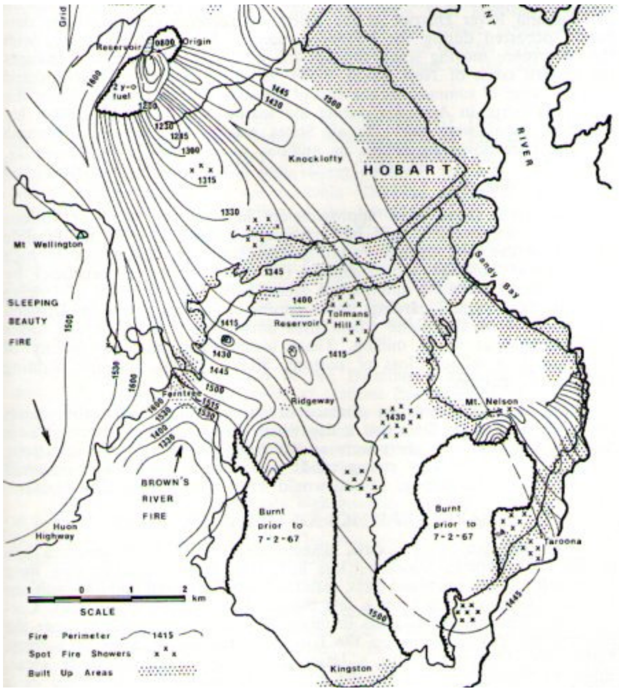
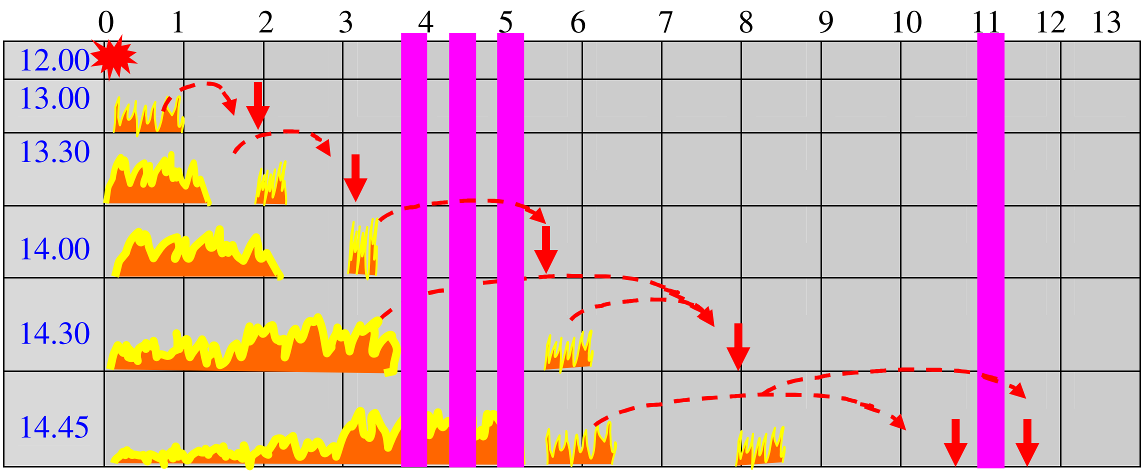


Figure 7 Map of Hobart fire isochrones, from Cheney (1976)

Chart 2 describes the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 2 Hobart bushfire 7 Feb 1967 FDI 95



NOTES:
Mauve areas are mapped as residential areas / built up areas.
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 2:
Rate of spread of original fire front
Original flame front probably travels at approx 1+ kph.

Rate of spread of each new flame front ignited by spot fires
Each new flame front in forest probably travels at 1+ kph (unable to verify with McArthur observation)

Net or effective rate of spread of leading fire front
At 14.00 leading fire front is 3 km from point zero - ROS = 1.5 kph, but there are unburnt gaps behind it. At 14.45, leading fire front is at 8 km from origin - ROS = 3 kph, but there are unburnt gaps behind it.

Rate of spread of leading leap frog spot fire
At 14.45, leading spot fire is 11 km from point zero - ROS = 4 kph (= 11/2.75).

Weather / site details:
Weather during Hobart fire

Time	**Temp C / RH**	**Wind speed, direction**	**FDI**
11.00	36 / 16%	41 kph / NNW	60
12.00	38 / 14%	43 kph / NNW	75
13.00	39 / 12%	44 kph / NNW	85
14.00	38 / 13%	53 kph / NW	95
15.00	36 / 15%	43 kph / W	65
16.00	32 / 20%	37 kph / WNW	40

McArthur's observations
The rate of spread of fires in high forest was generally in the range 2 to 2.5 kph on level ground. Some upslope spread increased to around 4 kph in localised areas.

The Hobart fires featured "heavy short distance spotting mainly from E obliqua … creating a localised firestorm effect in front of the fire". In these mixed fuels (mixed forest and grassland), "the rate of spread continued to accelerate as spot fires were thrown from patches of timber into open grasslands. The Hobart fire reached a rate of spread of 6 kph by 1500 hrs"

My explanation:
McArthur's comments show confusion between line of flame rate of spread and speed of leading fire front. He mentions a maximum speed of 6 kph, but these figures do not correspond with the Chart 2 analysis for any of the types of rate of spread.
Chart 2 suggests leading fire fronts are initially around 1.5 kph and later up to 3 kph.
Chart 2 shows these details: the distance between the 14.15 and 14.30 isochrones was 1.5 km (= 4 kph) and between 14.30 and 14.45 isochrones was 4 km (= 16 kph). The average ROS between 14.15 to 14.45 was 13 kph (= 6.5 / 0.5). Clearly, this rate refers to leading fire front or leading spot fire rate, and not to the rate of the moving line of flame.

Bushfire Case Study 3 Wandilo bushfire 5 April, 1958
(McArthur et al, 1966)

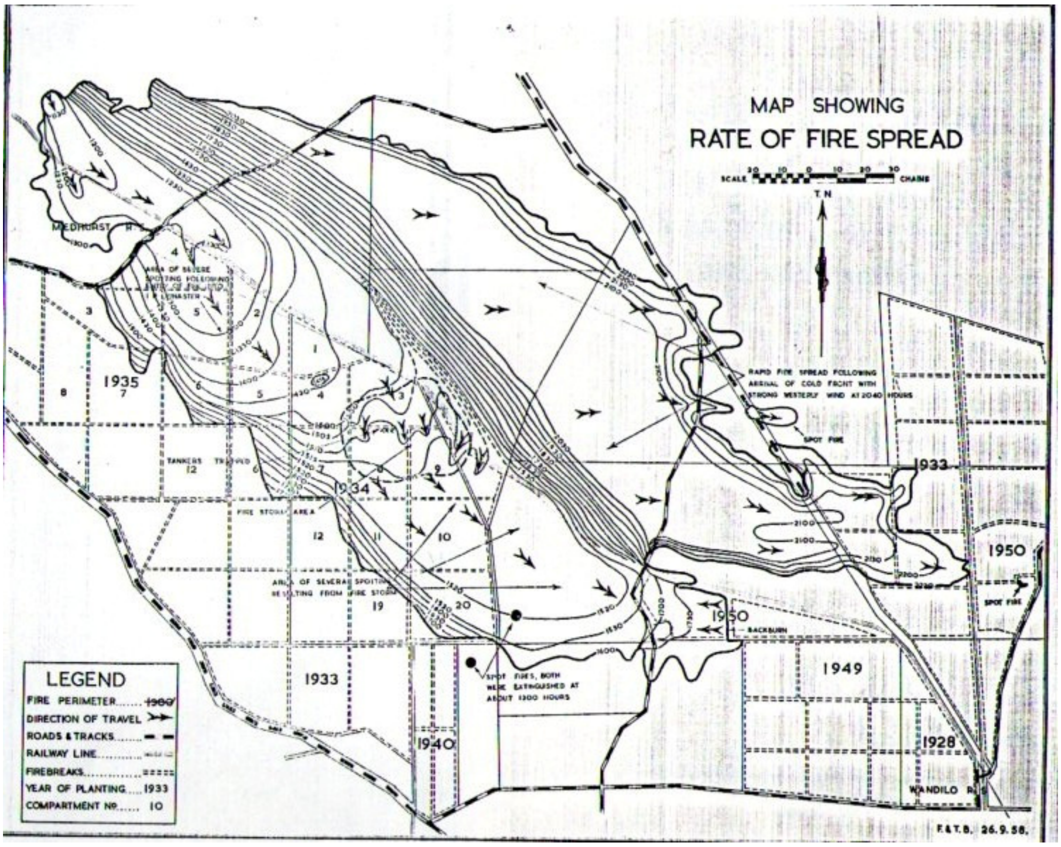
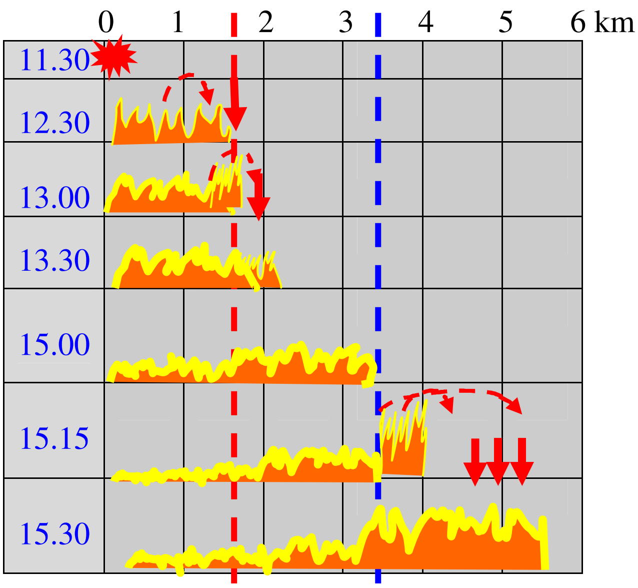


Figure 8 Map of Wandilo fire isochrones, from McArthur et al (1966)

Charts 3A and 3B describe the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 3A Wandilo bushfire, 5 April, 1958 Before wind change FDI 35



NOTES:
Point zero is 11.30 isochrone, when slow fire emerged from swamp into shrubby woodland.
Left of dashed red line is shrubby eucalypt woodland, right is P. pinaster until 2 km mark, and then P. radiata. Right of dashed blue line is spindle P. radiata until the 5 km mark, when healthy P radiata resumes.
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish three distinct rates of spread in Chart 3A:

Rate of spread of original fire front
Original flame front travels at approx 1.5 kph through shrubby eucalypt woodland.
Flame front ROS through P pinaster is 0.8 kph
Flame front ROS through mature P radiata is 0.4 kph

Rate of spread of leading fire front
Leading spot fires are overtaken by the main front because the spotting distance is short. By 15.30, the leading fire front is 5.4 km from point zero - ROS = 1.8 kph (= 5.4/3). This rate is slightly above the spread rate through the eucalypt forest, but is two to three times the rate of spread through the plantation.

Rate of spread of leading leap frog spot fire
At 15.15, the local leading spot fire speed is approx 8 kph (ROS = 2km in 15 min).
By 15.15, the average leading spot fire is 5.4 km from point zero - ROS = 2 kph (= 5.4/2.75).

Weather / site details:
Weather

Time interval	**Temp C / RH**	**Wind speed, direction**	**FDI**
8.25 - 11.40	30 / 32%	27 kph / NNW	30
11.40 - 12.30	33 / 29%	32 kph / NNW	30
12.30 - 13.30	33 / 29%	33 kph / NW	30
13.30 - 15.00	33 / 31%	35 kph / NW	30
15.00 – 15.30	32 / 31%	43 kph / NW	35

McArthur's observations:
11.30 – 12.30 Shrubby eucalypt woodland
Open E. baxteri / ovata regrowth 13+ m with heavy understorey of tea tree and bracken, fuel load 25 t/ha
Observed fire behaviour: 1.5 kph, flame height 5m head fire, 3m on flanks
ROS = 15% of wind speed at fuel bed
ROS = 5% of wind speed in open
No crowning, leaf scorch up to 7 – 10m. Spotting across firebreak into unthinned, unpruned P pinaster
Predicted fire behaviour by McArthur's Meter:
For 25 t/ha at FDI 30, ROS= 0.9 kph.
He allows adjustment for low open forest. This brings FDI to 50, to account for open forest (ie, wind speed increases from 30 to 50 kph to allow for extra wind speed at ground level). Therefore predicted ROS is now 1.4 kph = agreement.

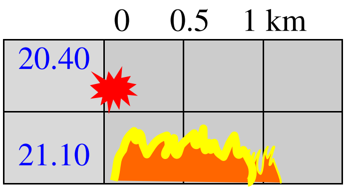
12.30 – 13.30 For a short distance, Unthinned unpruned pinaster, 23 years 10m tall litter and elevated fuel load 25+ t/ha
Observed fire behaviour: ROS 0.8 kph, flame height 10+ m
Fire crowns on narrow front and threw spots 400 – 600m downwind
ROS = 10% of wind speed at fuel bed
ROS = 3% of wind speed in open

13.30 – 15.00 Mature radiata 24 yo 20 – 30m
Observed ROS = 0.5 kph, Surface fire
Text says - as predicted by McArthur - unpublished data"

15.00 – 15.15 Fire storm developed on an upslope in a "spindle" stand of P radiata with heavy understorey, induced by active fire tongues in adjacent valleys on either side of it. Flame convergence induced crowning on ridge top and massive convection threw embers downwind, simultaneously igniting up to 2 km ahead, "and some 600 acres (250 ha) of Pinus radiata plantation was burnt by crown fire within 15-20 minutes"
Note: This ember attack is the source of the "mass ember spot fire mechanism".

My explanation:
McArthur's Meter accounts for observed ROS of moving lines of flame. His adjustment for open forest shows how flexible the Meter is in explaining observed ROS, but he provides no basis for estimation or prediction. His Meter clearly cannot account for ROS due to mass spotting for 2 km downwind.

Chart 3B - After wind change at 20.40 FDI < 10



Types of rate of spread
I can distinguish one rate of spread in Chart 3B:

Rate of spread of original fire front
The map shows the 3 km long NE flank converted into a head fire and travelled approx 1 km in 30 minutes = 2 kph through shrubby eucalypt woodland. (McArthur's text says 3 kph).

McArthur's observations and weather / site details:

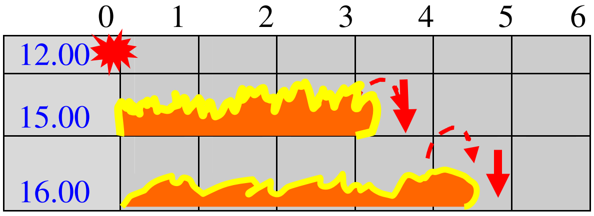
Time interval	Temp C / RH	Wind speed / direction	FDI
20.40 – 21.10	24 / 90%	42 kph / W	< 10

Cold front arrived and wind changed from 340^0 to 280^0 and increased from 17 to 42 kph. The whole NE flank which was within shrubby eucalypt forest spread rapidly. ROS during the first half hour was 2 kph Flame height 8 – 10m, but not a crown fire.

In the Longford report, McArthur 1965) states that when a wind change converts a long flank into the main front, rate of spread doubles, but the reason is unknown. He says the fire broke away at 3 kph, which is "double the spread in similar eucalypt fuel types during the afternoon under apparently more severe conditions"

Bushfire Case Study 4 Longford bushfire 17 Nov 1962
(McArthur 1965)

Chart 4A Longford bushfire - before the wind change FDI 40



Notes: The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish one type of rate of spread in Chart 4A:

Rate of spread of original fire front
Flame front travels at 1.4 kph through shrubby eucalypt woodland

McArthur's observations, including weather / site details:
Eucalypt forest: stringybark / peppermint, max height 13–15m, but if stunted 5 – 8 m.
Fuel load comprises - litter 5 – 7 t/ha, heavy bracken up to 1m tall over most of area 5 t/ha, total 12 t/ha.
The height and composition of this low forest "would allow strong wind movement at ground level. The rate of spread under such conditions would be at least double the spread which would occur under high forest carrying comparable fuel quantity"

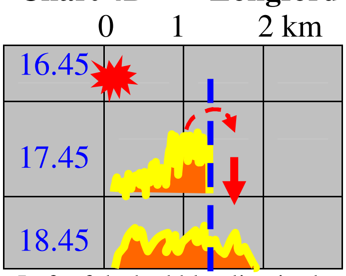
Between 12.00 and 15.00
Weather 33^{0}C and 14% RH, average wind speed rises from 40 to 50 kph WNW
FDI calculates to 60 – 65 (McArthur text says 55-60)
Observed fire behaviour: ROS rises to 1.4 kph, no long distance spotting, no crowning, but intense short distance spotting 100 – 200m
ROS = 3% of wind speed in open

At 16.00 prior to wind change, wind decreases to < 30 kph, WNW FDI = 40
Observed ROS = 1.3 kph, no crowning,
Predicted ROS McArthur says this is twice the rate expected "under these meteorological and fuel conditions in a pure eucalypt forest type. It appears fairly obvious that the very fast rate of progress of the fire has resulted from the presence of a heavy bracken ground fuel. Bracken fires are very intense and normally give a much higher rate of spread than a more normal eucalypt ground fuel with scattered shrubs".

Summary of McArthur's adjustments:
Add bracken fuel load to litter load. This doubles rate of spread
Low quality eucalypt forest doubles wind speed at ground level, therefore doubles rate of spread.

Wind change acting on a long flank fire causes rate of spread to double for a given FDI.

Chart 4B Longford bushfire - after the wind change FDI < 40



Left of dashed blue line is shrubby eucalypt woodland, right is P. radiata.

Types of rate of spread
I can distinguish one type of rate of spread in Chart 4B:

Rate of spread of original fire front
Flame front travels at 1.6 kph through shrubby eucalypt woodland
Flame front travels at 0.6 – 0.8 kph, crowning through young pines

McArthur's observations, including weather / site details:
At 16.45, the wind changes to WSW, 32 kph FDI < 40, and falling
Observed fire behaviour through shrubby woodland: ROS = 1.6 kph
"The rate of spread increased very markedly to 1.6 kph although the fire danger index had fallen… the fire was not crowning, and only isolated patches of tree crowns were consumed".
ROS = 16% of wind speed at fuel bed
ROS = 5% of wind speed in open
Prediction with McArthur Meter: "The very fast spread associated with the passage of a cold front where a broad front is carried away by the wind change defies any reasonable explanation at the present stage of our fire behaviour knowledge. Generally the rate of spread is doubled for a given fire danger index." McArthur also notes the same occurrence at Wandilo.

At 17.50 fire hits plantation:
P radiata, 10 years old, unthinned unpruned, height 10 – 13m
Fuel load litter 10 – 12 t/ha, bracken and grasses 2 – 5 t/ha, suspended dead needles 2 t/ha, total 18 t/ha (He did not include green foliage)
Observed fire behaviour crown fire: ROS = 0.6 kph, but short runs up to 0.8 kph, flame height 10 – 15m, spotting to 300m.
Prediction with McArthur's unpublished data: McArthur notes that ROS in this unpruned plantation is almost three times that in a pruned plantation.

My explanation:
McArthur reinforces that his Meter applies to eucalypt forest with scattered shrubs. He uses it as a basis for explanation of observed ROS, eg, ROS in heavy bracken is double. But he provides no basis for estimation of prediction. These examples have insignificant spotting and observed ROS refers to moving lines of flame.

2.7 Summary of McArthur's contribution to rate of spread knowledge

Huge and positive - because his work educated two generations of bushfire exponents to the fundamental science behind bushfire behaviour and how to predict it.

The fire behaviour prediction system on the McArthur Meter technically applies to a line of moving flame in a tall eucalypt with litter bed fuel and scattered understorey. The default fuel loading is 12.5 t / ha. He assumes the fuel load is either consumed, or is a proxy indicator of fuel load consumed by the moving flame. His writings show that he uses the Meter very flexibly when explaining observed bushfire rates of spread. He seems to want it to fit all situations. He uses the Meter as a basis for hindsight explanation of observed ROS, but he provides no basis for estimation or prediction.

McArthur shows there are two methods of adjustment for estimating ROS. The FDI can be changed and the fuel load can be changed.
FDI: If the forest is low or open, more wind penetrates the fuel bed which increases ROS. Therefore, he increases FDI to achieve a higher ROS prediction.
Fuel load: If the flame is tall and consumes two or more lower fuel layers, he adds dead fuel load in litter bed, shrub and elevated layers to derive a total fuel load that raises ROS to match observed ROS. Unfortunately, his extrapolation examples take the Meter beyond its design capability. He has thus unwittingly shown how a useful instrument can be used invalidly, simply by loading up the fuel loads. Even more unfortunately, these lazy scientific short-cuts have bypassed the need to seek proper explanations for observed fire behaviours.

The above Chart analyses show that it is easy to confuse line of flame spread rate with leading fire front rate and leap frog rate of spread. McArthur himself was confused. But in the Daylesford example, he clearly identifies that its leading fire front was spot fire driven. He uses his Meter (ie, designed for moving line of flame) to compare to rates of spread. This is the appropriate use for his Meter.

The bottom line is that the McArthur chart is based on research in predominantly litter bed forests, and is designed for moving lines of fire in predominantly litter bed forests. It therefore cannot be applied to or expected to be applied to different vegetation types.

Its major flaw is the McArthur belief that rate of spread is proportional to fuel load. When I look at the way that rate of spread has doubled for the same FDI over the first 20 years of its prediction story, I have formed the view that the earlier measurements are likely to apply to the true litter bed forest. For this reason, plus the fact that only the lop layer of the litter bed contributes to rate of spread (refer Burrows and Vesta findings below), I believe the McArthur Meter prediction system remains valid for predicting rate of spread in a litter bed forest of any fuel loading if we use the ROS figures for the 10 t/ha fuel loading on the Meter. It not only remains valid, it is a very instructive introduction to the several influences on fire behaviour.

I remind the reader that the McArthur ROS model is designed for the wind driven / convection mechanism in a litter bed, ie, wind speed feeds oxygen to the combustion zone and pushes the flame body across the litter bed surface. It is not designed for predicting for a shrub layer or for the mass transport and subsequent ignition of firebrands.

McArthur's observations suggest a benchmark that a wind driven surface fire in severe weather in a tall forest with light shrub cover runs at around 2% of wind speed in open (= approx 8 - 10% of wind speed at fuel bed level) and that a wind driven fire in shrubby open short forests runs around double that ratio, eg, 4 – 5%. (= approx 16 - 20% of wind speed at fuel bed level).

Chapter 3 Project Aquarius 1983-1985

The purpose of Project Aquarius was to examine the impact of bushfires and fire fighting on fire fighters. As part of the exercise, they collected a large amount of data about fire behaviour in forests in low to moderate fire danger weather.

"Experimental bushfires were lit over two summers in Australian eucalypt forests with mean fuel loads (and range) of 11.3 (8-14) tonnes per hectare, in air temperature *25* (17-33)^{O}C, relative humidity 47 (14-81)%, and wind speed 4.4 (2-9) m s^{-1}. The McArthur Forest Fire Danger Index (FFDI) ranged from 2 to 24. Fires were lit on a cross wind ignition line of 50-200 metres, and were allowed to develop for 10-50 minutes before a seven-man hand-tool crew commenced its attack". (Budd et al, 1997)

Project Aquarius fires of 1983 were in McCorkhill forest, Western Australia and 1985 fires were in Nowa Nowa forest, Victoria. Aquarius recorded only rate of spread and two inputs - FDI and fuel load, and usable data is summarised in Table 1. The weather details of some of these fires were published later (Project Vesta, 2007), and are listed in blue in the more detailed Table 2. Tables 1 and 2 also include ROS predictions form the McArthur Meter Mark V.

Table 1 Summary of usable fire behaviour data

FDI	Temp (^{0}C)	RH %	FMC %	Wind kph 10m Kph	Wind at fuel bed Kph	ROS Observed Kph	ROS as % of open wind	ROS as % of wind at fuel bed)	ROS Prediction McArthur Meter
6	19	48	8.5	18	5	0.5	2.8	10	0.06
4	19	48	8.5	18	5	0.7	3.9	14	0.06
16	26	31	5.5	19	5	0.76	4.0	15	0.18
16	26	31	5.5	19	5	0.96	5.1	19	0.18
14	**26**	**31**	**5.5**	**19**	**5**	**1.3**	**6.8**	**26**	**0.16**
24	33	20	4	11	3	0.385	3.5	13	0.3
24	33	20	4	11	3	0.69	6.3	23	0.3
17	33	20	4	11	3	0.44	4.0	15	0.2
7	23	50	8	16	4.5	0.405	2.5	9	0.12
7	23	50	8	16	4.5	0.48	3.0	11	0.12
5	25	60	9	13	3.7	0.195	1.5	5	0.075
5	25	60	9	13	3.7	0.3	2.3	8	0.075
15	31	30	5	10	3	0.414	4.1	14	0.22
10	26	38	6	8	2.5	0.617	7.7	25	0.15
10	26	38	6	10	3	0.364	3.6	12	0.15
18	26	38	6	12	3.5	0.22	1.8	6	0.23
23	30	24	4.5	12	3.5	0.253	2.1	7	0.33
23	30	23	4.5	12	3.5	0.223	1.9	6	0.33

Green shading shows the Victorian trial fires
Yellow shading is the only fire where flame height was mentioned

Table 2 Detailed data

							Observed		Prediction
Reference fire source	Temp (^{0}C)	RH %	FMC %	Wind kph at 10m / at fuel bed level	FDI	Fuel load t/ha	ROS Kph (% at FB)	Flame height m	McArthur Meter
25/1/83 14.50-16.12 Vesta McCorkhill	19	48	8.5	18 /3.5=5	6		0.5 10%		0.06
25/1/83 16.13 – 17.33 Aquarius #1					4	7.4	0.6-0.8 6-8%		0.06
23/2/83 15.45 – 18.15 Aquarius #3					5	7.1	0.2-0.28		0.06
28/2/83 14.35 – 15.10 Vesta McCorkhill	26	31	5.5	19 /3.5=5	16		0.76 15%		0.18
28/2/83 14.40 – 15.35 Vesta McCorkhill	26	31	5.5	19 /3.5=5	16		0.96 20%		0.18
28/2/83 14.40 to 14.47 approx #4					14	7.7	1.3 26%	5-6	0.16
1/3/83 14.07 – 15.19 Vesta McCorkhill	33	20	4	11 /3.5=3	24		0.385 12.5 %		0.3
1/3/83 14.15 – 15.19 Vesta McCorkhill	33	20	4	11 /3.5=3	24		0.69 23%		0.3
1/3/83 14.33 – 15.33 Aquarius #5					17	8.2	0.39-0.5 13-16%		0.2
3/3/83 14.20 – 15.53 Vesta McCorkhill	23	50	8	16 /3.5=4.5	7		0.405 9%		0.12

3/3/83 14.29 – 16.18 Vesta McCorkhill	23	50	8	16 /3.5=5	7		0.48 10%		0.12
10/3/83 12.22 – 14.57 Vesta McCorkhill	25	60	9	13 /3.5=3.7	5		0.195 5%		0.075
10/3/83 12.26 – 15.02 Vesta McCorkhill	25	60	9	13 /3.5=3.7	5		0.3 8%		0.075
6/2/85 13.17-14.43 Vesta Nowa Nowa	31	30	5	10 /3.5=3	15		0.414 13%		0.22
11/2/85 13.10 – 16.47 Aquarius #10					4	10.3	0.1- 0.49		0.06
12/2/85 11.50-13.12 Aquarius #11					9	10.2	0.12- 0.22		0.12
13/2/85 13.20-13.55 Aquarius #12a					5	11.2	0.06- 0.2		0.07
13/2/85 15.17-16.24 Aquarius #12b					5	9.4	0.1- 0.29		0.07
15/2/85 12.20-13.26 Aquarius #13					13	11.5	0.05- 0.1		0.2
19/2/85 14.69-15.46 Vesta Nowa Nowa	26	38	6	8 /3.5=2.5	10		0.617 30%		0.15
19/2/85 15.24-16.08 Vesta Nowa Nowa	26	38	6	10 /3.5=3	10		0.364 12%		0.15
20/2/85 14.42-16.13 Aquarius #14					13	11.3	0.34- 0.58		0.2

21/2/85 14.55-15.35 Aquarius #15				12 /3.5=3.5	18	10.9	0.16-0.3 4-9%		0.23
21/2/85 14.30-15.37 Vesta Nowa Nowa	30	24	4.5	12 /3.5=3.5	23		0.253 7%		0.33
21/2/85 15.37-16.42 Vesta Nowa Nowa	30	23	4.5	12 /3.5=3.5	23		0.223 6%		0.33

Discussion

This data was used as evidence that the McArthur Meter model under predicted ROS. "Preliminary analysis of the behaviour of high-intensity experimental fires in dry eucalypt forest on a scale of 50 – 100 ha burnt area during Project Aquarius (Gould et al., 1996), and work by Burrows (1994, 1999) suggested that both the FFDM and FFBT consistently under-predict the rate of spread of fires burning under dry summer conditions by a factor of 2 or more". (Cheney et al (2012)

If we take the view that the McArthur Meter indicates ROS expected in a forest due to the wind driven mechanism, Figure 9 shows that a minor percentage of these fires qualify, and suggests that another spread mechanism is involved. This aspect has never been investigated. Instead, Project Vesta used the Aquarius data as one of its proofs that the McArthur Meter under predicts ROS by up to three times, and was therefore unreliable. Yet when the extent and the position (ie, low FDI) of the Aquarius data are seen in perspective across the whole FDI scale, the case for unreliability weakens.

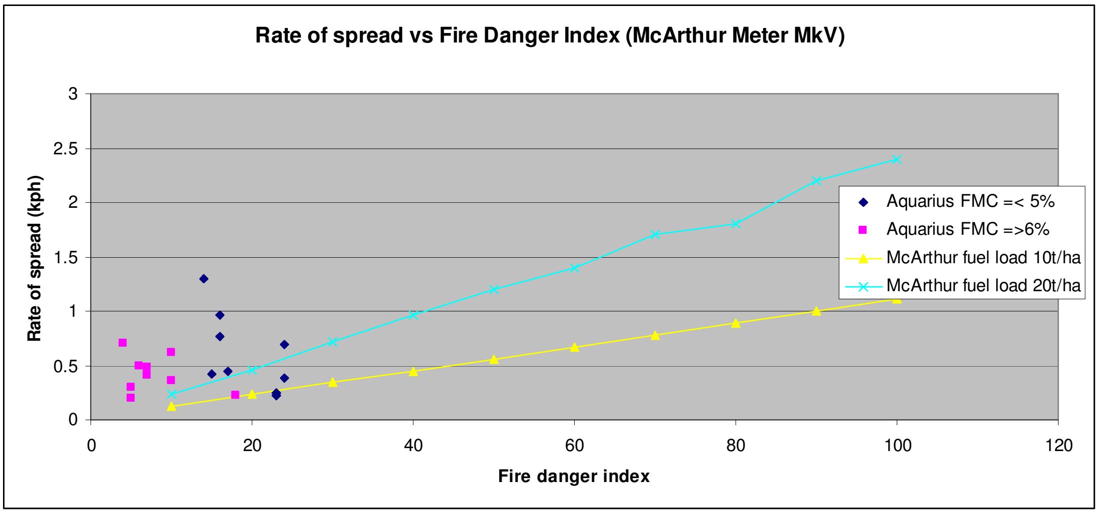


Figure 9 If the focus of researchers was to discover how fire behaviour works, the limited range of these anomalies would have been seen as a thing to be investigated rather than as proof of failure of a fire behaviour model.

The combination of high ROS and low wind speeds suggest a wind driven mechanism was not involved. The highest in-forest wind speeds were 5 kph, and the lowest were 2.5 kph. Yet the ROS ranged from 0.5 to 1.3 kph. The only published account of the Aquarius fires gives a clue about the probable spread mechanism because it lists some of the ingredients of the tall flame / piloted ignition spread mechanism. The highest fire intensity was recorded at FFDI of 14 on 28 February 1983. "Shortly after ignition the fire averaged 7080 kW per metre of fire front (kW m^{-1}) over a 7 minute interval and travelled at more than 1300 metres per hour (m h-1). Flames were commonly 5-6 m high, intermittently extending into the tree crowns more than 25 m above the ground, and numerous spot fires were ignited up to 300 m down-wind of the head fire" (Budd et al, 1997 - see Aquarius #4 in Table 2).

It is also useful to examine the range of ratios of ROS to wind speed at fuel bed level as an indicator of the wind driven spread mechanism. If my estimate of McArthur's wind driven data is correct, a ratio around 10 to 12% of wind at fuel bed level or 3 - 4% of open wind speed is a reasonable estimator of a wind driven line of fire. Figure 10 suggests ROS of most of the fire plots exceeds this ratio and supports the view that ROS may be due to another spread mechanism.

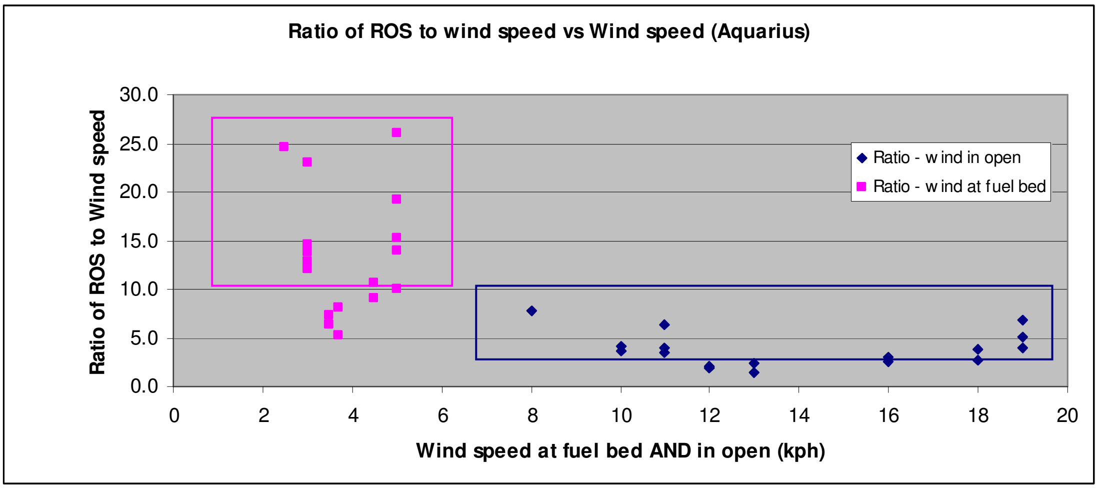


Figure 10 The combination of high ROS and low in-forest wind speeds suggest a wind driven mechanism is not involved. The highest winds were 5 kph, and the lowest were 2.5 kph, yet the ROS to wind speed ratio ranged from 5 to 30%.

Conclusion

The McArthur Meter prediction model was condemned by Project Vesta luminaries for consistently underestimating ROS of the project Aquarius trial fires by a factor of 2 and more. Yet they did not investigate the true reason for the underestimation, namely, the Meter's design is for the wind spread mechanism, whereas most of Aquarius fires were due to a different spread process - the tall flame / piloted ignition mechanism.

Chapter 3 Burrows - rate of spread

3.1 Burrows comments about McArthur's model

Burrows (1999a) said the models that McArthur and Peet developed from small, low intensity experimental fires perform adequately for low intensity fires but are deficient in predicting moderate and high intensity fires. He said they extrapolate from low intensity to high intensity fires based on assumptions with little supporting evidence. He wanted to test these assumptions, but they were not actually specified. His excellent work concluded with him extrapolating his low intensity findings and proposing a model for high intensity bushfires.

3.2 Burrows' theories

He is guided by several theories:
ROS is positively correlated to fuel bed dryness, wind speed, and up slope angle
ROS is negatively correlated to fuel moisture content and down slope angle.

3.3 Burrows' data

Refreshingly, Burrows conducts basic laboratory trials as well as field trials in West Australian forests with predominantly litter bed and sparse understorey. I reproduce his data in Figure 8, to match the same format as McArthur's in Figure 1.

Burrows' data derives from the radiation spread and the wind spread mechanisms in a line of fire in litter bed or predominantly litter fuel bed. He presents data points in graphical form for both lab and field trials.

The laboratory trials are done on a 4 x 2m table using litter bed of leaf and twigs from jarrah forest floor. The bulk density of the fuel bed is around 46 kg / cu m, and fuel load ranged from 3 to 16 t / ha (0.3 – 1.6 kg / sq m). Burrows also uses a larger table with fuel load 7-8 t / ha to examine fire shape and a smaller table with fuel load 7-8 t / ha to examine effect of slope changes.

The field trials are in forests of Western Australia, predominantly litter bed with low density understorey of low shrubs and scattered taller sapling sized shrubs. One forest has up to 30% cover of shrubs up to 0.6m high, but most have scattered shrub cover. Burrows physically measures FMC by drying and weighing. Plots are typically 100m wide and 200m long. They are lit with a line of flame 100m long, sometimes 50m.

Burrows also includes a data point from a nearby bushfire (McCaw et al, 1992), described in Case Study 5. That forest, however, has much higher density of shrubs and saplings than his study plots. He uses one of its data points - 1 kph ROS when wind is 30 kph. This is a ratio of 3% of wind in open, which is almost double the Daylesford benchmark. This might mean it is spreading by the wind driven mechanism. Case study 5 also quotes another data point – 1.8 kph ROS in 30 kph wind, which is 6% of wind speed in open. That is probably also due to another spread mechanism.

2.4 Burrows' findings

Burrows finds that most variation in rate of spread in the litter bed can be explained by wind speed and fuel moisture content. His ROS equations use only these two inputs – fuel moisture content (FMC) and wind at fuel bed. His variables clearly sit within the wind driven mechanism, as Figure 11 shows.

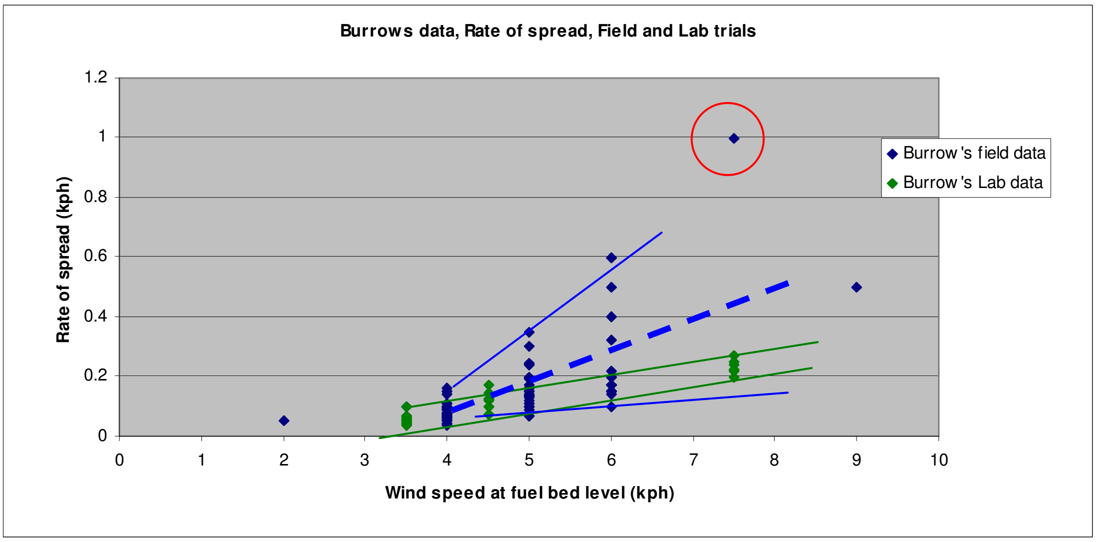


Figure 11 The green lines indicate the approximate ranges for 3 and 10% FMC in the lab. The blue lines indicate the approximate ranges for 3.5 and 10% FMC in the field.
The record circled in red is the McCaw et al (1992) reference. Burrows said he includes it because it was a well documented bushfire in a nearby area. Burrows uses the 1kph data point, but does not quote the subsequent 1.8 kph sprint (see Case study 5 below).

(1) Presumed definition of Burrows' Rate of spread (ROS)

Burrows' rate of spread data refers to a line of continuous moving flame.

(2) Effect of fuel moisture content (FMC) on ROS

Burrows' laboratory trials provide rate of spread data for three wind speeds and fuel moisture contents between 3% and 10%. He finds for a given wind speed that rate of spread is inversely proportional to FMC. The best correlations are linear to almost linear, ie, $FMC^{-0.83}$. His highest level correlation had the function (***exp (-0.11 x FMC)***, which is identical to the grass FMC function for grass in Cheney et al (1998). It is equivalent to the power -0.64. He found that for a given wind speed, ROS increased by 50% as FMC decreased from 7% to 3%. This is vastly different from McArthur's power function (- 2 to 2.5) where ROS quadrupled from 7% to 3% FMC.

Burrows' field trials physically measured FMC, but weather records were not available for comparison of measurements with McArthur's EMC chart. His charts for given wind speed above 4 kph show ROS and FMC were related inversely, with powers -1 and -1.5 having equally strong correlations. Burrows adopted $FMC^{-1.49}$ for his model, and this was copied by Project Vesta.

He reported that for a given FMC, the best correlations between ROS and wind speed were linear. I have superimposed these correlations in Figure B1 onto his Fig 6 results summary for 3.5, 5, 7 and 10% FMC. His values for 10% are close to lab findings. There is little difference between 5 and 7%, but the 3% FMC chart is puzzling. It is much steeper and seems to derive from a different data population. It intersects with his bushfire inclusion data (see Case Study 5). It is even more curious how such a low FMC was obtained in trial fires when maximum FDI was only 33. In-forest wind speed was 6 kph, suggesting tower wind was around 24 kph. To achieve 3.5% FMC requires a very dry day. Likely contenders such as 35^{0}C and 25% RH or 30^{0}C and 20% RH generate 4% FMC according to McArthur's EMC chart.

Figure 12 shows that when wind is 4 to 8 kph, most of Burrow's data is for 5 - 9% FMC, which suggests that an average trend line through his data should be approx half of the brown line. The fact that it is within this ball park gives credibility to the McArthur benchmark.

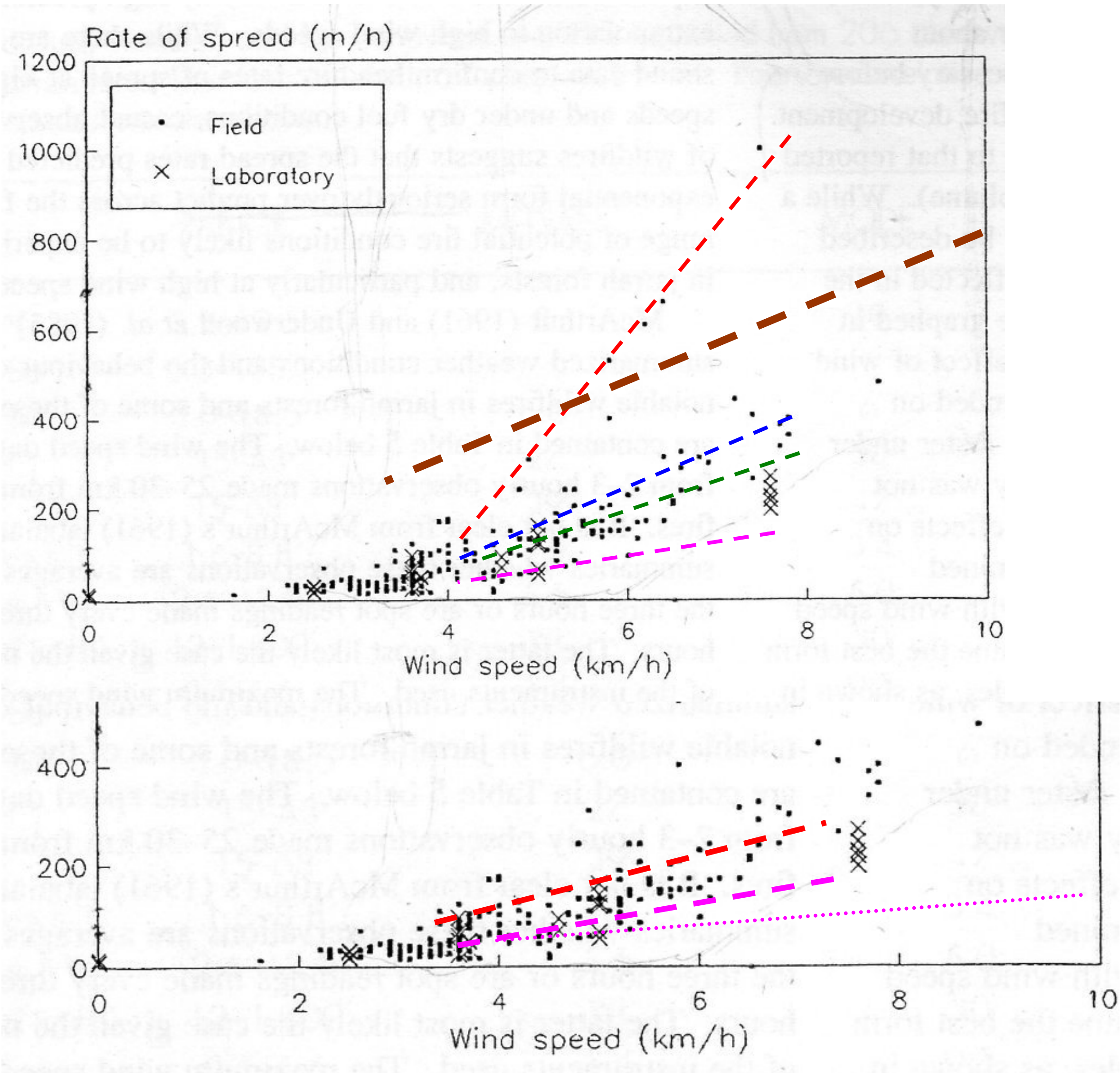


Figure 12 Copy of Fig 6 in Burrows (1999b) . Wind speed is at fuel bed level. Red dash line is 3.5% FMC, blue dash line is 5% FMC, green dash line is 7% FMC and pink dash line is 10% FMC. The brown dash line is the McArthur 2% benchmark for ROS in driest litter bed fuels as percentage of wind in open (= approx 8% of wind speed at fuel bed).
Inset shows red and pink for 3 and 10% FMC for lab trial data from Burrows (1999a). Pink dotted line is ROS trend line for 10% FMC eucalypt litter in wind tunnel (Mulveney et al, 2016)

Is this finding usable? Not definitively. The linear inverse correlation between ROS and FMC seems more credible because the conditions are controlled and the spread mechanisms are identical. The inverse power function -1.5 occurred only in field trials, and may have been influenced of other factors, eg, additional shrub fuel

and different spread mechanisms (eg, the 3.5% FMC line of Burrows' data may be due to a non wind driven spread mechanism)
It would be useful to have weather data to compare Burrows' measured FMC with FMC derived from McArthur's EMC chart.
Burrows does not explain the reasons for the difference between lab and field trials. Most likely reasons derive from significantly different fuel bed structures – pure litter in the lab and in the field is a mixture of litter bed and near surface herbs grasses and low shrubs with a proportion of dead fine particles. Thomas observed that flame runs in the driest and finest fuel particles. Rothermel said the flame runs in the finest particles

For flame height
Burrows does not explain the reasons for the difference between lab and field trials. Most likely reasons derive from significantly different fuel bed structures – pure litter in the lab and in the field is a mixture of litter bed and near surface herbs grasses and low shrubs with a proportion of dead fine particles, and taller shrubs. The multi layer forest readily allows a multi layer tall flame to develop, whereas the litter bed flame height of the lab is a single layer.

(3) Effect of wind velocity on ROS

Burrows finds that a radiation spread mechanism operates when wind speed is less than a threshold 3-4 kph at fuel bed and a wind dominant mechanism operates at higher wind speeds. More details in section 3.5.

For the wind driven data, Burrows lab studies find for given FMC that this linear formula has a high correlation level: ***ROS = 0.048 x wind speed – 0.125***
but he decides on a power function ***ROS (m/hr) = (0.032 x*** $U^{2.1}$ ***+ 0.004***
Where U = kph. His final best fit correlation is as follows:
ROS (m/hr) = (0.0245 x $U^{2.72}$ ***+ 0.071) / (0.003 + 0.0000922 x FMC)***

Some recent wind tunnel data for a eucalypt litter bed has been published for FMC 10% (Mulveney et al, 2016). For wind speeds of 3.6, 9, 14.4 kph at fuel bed level, ROS were 0.04, 0.1 and 0.2 kph respectively. Its trend line plotted on Figure B1 is approx 2/3 of Burrows 10% FMC line.

In field studies, Burrows reports that his best correlations for ROS are linear with wind speed at fuel bed is above 3 kph. Respective equations for 3.5, 5, 7 and 10% FMC's are
ROS (kph) = 0.22 x wind speed (kph) – 0.73
ROS (kph) = 0.066 x wind speed (kph) – 0.17
ROS (kph) = 0.069 x wind speed (kph) – 0.21
ROS (kph) = 0.023 x wind speed (kph) – 0.04

Figure 12 shows that in the driest fuel bed (3-4% FMC), Burrows highest trial data point of approx 6.5 kph generates 0.65 kph ROS, ie, ROS = 10% of wind speed. This converts to 2.5% of wind speed in the open (= 0.6 / 24). It sits above the brown dash line on Figure B1, as does the bushfire point at 13% of wind speed at fuel bed level = 1kph ROS when wind is an unverifiable estimate of 7.5kph. The strong possibility exists that another mechanism may be involved along the red dashed line, particularly when high ROS occurs when wind speeds at fuel bed level are reasonably low.

Burrows commented about the reasonable correlation between FDI and his field data. His data range (from Burrows, 1999b, Fig 16) is reproduced on Figure 13, and it is seen to bisect the 10 and 20 t / ha lines of the McArthur Meter with this equation:
ROS (kph) – 0.0186 x FDI – 0.0058

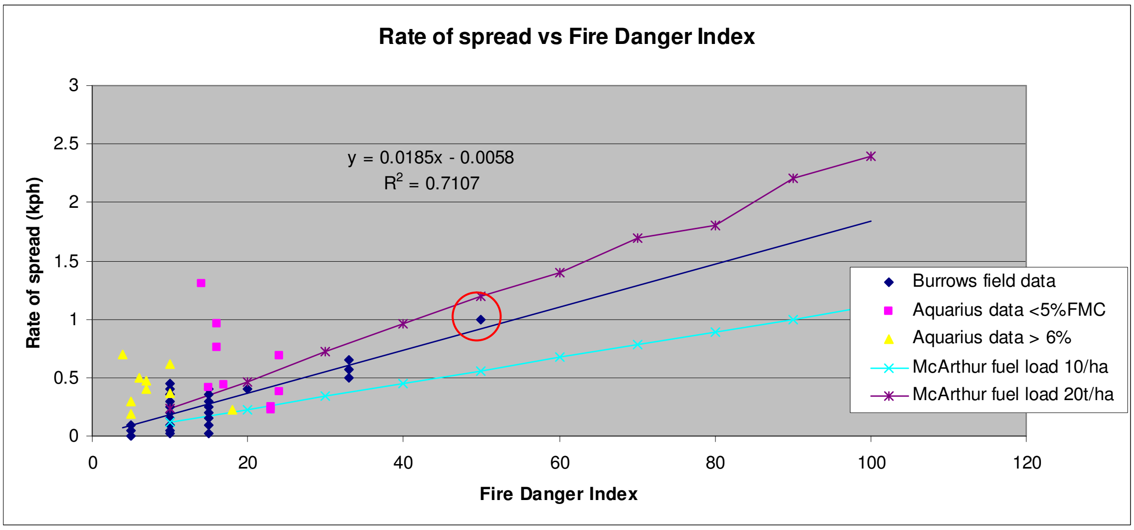


Figure 13 Burrows range of field data is superimposed onto McArthur's FDI prediction chart for 10 and 20 t/ha fuel loads, with Aquarius data range for reference. The Case Study 5 bushfire is circled in red.

Almost all his data points were less than FDI 17, and the peak ROS was 0.5kph. The fastest runners were 0.5 – 0.65 kph at FDI 30 – 35 and the bushfire's 1 kph at FDI 50. (The actual FDI was 65, but this does not significantly change the correlation.)
The record circled in red is the McCaw et al (1992) reference. Burrows said he includes it because it was a well documented bushfire in a nearby area. Burrows uses the 1kph point. He does not quote the subsequent 1.8 kph sprint (see Case study 5 below).

Is this finding usable? No. The switch from linear correlation to exponential is confusing and not explained. The ratio of Burrows' wind driven ROS data to FDI shows consistency with the findings of the McArthur Meter's range for wind driven mechanism fires.

(4) Effect of fuel bed on crowning and ROS
Not addressed. Burrow's trials are confined to litter fuel bed.

(5) Effect of fuel quantity on ROS
In the lab, he finds a linear correlation between rate of spread and fuel load on the fire table in zero wind and in backing fires, but for wind speeds 0 – 3 kph, he varies fuel load from 3 to 16 t / ha, and finds ROS consistently flat lines between 10 and 30 metres per hour.

In the lab, Burrows describes how only the top layer of fuel bed is consumed by the flash flame as it spreads in a wind driven fire, and the deeper layers are consumed after it passes during the smoulder phase. He estimates fuel load consumed in the flame phase is approx one third of the load on the fire table.

Burrows can find no correlation between rate of spread and fuel load on the fire table in the wind driven phase (ie, > 3-4 kph wind speed) in either the lab or the field studies.

In the field, he assumes that all fine fuel (< 6mm dead and < 4mm live particles) is consumed in the flame phase.

Is this finding usable? Yes. It confirms that fuel load is not an influencing variable on ROS in the wind driven mechanism, and describes how the flame runs across the fuel bed surface.

(6) Effect of slope

He finds the following correlation ***ROS (m / hr) = 2.36 x exp (0.687 x slope)***
He compares it to the McArthur correlation and the charts show similar multiplier for each in the range 0 to 15^0 slope.

He finds the effect of slope on flame angle has a similar effect on ROS as the effect of wind caused flame angle. As flame angle increases from vertical, ROS increases. Eg, if slope is 10^0 from vertical, flame angle is also, and ROS doubles. If slope and flame angle are 20^0 from vertical, ROS quadruples.

(7) Effect of spotting

Not addressed

(8) Fire acceleration effect

Not addressed

(9) Burrows' prediction system

His model is as follows:
ROS (m/hr) = FMC^-1.49 x $\boldsymbol{U^{2.67}}$ ***+ 11.6***
Where U =wind at fuel bed in kph.

His final equation and charts are presented in Fig 9 in Burrows et al, 1999b):
ROS (m/hr) = 23.192 x $\boldsymbol{FMC^{1.49}}$ ***x (0.33 x*** $\boldsymbol{W^{2.67}}$***)***
Where W is tower wind in open in kph.

Burrows extrapolates his equations (exponential, power and linear) derived from the wind driven mechanism trials to ten bushfire reported in studies by McArthur and Underwood et al. All have reported ROS above 1kph. I do not have access to McArthur's study, but I have examined the Underwood et al (1985) fires and find that many are rates of spread for spot fire driven fires. They are therefore not validly comparable to a line of flame wind driven mechanism. Unfortunately, he was comparing apples and oranges.

Apart from incompatibility issues, Burrows' choice of this reference is also very surprising because their data is sketchy and of low scientific value. Examples from Underwood et al (1985) follow:
(1) The Rocky Gully fire report is six short paragraphs and a map of final area burnt. Fuels were jarrah forest and open ti tree flats. The only reference to fire

behaviour was this note: "At a rate of spread of approx 6.4 kph, the fire ran 15 km in 2.5 hours. Spot fires were numerous and developed 2km ahead of the front".

(2) The Lake Muir fire report was similarly sketchy. The weather station was 60 km away - 34^{0}C, 24%, 20 kph NE. Fuel was jarrah, paperbark and swamp. Flame heights were up to 8m, and average ROS was 1kph. Spotting was estimated at 200m. Next day was 37^{0}C, 29% 30 kph NW, and ROS reached 3kph. Then the SW change came and the new 7km fire front had ROS 7 kph and 35 m flame height.

(3) The Gervasse fire report was even sketchier. It said "fire behaviour was not closely observed, but it appears that head fire ROS varied between 5 and 10 kph through privately owned bush and pine plantation … 100 kph winds … spot fires occurred up to 3km ahead".

Nevertheless, although Burrows' fastest recorded ROS data was 0.6kph for wind at fuel bed of 6kph, he was comfortable extrapolating it to the Rocky Gully fire's ROS of 6.4 kph for 15 kph wind at fuel bed and 4% FMC, to the Lake Muir fires of ROS 1 kph for 6.6 kph wind at fuel bed and 4% FMC, and ROS 3 kph for 10 kph wind at fuel bed and 4% FMC, and the Gervasse fire ROS 10 kph, for 25 kph wind at fuel bed and 4% FMC.

Is this finding usable? No. Burrows' attempt to verify his wind driven mechanism equations for continuous lines of flame against these documented bushfires is not only invalid because they were spot fire driven bushfires, but they fail to predict his own data. Eg, **his case study 5 bushfire data (3% FMC and 30 kph winds) predicts 2.2kph, which is double the actual, and his 7% FMC data predicts double the actual. fix**

(10) Byram's Fireline intensity

In lab studies, Burrows found only the top layer of the litter bed was consumed during the moving flash flame phase. He proved that if Byram's fireline intensity is calculated using consumed fuel load, as Byram intended, it calculates at one third of the value if total fuel loading is used (see Fig 11 in Burrows 1999a).

However, in the field studies, he assumed all fine fuel was consumed, which included both litter bed and elevated fuel loads. He derived the following flame length / Byram fireline intensity (BFI) equation for jarrah forest: $BFI = 0.0147 \times BFI^{0.767}$

He referred to Byram's original equation for pine forest litter, $BFI = 0.0775 \times BFI^{0.46}$ noting that fireline intensity should not be used to compare between fires in different fuel types. He also noted that flame length is not a reliable estimator of fire intensity when comparing fires in different fuels.

Is this finding usable? Yes. It is useful to know that total fuel load in the equation can cause substantial over-prediction of BFI.

3.5 Burrows' new findings for Australian litter bed fires:

Influences on rate of spread

(1) Two-speed spread mechanisms

He reports a two-speed rate of spread relationship with wind speed that is correlated with spread mechanism of the fire. At wind speeds below 3-4 kph (at fuel bed level), the dominant mechanism of flame spread is radiation. At higher wind speeds, the dominant mechanism is wind driven, ie, convection. The former is slower, dependent on fuel load and flame height. The latter is linear with wind speed.

Is this finding useable? Yes. It helps to identify different fire spread mechanisms

(2) Influence of fuel load in each spread mechanism

Radiation mechanism

Backing fires and fires burning under zero wind conditions were erect with stable, discrete flames. "Rate of spread was controlled by fuel quantity and moisture content".

Wind driven mechanism

He describes the mechanism of the wind driven flame burning across the surface as follows: "At high wind speeds, the flames spread rapidly across the surface of the fuel bed. In deep and heavy fuel beds, only the surface 15-20mm of the fuel bed was actually consumed in the flaming zone during wind driven fires. The remainder of the fuel bed burnt by smouldering and glowing combustion, after the passage of the main flaming zone". During the smoulder phase, "the vertical rate of spread (down through the fuel bed) … varied from 4 to 14 m / hr, with a modal value of 5 m / hr". This is an average rate of 1 cm per 8 sec (range 1 cm per 3 – 10 sec).

He says the fuel load finding means that the combustion rate per unit area of fuel bed is lower at high wind speeds because only the top layer burns. At low wind speeds when the entire fuel bed depth contributes to flame size, the combustion rate per unit area is higher.

Is this finding useable? Yes. Both are very relevant advances in scientific understanding.

3.6 How does Burrows' data compare with McArthur's charts and data?

Figure 14 shows that Burrows' field data is within the range of McArthur's 1967 graphs, within and perhaps 20% less than McArthur's (1967) driest fuels.

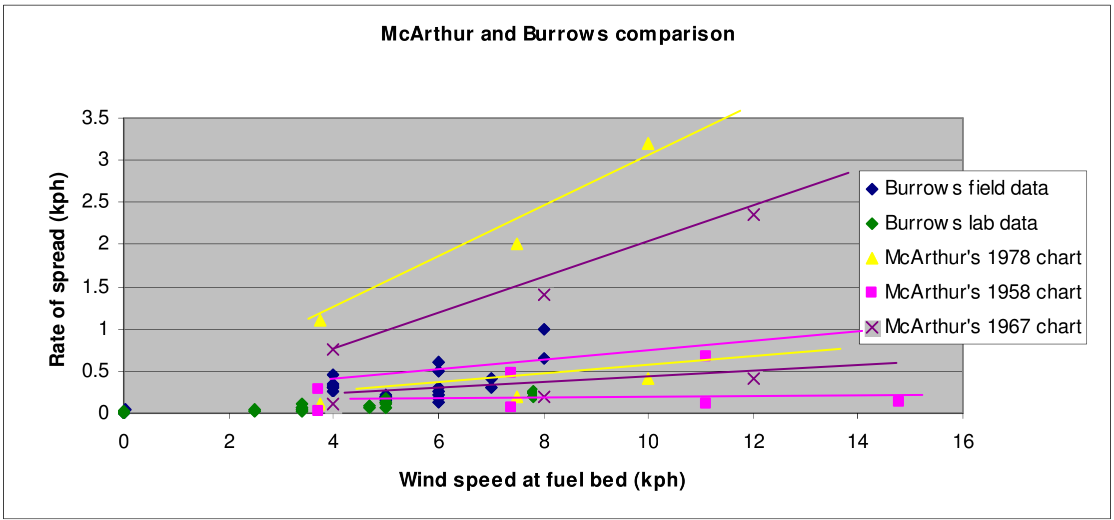


Figure 14 Each set of McArthur's data has two lines, upper line is for 3% FMC and lower line is for 10% FMC. The Burrows' trend line for driest conditions shows rate of spread to be up to 15% of wind speed at fuel bed.

Burrows (1999a) compares his rate of spread observations with the Noble et al (1982) equations taken from the McArthur Meter and finds they “over predicted during periods of low fuel moisture, low wind speed and high fuel quantities, and seriously under predicting (by a factor of three) during conditions of high wind and low fuel quantities”. He then compares his observations with McArthur’s Fire Danger Index (FDI) (for a fixed fuel load, not specified, but probably 12.5 t/ha) and says it is a “better” correlation.

Figure 15 compares Burrows’ field data with McArthur’s original data. Ignoring McCaw’s bushfire point (8 kph wind and 1 kph ROS) for the moment, Burrows’ data for the driest fuel bed is 50% higher than McArthur’s for 4 – 8 kph wind speeds.

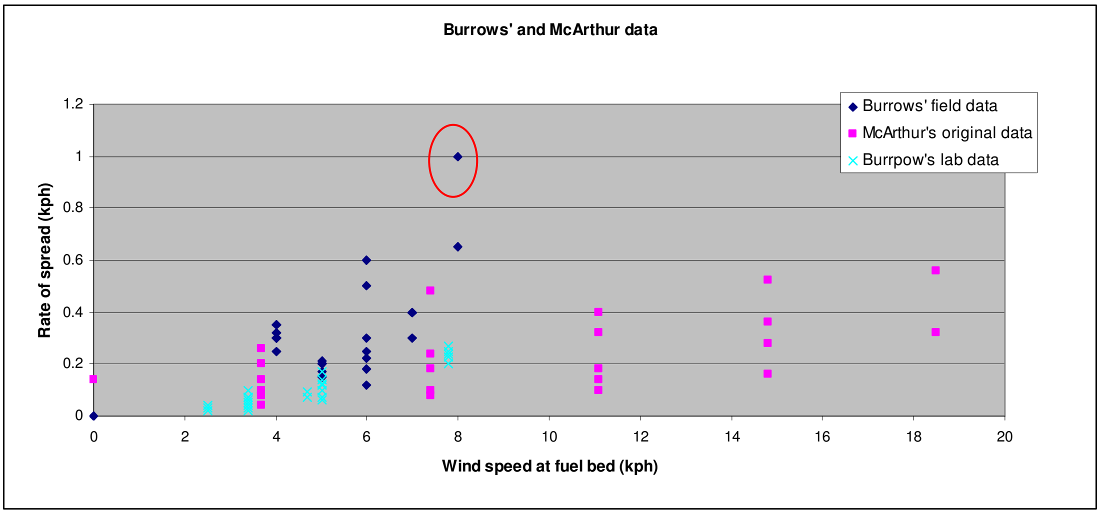


Figure 15 Burrows‘ data compared with McArthur’s 1958 data. Burrows’ bushfire data point is circled in red.

3.7 Summary so far

Burrows’ data is the first and, until very recently, the only documented data set of fire behaviour in eucalypt litter bed in both lab and field. It is unfortunate that McArthur’s data base is not available for comparison, but based on comparisons with McArthur’s Meter predictor, Burrows’ ROS data sits comfortably between McArthur’s 10 and 20 t/ha fuel load values. This is verified by another comparison. When compared to wind speed at fuel bed level, Burrows’ ROS data is substantially higher (50%) than McArthur’s original 1958 data, which in turn is substantially lower than McArthur’s Meter values.

Burrows distinguishes two rate of spread mechanisms – radiation driven which manifests at zero or very low wind speeds and wind driven, which takes over above wind of 3-4 kph at fuel bed level. Burrows ROS prediction equations use only wind speed at fuel bed level and fuel moisture content as inputs. The fire spread mechanism is wind driven.

Burrows includes selective data from the McCaw et al (1992) bushfire as a data point and it seems to fit along Burrows 3% FMC line. He does not include their 1.8 kph observation for 7.5 kph wind at fuel bed.

Burrows criticised McArthur's predictions because they extrapolated low intensity fire data to high intensity fires. Yet Burrows extrapolated his low intensity fire data (which included one high intensity fire) to high intensity fires to derive a prediction model. Unfortunately, when his trial data and the one bushfire data point is fed into Burrows' model, it predicts double the actual speed.

3.8 Bushfire case study

Bushfire Case study 5 The Andrew Fire, Manjimup 31 Jan 1991
(McCaw et al, 1992)

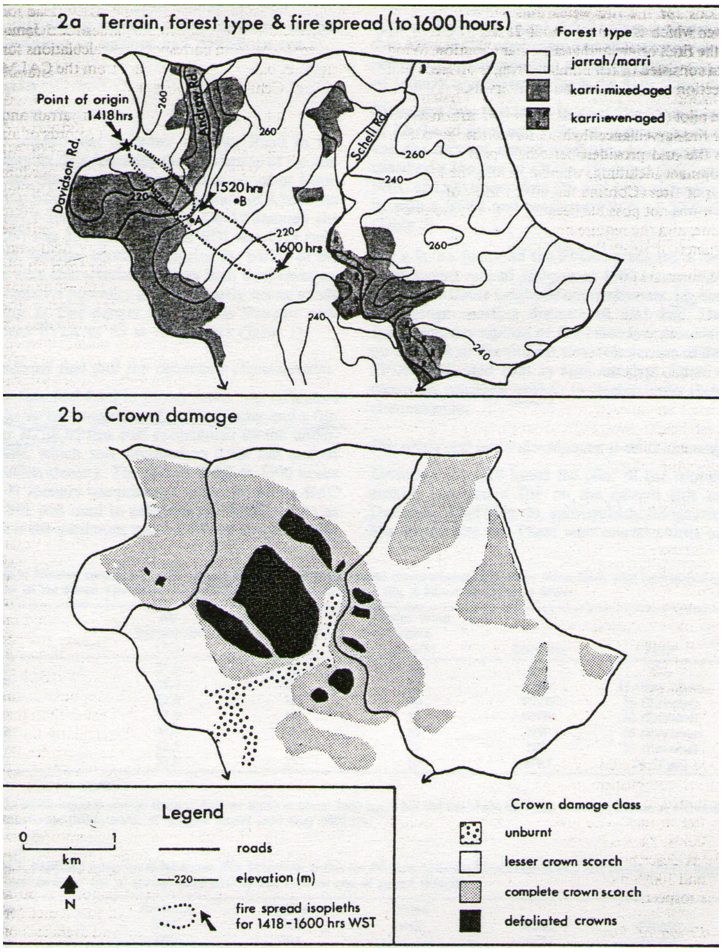
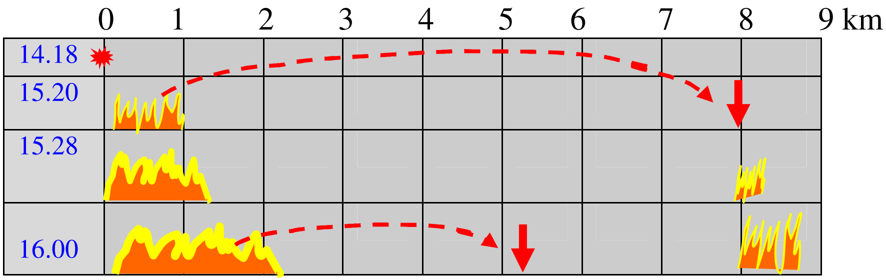


Figure 16 Copy of map of Andrew fire area (McCaw et al, 1992)

Chart 5 describes the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 5 The Andrew Fire, Manjimup FDI 65



Notes: The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin. Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 5:

Rate of spread of original fire front
Original flame front travels at 1 kph for first 60 minutes and at 1.8 kph for next 40 min, averages 2.2 km in 1.7 hours = 1.3 kph.

Rate of spread of each new flame front ignited by spot fires
New spot fire front travels at approx 1 kph

Rate of spread of leading fire front
At 15.28 leading fire front is 8 km from origin
ROS of leading spot fire front = 7 kph (=8/1.17), but there is a large unburnt gap behind it.

Rate of spread of leading leap frog spot fire ignition
At 15.20, leading spot fire, is 8 km from origin
ROS of leading spot fire = 8 kph.

Weather / site details:
Weather 43^{0}C, 16%, 30 kph NNW to NW FDI 60 - 65

Fire behaviour observations:
14.28 Fire origin
14.28 – 15.20
Terrain: Flat land for 0.5 km, down slope 6 degrees for 400m to gully then 100m upslope
Vegetation on flat land is jarrah / marri, height 25 - 30m. Karri increases towards gully.
Observed fire behaviour: Main fire front travels 1km, width = 250m
Flame height 4 – 6 m, scorches the crowns. Local torching into crowns is due to fibrous bark on upper branches.
Firebrands - most land within 100m of fire front. Large quantities of fire brands are visible in convection column up to 1000m high, including karri's ribbon bark.
Observed ROS: 1 km in 60 min, therefore ROS = 1 kph
Estimated wind at fuel bed of 7.5 kph.
ROS = 13% of wind speed at fuel bed
ROS = 3% of wind speed in open

Compare to Predicted fire behaviour:
McArthur Meter predicts ROS of 0.7 kph and flame height 9m. (McCaw et al (1992) use a fuel load of 9 t / ha and FDI 65)
Burrows' linear model [ROS = 0.22U - 0.73 for 3% FMC] predicts 0.92 kph for 7.5 kph wind.

Burrows' prediction model chart (Fig 9 in Burrows, 1999b) predicts 2.2 kph for 3% FMC and 30 kph winds in open

15.20 – 16.00
Terrain Up slope 8 deg for 1 km and then slightly down slope for 0.2 km.
Vegetation Forest is jarrah / marri 25 – 30m, with dense understorey of eucalypt saplings, and Banksia and Persoonia shrubs, 3 – 16m tall.
Observed fire behaviour
At 15.28, crowning suddenly begins on 250m wide front and continues till 1600, flame pulses 20m above the canopy.
ROS: 1.2 km in 40 min Therefore ROS = 1.8 kph
ROS = 24% of wind speed at fuel bed (estimated wind at fuel bed of 7.5 kph)
ROS = 6% of wind speed in open
Flame height fluctuates 30 – 50m tall.

Compare to Predicted fire behaviour:
McArthur Meter predicts ROS of 0.7 kph and flame height 9m. (McCaw et al (1992) use a fuel load of 9 t / ha and FDI 65)
Burrows' linear model [ROS = 0.22U - 0.73 for 3% FMC] predicts 0.92 kph for 7.5 kph wind.
Burrows' prediction model chart (Fig 9 in Burrows, 1999b) predicts 2.2 kph for 3% FMC and 30 kph winds in open

15.28 Spot fire 8km SE is 0.5 ha.

15.45 approx, spot fires ignite approx 3 km to east of fire front

1600 A sudden SW wind change occurs.

My explanation
McCaw et al (1992) record 10m wind speed at around 30 kph, which means fuel bed wind is estimated at 7.5 kph. ROS during the 15.20 sprint is therefore 24% of wind speed at fuel bed, which is rather high. I suspect that a wind spread mechanism is not the appropriate explanation for the 1.8 kph sprint. I suspect it may have propagated by the tall flame / piloted ignition mechanism.

3.8 Summary to date

Burrows equations and McArthur's chart predictions refer to rate of spread of a continuous line of running flame. If leap frog spotting initiates other lines of running flame downwind, they each run at the predictable rate of spread. The net rate of spread of a leading fire front cannot be accurately predicted by Burrows equations or the McArthur Meter, although, as we see above, they can help explain it.

After criticising McArthur for extrapolating findings from low to high intensity fires, Burrows assumes that his findings in mild weather conditions can be extrapolated to severe weather. His choice of severe weather fires is inappropriate for verification because they are not only spot fire driven fires, but their data is poorly documented and unreliable. Inexplicably, Burrows' used this fire data to derive his prediction model, but when the data for this fire is entered, his model predicts double the ROS.

Chapter 4 Vesta - rate of spread

In essence Project Vesta was designed to replace the perceived errors of the McArthur Meter (Cheney et al, 2012). The major source document is Project Vesta (2007)

4.1 Vesta's disparaging comments about McArthur Meter

- Project Vesta (2007) states - in high intensity fires, the early Peet and McArthur models "at high wind speeds consistently under-predict by a factor of 2 or more". Their source fires are Project Aquarius and Burrows. But, as Figure MB shows, these are not high intensity fires.
- Vesta states - case studies of severe bushfires also under-predict rate of spread and fire intensity. Their sole reference is Rawson et al (1983), but this was not a formal case study.
- Vesta states - differences between observed and predicted in Aquarius are not due to spotting, but are more likely due to experimental error by McArthur and Peet.

Project Vesta (2007) also states "fuel load is the only fuel characteristic used in Australian fire danger rating systems to predict fire behaviour in a particular fuel type." "However there is very little published data to demonstrate a direct relationship between rate of spread and fuel load." McArthur's data "was obtained from fires of very low intensity and there is very little evidence to suggest that this relationship holds true for fires of high intensity"

4.2 Vesta's theories:

Strangely for an expensive research assignment, Project Vesta (2007) does not outline theories they wish to test, but instead explains that they are searching for new correlations, particularly around fuel bed age. Their plan is to throw all the data together and rely on the computer to find correlations. Nevertheless, I presume Vesta specialists were guided by many similar theories to McArthur and Burrows as follows.

In regard to the moving flame:
They probably agree with the theories that ROS is positively correlated to decreasing fuel particle size, increasing aeration, increasing fuel bed dryness, and increasing wind speed. However, Vesta's underlying theory seems to be that fuel bed age also has a direct influence on ROS.

In regard to spotting, I can identify three theories:

- "The longest spotting distances have resulted from the periods of the greatest observed flame height and hence fire intensity". They occur during the updraft phases, which are characterised by dense dark smoke, vigorous vertical flames and slow rate of spread.
- The shortest distance spot fires result from the downdraft phase, which occurs after the convection column weakens and the updraft phase ends. The down draft winds blow across the leading flame front, tilting the flame forward, throwing firebrands ahead and resuming rapid rate of spread. (They define short distance spotting for their trials as 50m.)

- The longer spotting distances result from firebrand uplift in air flow in the convection column to its equilibrium height and the lateral fall distance depends on wind speed aloft and terminal velocity of the firebrand. If the firebrand is still alive, it may ignite in the fuel bed down wind.

The Project Vesta report does not refer to any fire spread or flame height mechanisms in their text, nor do they refer to using mechanisms as a basis for testing theories. The approach appears to have been - light up many line fires, record as much information and footage as possible and look for correlations that can explain observed ROS. There was no focus on explaining how input variables influenced ROS, eg, how does height of elevated shrub layer physically cause ROS to increase? There was no investigation into whether any variables either cancelled out or bolstered the effect of other variables.

4.3 Vesta data

Vesta's field studies are done in two distinctly different forests in WA, Dee Vee with predominantly litter bed slightly higher cover of low shrub than McArthur and Burrows, and McCorkhill with litter bed and taller denser shrub cover. Vesta presents their data in a patchy way in graphs or summaries. There is raw data, standardised data adjusted to 7% FMC and zero slope and outlier data that they excluded.

ROS raw data

The graphs show ROS data against wind speed at fuel bed. Unfortunately, there is rarely a comprehensive set of data that shows all inputs (eg, weather and fuel data) against fire behaviour outcomes (eg, ROS, flame height, etc). The closest to full data is a few fires in Vesta's Chapter 10 – Spotting. Nevertheless, perhaps we can obtain most value from Vesta if we regard it as base data set for fire behaviour in shrubby forests at low to moderate wind speeds.

Vesta's data covers a narrow range of litter bed FMC: 6.1 – 8.6% in Dee Vee and 5.6 – 9.4% in McCorkhill. Figures 17 A and B derive from Vesta's Figure 6.4. Vesta explains that sub canopy wind speed at 5m height equates to wind speed at 1.5m (refer Vesta section 4). I therefore use 5m wind speed as proxy for wind at fuel bed level to enable comparison with Burrows' and McArthur's data.

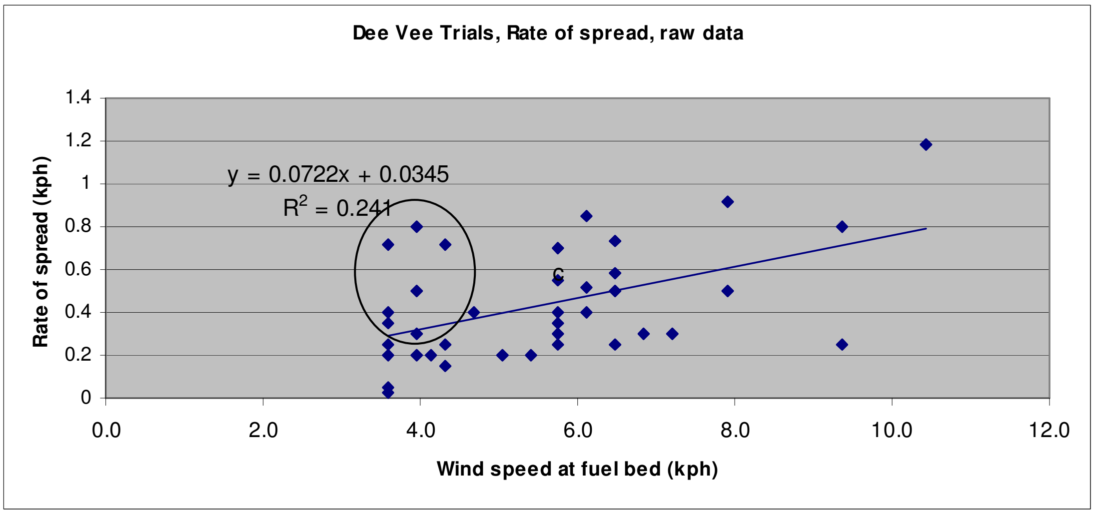


Figure 17 A	The Dee Vee data derives from litter bed forest with short shrub understorey of low density. The circle refers to spotting trials (see below).

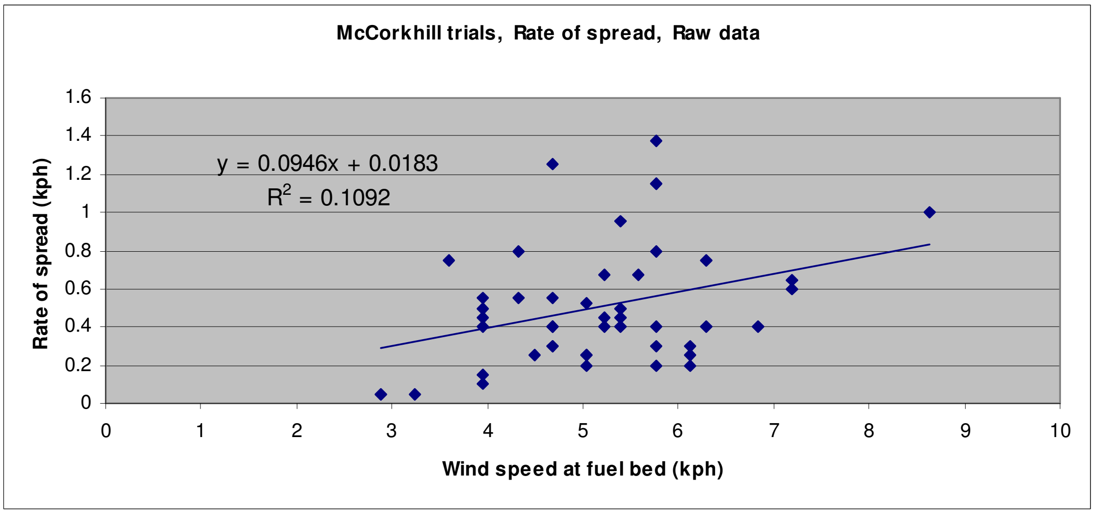


Figure 17 B	The McCorkhill data is from forest with much higher shrub density.

The charts show on both sites that for a given wind speed, there is a wide scatter of rate of spread around the average trend line (as indicated by the low correlation coefficients). However, the data shows a weak positive correlation between wind speed and rate of spread. For a given wind speed, the trend line of Dee Vee is approx 75% of the rate of spread in McCorkhill.

Standardised data

Vesta standardises the data for slope and 7% moisture content, using Burrows' FMC correlation (see below). Figure 18 derives data from Vesta's Fig 6.5, with help from Fig 6.6. It represents the range of raw data that has been adjusted for slope and moisture content. For reference, 7% FMC corresponds to 30^{0}C and 50% RH (Luke and McArthur (1978) equilibrium moisture content table p 42).

Outlier data

They dismiss "outlier" data without further investigation (p 67). Vesta identify two fires burnt on 5 Feb 1999 as outliers. They suspect measured surface moisture was higher than sub surface because they spread much faster than expected. But their FMC data in Table 5.2 does not support this statement – surface FMC 9.6%, profile FMC 9.2%, near surface FMC 10.6%. The raw data points are wind speed 1 m/sec and ROS 0.75 kph and wind speed 1.3 m/sec and ROS 1.25 kph. Standardised ROS are 1.25 kph and 2 kph respectively. Elsewhere in the Vesta report, I find further details about this fire: Temp = 25.5^{0}C and FDI = 8. More information is required.

On page 80, they mention this "fire spread outlier" again because they cannot explain its high average ROS (1.2 kph) and its maximum ROS of 3kph over 30 second period. They simply dismiss it without investigation. Their failure to identify it as a different mechanism is remarkable. Because the ratio of average ROS to open wind speed is 7.5%, I suspect the tall flame / pilot ignition mechanism can explain it.

The cautions of Finney et al, (2013) are relevant.
"If the historical experience with modelling our solar system is any guide for modelling wildfires then we ought to be concerned about anomalies observed in fire

spread. We are convinced that true advancement in modelling fire behaviour is not possible without having sufficient understanding for a comprehensive theory that addresses fire spread anomalies As long as such anomalies remain unexplained, progress and confidence in fire modelling will be held back".

4.4 Vesta Findings

(1) Vesta's definition of Rate of spread (ROS)

Vesta understands and measures ROS of line of moving fire front. It does not make reference to "apparent" ROS, as McArthur did, which is caused by leap frog spotting and is different from and faster than s moving line of fire within a forest.

(2) Effect of fuel moisture content (FMC) on ROS

They adopt the exponential function Burrows used in his prediction model, ie, $FMC^{-1.49}$ but even though Vesta studies are based on a narrow range of FMC, ie, 5.6 – 9.6%, they do not test their obvious assumption that the Burrows' correlation holds true for lines of fire in drier fuel beds, particularly at 3% FMC. When the origin of the Burrows' estimate is considered, along with the variety of contemporary correlations in use, this assumption is a scientific omission. For example, Cruz et al (2015) confirm that the FMC differential in litter for mallee fires in 1997 was the same as the one used in grass fires in 1993, ie, exp (-0.11 x FMC). These correlations generate a rise of 25% ROS for each 2% rise in FMC, compared to Burrows' doubling of ROS for each 2% rise in FMC. At least three other contemporary exponential functions existed for litter bed - exp (-0.227 x FMC), exp (-0.396 x FMC) and the local WA Red Book used exp (-0.6 x FMC). Nevertheless, Vesta's prediction model now extrapolates this correlation to severe weather without verification.

Project Vesta (2007) measured pre and post burn FMC in surface litter and profile litter and near surface. They found that measured FMC in surface litter was reasonably well estimated by McArthur's EMC chart, and that measured FMC of the near surface layer (which contains surface and elevated litter, grasses and low shrubs) was consistently higher than surface layer by 0.5 to 2% higher.

Is this finding useable? No. Although they identify a correlation for FMC, they do not confirm it with own research. A companion paper shows that both theory and systematic research prove Vesta's choice of FMC is a scientific mistake.

(3) Effect of wind velocity on ROS

Vesta finds a weak linear correlation between wind speed and ROS when wind speed exceeds 3 - 4 kph at fuel bed level. Standardising the data to 7% FMC and removal of data outliers reduces the scatter slightly, but the correlation coefficient remains low (see Figure 18). Thus at McCorkhill, when litter FMC is 7%, ROS is proportional to 11.9% of wind speed at fuel bed. At Dee Vee, ROS is proportional to 6.7% of wind at fuel bed.

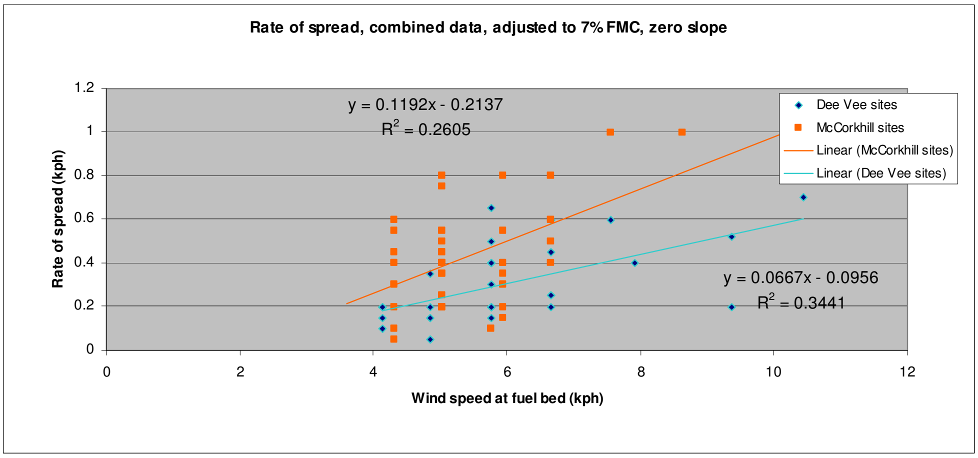


Figure 18 Indicative spread of Vesta's standardised data range with outliers removed.

Figure 18 shows that McCorkhill forest has a higher ROS for a given wind speed than Dee Vee. Vesta found no significant difference in sub canopy wind speed at either forest site for a given open wind speed at 30m. This suggests that the rate of spread in the shrubby forest is influenced by variables other than wind speed. Vesta believe the reason is related to fuel structure, which is related to age of fuel. To an investigative mind, this also suggests a different rate of spread mechanism may be operating, but unfortunately, Vesta did not investigate this possibility.

Vesta's oscillating updraft / down draft phases

Vesta's observers noticed a regular cycle of updraft and down draft as the line of flame progresses. Vesta's ROS data is the average of these fluctuating phases. Vesta believes they are caused by feedback mechanism between the fire and ambient wind (p129). Vesta identifies their occurrence by the ratio of peak ROS to mean ROS is usually 2, but is sometimes 3 (p 122).

Each cycle has a duration of 1 to 3 minutes. The cycles occur below the canopy in all fuel bed ages. The updraft phase has dense dark smoke, vigorous vertical flames and slow ROS and is the source of longer distance spotting. The downdraft flames lean forward, have less smoke and rapid ROS resumes, and they are the source of short distance spotting.

Table 3 below provides an interesting contrast to these ROS oscillations, where a taller flame produces a slow ROS. It shows a clear trend that when wind is identical, ROS becomes higher at the same time as flame height becomes higher. This is more evidence of another mechanism at work.

Are these findings useable? Yes. There is confirmation of a moderate linear correlation between wind and ROS at a given FMC.
There is clear evidence of a non wind driven mechanism is also at work, one that generates a faster ROS at lower wind speeds than the wind driven mechanism.
The oscillating cycles add to our knowledge bank.

(4) Effect of fuel bed age on flammability and rate of spread

Fuel bed variables used by Vesta include fuel load, % cover, % dead fine fuel, height, density, amount of loose bark. These variables act as indicators of fuel age and fuel bed flammability, confirming Vesta's underlying theory that fuel bed flammability is directly correlated with rate of spread and that age is an indicator of flammability.

Fuel bed predictor variables

Vesta's correlation study concludes that the best predictors of rate of spread are fine fuel moisture and wind speed as expected but also flammability indicators such as surface fuel hazard score (= litter bed depth), and the product of near surface fuel hazard (NSFH) and near surface height. Vesta does not explain the causal linkage between the fuel characteristics and the wind driven mechanism, other than the implication that as flammability increases, so does ROS.

Two other observations:

- The product of NSFH and near surface height seems to magnify the relative influence of the most flammable fuel, ie, fine elevated fuel particles in the low shrub layer. Vesta does not quantify these variables with ROS or explained the casual linkage.
- The surprisingly strong correlation between litter depth and ROS is not explored further by Vesta. The causal link between litter depth and ROS is not explained, which is an omission because it contradicts their observation that wind driven flame skims across the litter surface.

Influence of fuel age

Vesta finds that age of fuel has a strong correlation with ROS. Vesta's Appendix III charts list each fuel bed variable with age of fuel. Their values each trend upwards with age. Most tend to increase rapidly in value until age 5 and then plateau gradually with additional age. Two exceptions are % dead material in the near surface fuel and surface fuel load, both of which continue to rise steadily with fuel age. Perhaps these variables are seen as key drivers of flammability increasing with fuel age.

Figure 19 (below) displays Vesta's prediction chart (Cheney et al, 2012), which shows the correlation between age and ROS more clearly.

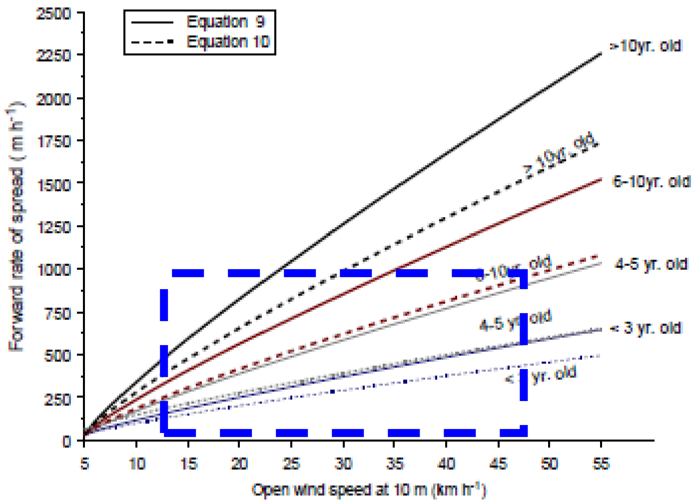


Figure 19 Copy of Fig 6 from Cheney et al (2012). It is standardised at 7% FMC and zero slope. The blue dashed line is the approx extent of Vesta's standardised data, excluding the two outliers.

Trend line prediction data from Figure 16 for 7% FMC:

Young fuel < 3 years	ROS = 1.1% of wind speed in open (1 – 1.2%)
Fuel age 4-5 years	ROS = 1.5% of wind speed in open (1.2 - 1.8%)
Fuel age 6-10 years	ROS = 2.4% of wind speed in open (1.8 – 3%)
Fuel age >10 years	ROS = 3.7% of wind speed in open (3.2 - 4.2%)

Compare this stylised data to some usable fire behaviour data from Table 3 below, which includes raw data for FMC 6% in same fuel type and same wind speed (12-16 kph in open):

Fuel age, 3 years	ROS = 0.38 kph = 2.7% of wind in open (= 0.38/14)
Fuel age, 5 years	ROS = 0.62 kph = 4.4% of wind in open (= 0.62/14)
Fuel age, 22 years	ROS = 0.75 kph = 5.3% of wind in open (= 0.75/14)

The Table 3 data also shows that one or more age based variables seem to be the cause of increasing ROS in a given fuel type at a given wind speed.

Is this finding useable? Partially. It describes how older fuels have a higher ROS for a given wind speed, but does not identify the causal trail, ie, how fuel age influences ROS.

(5) Effect of fuel quantity on ROS

Vesta finds a weak correlation with fuel load but they find that other aspects of the surface layers have more influence, especially the near surface layer (= low shrub layer).

Is this finding useable? Yes. It confirms that fuel load has minor influence on ROS, and suggests that it has probably been used in the past as a blunt indicator of other fuel factors.

(6) Effect of slope on ROS

They use McArthur's equation without any testing.

(7) Effect of spotting on ROS

Vesta does not explore the effect of spotting on spot fire ROS. However, Vesta's chapter 10 and Appendix VIII provide some comprehensive data on several fires. Six fires were conducted over two successive days in the Dee Vee forest. Weather conditions for duration of fires were similar:

Temperature	23.5^{0}C and 25.2^{0}C
RH	40% and 37%
Wind speed at 10m	16.2 and 12.7 kph respectively (= 4 and 3 kph at fuel bed)
FDI	10 and 12
FMC	6 and 6.2%

Table 3 lists input variables and fire behaviour outcomes. Table 4 describes spotting behaviour during the moving flame and when it stops at the firebreak. Table 5 indicates that Vesta is able to associate specific long distance spotting with identifiable periods of tall updraft flame.

Table 3 Fire behaviour details

Fire No.	Fuel age years	Likely initial fuel load * t / ha	Estimated fuel consumed ** t / ha	Bark depth consumed *** mm	Mean rate of spread **** kph	Estimated mean flame height ***** m	Maximum flame height **** m	Ratio ROS to wind at tower level
J	3	9	3.3		0.38	0.5	0.7	2%
D	5	12	10.5	5.4	0.52	3 - 3.5	6	3.2%
F	22	16	13.1	11.5	0.8	4	6	5%
B	3	9	4.7		0.39	1.5	2	3.2%
H	5	12	11.3	5.7	0.72	3 – 3.5	5	6%
M	22	16	12.2	11.8	0.72	4	8	6%

NOTES:

* Estimated from Vesta Fig 3.4 – surface and near surface

** Estimated from Vesta mean intensity / mean rate of spread in Table 10.3

*** From Table 10.4. Vesta also estimates that in older fuel, bark consumption is 5 – 8 t / ha

**** From Table 10.3

***** Estimated from Fig 6.18. Vesta notes that most fires had ratio of maximum ROS to mean ROS of 2, but some fires exceeded 3.

Table 4 Spotting from short distance spot fires

Fire No.	Fuel age years	Spotting observed from moving fire (Table 10.7)	Spotting observed downwind when moving fire hits firebreak (Table 10.7)	Maximum firebrand density downwind of fire break* No. / sq m
J	3	A few to 5 m	A few to 15 m	
D	5	Numerous to 15m, one to 40m	7 up to 20 m	7
F	22	Numerous to 10m, one to 30m and 3 to 50m	60 up to 50 m	180
B	3	A few to 3 m	A few to 20 m	
H	5	Numerous to 20m, two to 50 m	40 up to 15m, 8 up to 50m	39
M	22	Numerous to 50m	Not measurable	3.6

* Maximum firebrand density within 30m downwind of firebreak during first 10 min (Table 10.5 & text)

Table 5 Spotting from longer distance spot fires

Fire No.	Fuel age years	Max flame height / depth at the time	Longer distance spot from this moving flame	Maximum spotting distance during fire run – origin not identified (Table 10.8 and 10.9)	
J	3	0.7 and 2	none	15m	none
D	5	6 and 8	1 at 160	500m	1 at 500m
F	22	6 and 6	8 between 50 and 100	280m	5 between 60 and 280m
B	3	2.1 and 2.5	none	20m	none
H	5	5 and 4	6 between 50 and 100	180m	9 between 50 and 180m
M	22	8 and 4	None beyond 200	Not measurable	None beyond 200m

Summary of findings about short distance spot fire behaviour

- There is an exponential decrease in fire brand density with distance downwind of fire break
- Maximum density of firebrands downwind of moving flame is positively correlated to fuel age.
- Increasing fuel age provides greater bark quantities for consumption and ember generation.
- A large proportion of ember material is jarrah bark flakes 2 – 4mm thick. Vesta experiments confirm they can remain alight for up to 2 minutes and more. This means they could ignite up to 450 m distant in the prevailing wind conditions of the day, 3.5 – 4.5 m/sec (= 10 – 14 kph).
- All fires have two oscillating convection cycles below canopy height – updraft and downdraft. When the downdraft phase reaches the firebreak, it blows a mass of firebrands across the firebreak. When the updraft phase reaches a firebreak, the plume can either break down and then blow dark smoke and firebrands across it or it could remain erect and not blow smoke and firebrands across.

Vesta also develops a model for estimating maximum spotting distance. They do not verify it nor compared it to the McArthur Meter prediction table, which estimates spotting distance = approx 3 x ROS.

Are these findings useable? Yes and No
Yes. Better understanding of spot fire behaviour adds to knowledge pool.
No. Maximum spotting distance has not been verified. It is low on the bushfire manager's "need to know" scale.
Unfortunately, Vesta has not increased our knowledge about the effect of spotting on ROS, which was the reason that McArthur's prediction charts differ from his original data.

(8) Fire acceleration effect

Vesta believes each line of flame reaches a steady state rate of spread well within the 200m fire run.

Is this finding useable? Fire acceleration and steady state of ROS are low on the bushfire manager's "need to know" scale

(9) Vesta's prediction system

Project Vesta sets out to "identify the fuel characteristics which can be best correlated with forward spread". They want to produce a national eucalypt fire behaviour model that will replace or amend the McArthur model.

The extant eucalypt fire behaviour model is the McArthur Meter, Vesta is critical of it because is was "developed independently from measurements of small experimental fires in dry eucalypt forest fuels comprised of leaf, bark and twig litter and occasional low shrubs … designed primarily to predict the behaviour of low-intensity fires for prescribed burning operations, but has been extrapolated to predict the full range of expected fire behaviour (from) observational reports of spread of wildfires" (Cheney et al 2012).

The following section explains how the Project Vesta prediction model extrapolates its low to moderate intensity fire data "to predict the full range of expected fire behaviour (from) observational reports of spread of wildfires". The reader can assess whether their extrapolation was better or worse than McArthur's.

Firstly, Project Vesta (2007) develops an equation that best fits standardised data (ie, ie, 7% FMC and zero slope). The equation was:
ROS = 30 + 3.102 (U_{10} – 5)^ 0.904 x exp (0.279 FHS score + 0.611 NS_{FHS} score + 0.13NS_{height}).
The correlation coefficient was high at 0.69. It was slightly different five years later, and is accompanied by another version (Cheney et al 2012):

FHS version $$R_A = 30 + 1.5308(U_{10} - 5)^{0.8576} FHS_s^{0.9301} * (FHS_{ns} * H_{ns})^{0.6366} * B_1.$$

FHR version $$R_A = 30 + 2.3117(U_{10} - 5)^{0.8364} \exp\left(\sum_{i=2}^{5} b_{2i}(I_s)_i + \sum_{i=1}^{5} b_{3i}(I_{ns})_i\right) * B_2.$$

Cruz et al 2015) reports the same versions three years later.

Secondly, Vesta's Fig 8.1 compares the prediction model with standardised experimental data (ie, 7% FMC and zero slope). Five years later, Cheney et al (2012) also compare standardised data against their later prediction equation data and declare an acceptable level of agreement. Both are reproduced in Figure 20. There appear to be some data differences, perhaps too minor to be of concern. Two observations:
(1) There is a rather large range of variability. For example, when both models predict 0.8 kph, the range of data for both is 0.5 to 1.05 kph.
(2) The highest measured ROS is 1.05 kph and the highest predicted ROS is 1.2 kph.

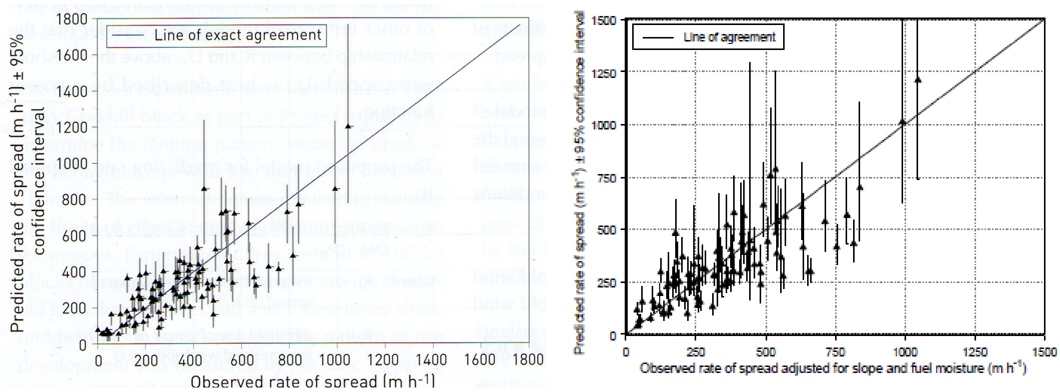


Figure 20 Vesta report Fig 8.1 is on the left, It standardises data to 7% FMC and zero slope. Fig 5 from Cheney et al (2012) is on the right. It standardises data to 7% FMC and zero slope.

Thirdly, Vesta then make adjustments to incorporate fuel moisture and slope correlations and produce the model algorithm that is ready to test against ROS observations during severe bushfires in Australia. Neither Project Vesta (2007) nor Cheney et al (2012) mention the term mechanism in relation to this model, but it is clearly an algorithm for a wind driven spread mechanism. This may be an unfortunate omission, because their model creation process overlooked the possibility that most of their trial ROS data was generated by the tall flame / piloted ignition mechanism, and the model's extrapolation process compares a wind driven algorithm to ROS of bushfires generated by spot fire spread mechanisms. They have therefore overlooked a scientific principle that a specific mechanism can only be extrapolated or amalgamated validly into a like mechanism.

Fourthly, they compare the model to "observational reports of spread of wildfires", which they criticised McArthur for doing. "Predictions from these models are tested against observed rates of spread of independent experimental fires and wildfires" (Cheney et al. 2012).

Project Vesta's (2007) first comparison group is documented bushfires up to 2.5 kph ROS. I reproduce their Fig 8.5 in Figure 21. Vesta text claims "there was good agreement between predicted and observed rates of spread up to 2.5 kph". But this is stretching the truth. Their Fig 8.5 shows that only 12 of 25 data points fall within a band width of 25% of predicted ROS. Of these two are from Victoria and two from NSW. The rest are from WA. Half of the other data points are outside 50% of predicted ROS.

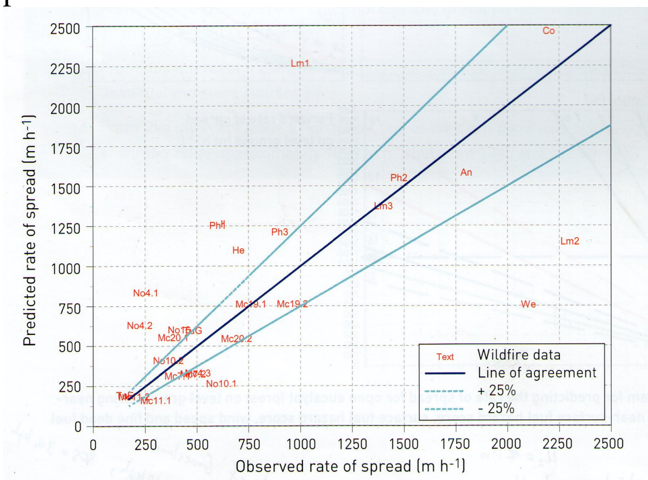


Figure 21 Verification bushfires up to 2.5 kph ROS Copy of Vesta's Fig 8.5

Vesta next comparison group is ROS between 2.5 kph and 20 kph. Figure 22 reproduces their Fig 8,6. It shows that only 2 of 10 data points fall within a band width of 25% of predicted ROS. Most of the remainder fall outside a 50% bandwidth. The highest observed bushfire ROS on this chart of 16 kph for Deans Marsh is a double error. Vesta's Table 8.3 reports it as 10 kph, and their authoritative reference describes it as a leap frog spot fire, and not a continuous running line of flame driven by the wind. I am familiar with many of their verification fires in Victoria, and I show in the case study section that several have been misquoted, eg, Vesta reports them as higher ROS than the reference reports.

Five years later, Cheney et al (2012) present another documented verification, using mainly the same bushfires. It is reproduced in Figure 22. They claim there was "reasonable agreement between predicted and observed rates of spread for fires with observed rates of spread up to 2500 m h^{-1} (Fig. 8 and 9). Observed values were mostly within 25% of the rate of spread predicted by the model, including those from several wildfires". They add that "examination of the full set of independent fires … indicates that model predictions match the general trend of observed spread rates although many observations fall outside the ± 25% bounds (Figs. 8 and 9)". The discerning observer cannot agree with the "reasonable agreement" comment, nor accept the feeble assurance that the model matches the trends not the individual fire data.

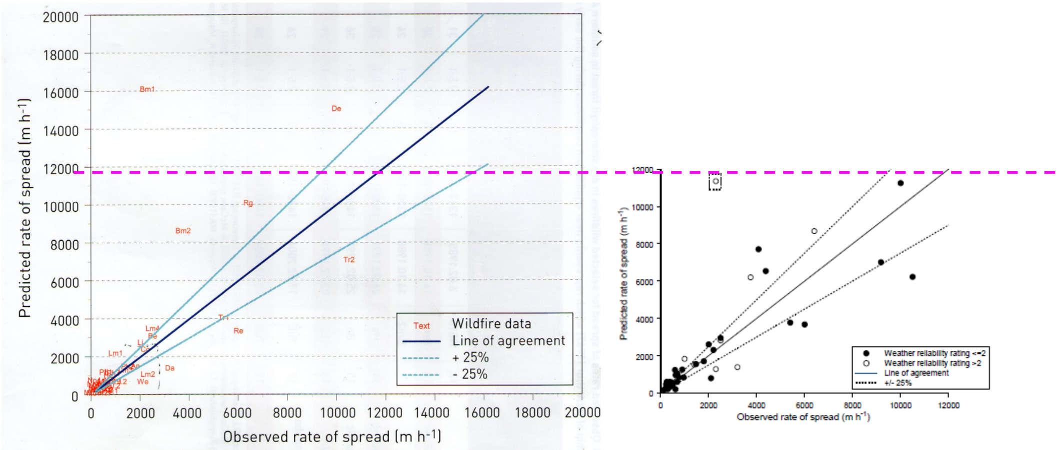


Figure 22 Verification bushfires 2.5 - 20 kph ROS On left, copy of Fig 8,6 of Project Vesta (2007); on right, copy of Fig 8 of Cheney et al, (2012)

The final step in the uncritical verification process, despite the substantial discrepancies between documented bushfires and transcribed observations, between bushfire spread mechanisms, and between predicted ROS and observed ROS, is for Project Vesta (2007) to proclaim "the model compares well with wildfire data" (p 101). Vesta's executive summary proclaims their outcome is the "development of a national fire spread prediction system for dry eucalypt forest". Five years later, Cheney et al (2012) triumphantly conclude - "the fire spread models developed here are designed for application in dry eucalypt forest with a litter and shrub understorey". Another three years pass and Cruz et al (2015) proclaim that the Vesta Model will now replace the McArthur Model because it is only suitable for low intensity fires.

Is this finding useable? Not really. The Vesta prediction process is arrived at by extrapolating findings from wind driven spread mechanism trials in low to moderate intensity fires to severe bushfires. Vesta process lacks integrity for criticising McArthur for extrapolating his model using comparisons with "observational reports of spread of wildfires" and then follows the same process to extrapolate their model.

Vesta extrapolated the wind spread mechanism fire trials to at least two other spread mechanisms in very high intensity bushfires. Vesta has failed to recognise the models and that it is scientifically invalid to extrapolate a model based on the wind driven mechanism in moderate fires to three spread mechanisms – wind driven, tall flame / piloted ignition and spot fire - in severe bushfires. Thus the verification process is flawed and unconvincing.

The fuel bed variables are selected on the basis of correlation levels, but there is no logical or causal linkage between them and ROS.

Case studies below show that Vesta interpretations of documented fires are selective and inconsistent, and they have omitted the important step of screening the fires for dominant spread mechanisms. In particular, the bushfires that spread by leap frog spot fires have not been identified for exclusion.

4.6 How does Vesta prediction model compare to Burrows and McArthur?

Figure 23 shows that Vesta's predicted ROS towers above the McArthur Meter for the same wind speed and FMC. It shows that Vesta predicts four times the ROS as the McArthur Meter. ROS in the driest and oldest fuel bed is approx 80% of in-forest wind speed, or 20% of open station wind speed. To the experienced bushfire manager, such speeds are impossible for a wind spread mechanism. They are certainly possible for the tall flame / piloted ignition mechanism. But Cheney et al (2012) remind us this model is for the wind driven mechanism - "our assumption of an approximately linear relationship between rate of spread and wind speed is reasonable for 10 m winds up to at least 50 km h^{-1}, and possibly stronger".

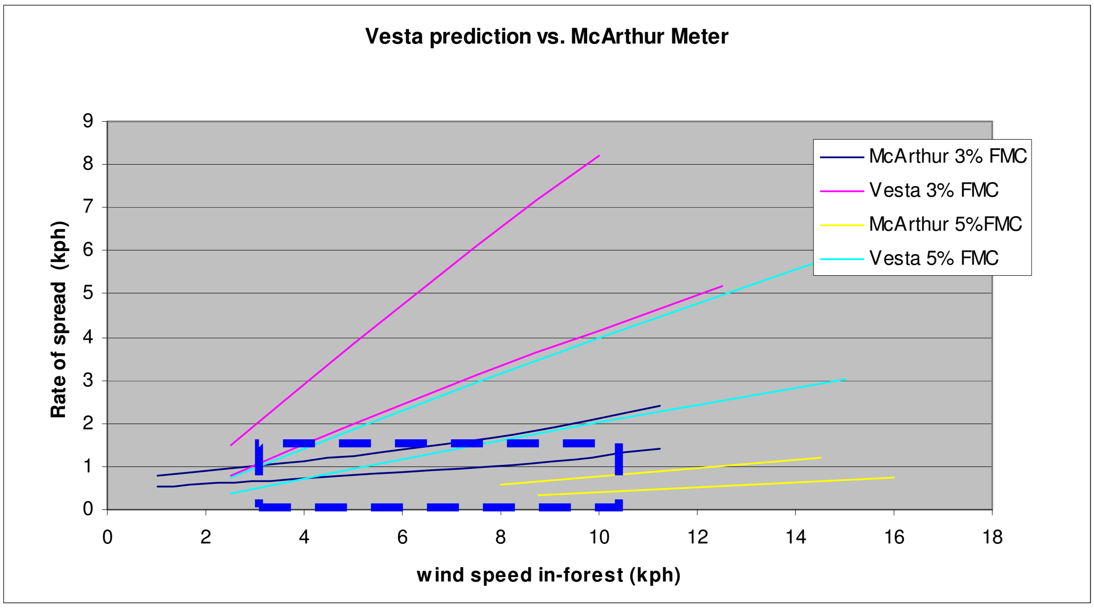


Figure 23 The upper Vesta line corresponds to hazard multiplier sum of 30 (equivalent to 22 year old fuel) and lower line is 15 (equivalent to 5 year old fuel). I use the equation in Vesta Report. Upper McArthur Meter line is 20 t / ha and lower line is 12.5 t / ha. The blue dashed box is the approx range of Vesta's raw data, indicating the extent of extrapolation undertaken by Vesta.

The Cruz et al (2015) statement that the McArthur prediction model has been replaced with the Vesta model is premature because its alleged flaws have not been defended.

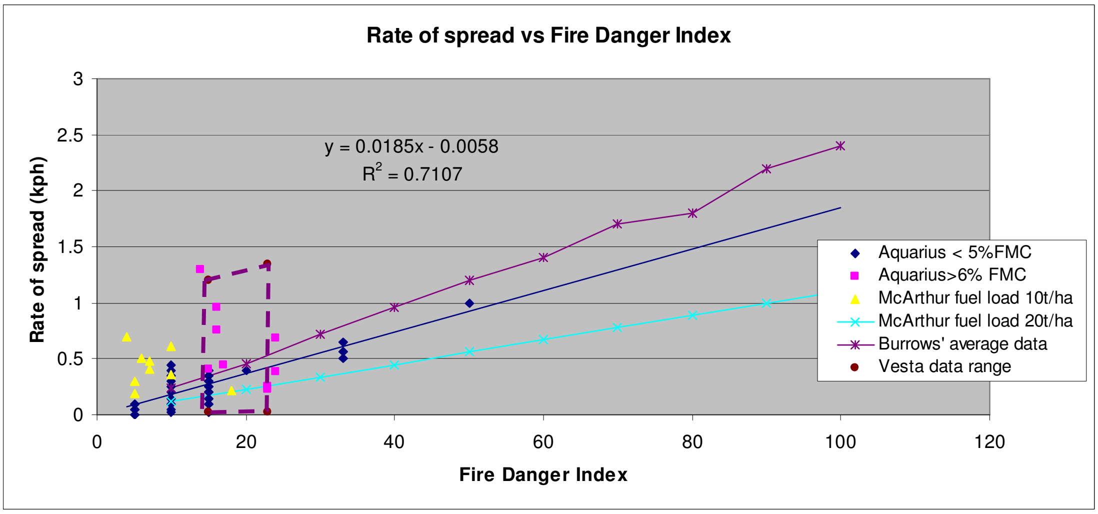


Figure 24 Indicates the extent of the in-forest ROS aberrations for which the McArthur Meter has been criticised and replaced. Aquarius data is shown in pink and yellow, Burrows' data falls between McArthur's 10 and 20 t/ha fuel load. Vesta data falls within the purple dash box.

What is missing is a balanced perspective view of McArthur's alleged aberrations. For example, firstly, Figure 24 shows the criticised prediction aberrations occurred only at low to moderate FDI, ie only a small part of the FDI scale. Secondly, the aberrations have four features in common - low wind speed, high ROS, tall shrub understorey and they usually occur in WA forests. If the critics had explored the theory that these aberrations can be explained by a different spread mechanism to McArthur's wind spread mechanism, perhaps the knowledge bank of bushfire behaviour would have been increased much earlier.

4.7 Compare to Case studies / bushfires

Bushfire Case Study 6 Otway fire 16 Feb 1983 Ash Wednesday

(Rawson et al, 1983)

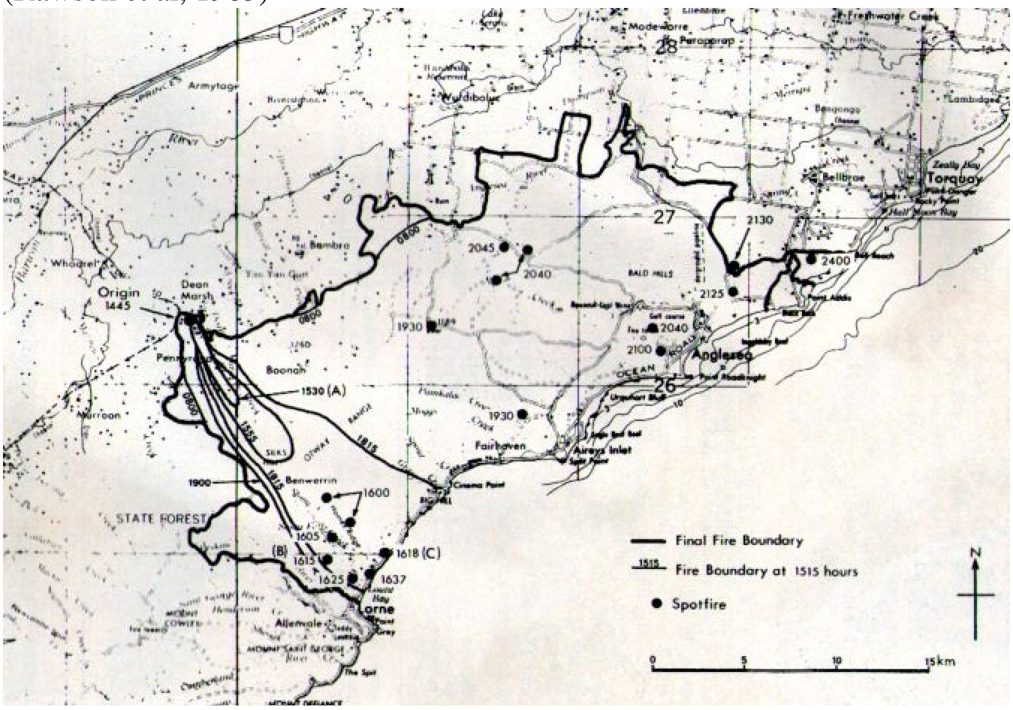
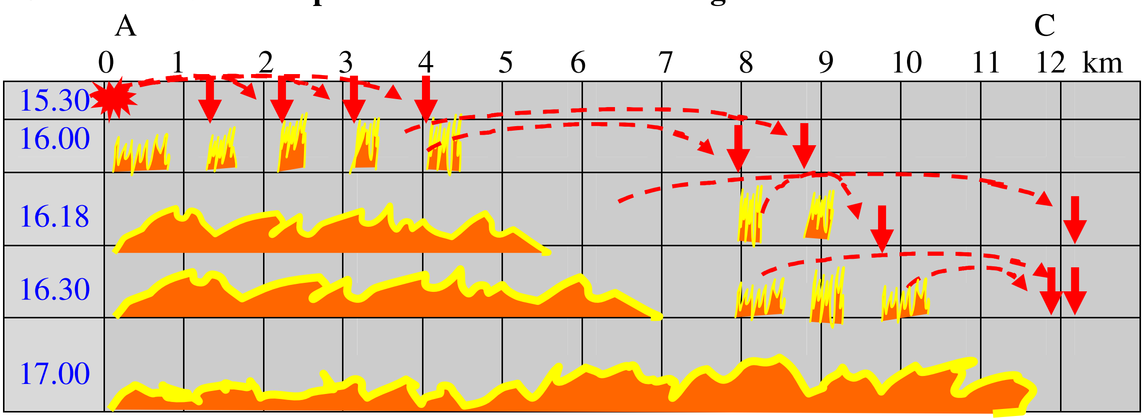


Figure 25 Map of Otway fire isochrones, from Rawson et al (1983)

Chart 6A and 6B describe the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 6A - NW wind phase – before the wind change FDI 100



NOTES:
Point zero is measured from 15.30 isochrone - point A on Figure 18, the approx start of the forest
I estimate spot fires ignite up to 4 km ahead of the initial fire front and run in tandem through the forest as shown.
Point C is Lorne, beyond which is Bass Strait
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 6A:

Rate of spread of original fire front
Original flame front probably travels at approx 1+ kph. At 16.00, fire front is 0.5 km from point zero.

Rate of spread of each new flame front ignited by spot fires
Other spot fire fronts are running downwind through the forest at a similar rate.

Rate of spread of leading fire front
At 16.00 leading fire front is 4 km from point zero - ROS = 8 kph, (= 4/0.5), but there is a large unburnt gap behind it.
At 16.18, leading spot fire front is 9 km from point zero - ROS = 11 kph (= 9/0.8).

Rate of spread of leading leap frog spot fire
At 16.00, leading spot fire is 9 km from point zero - ROS = 18 kph (= 9/0.5).
At 16.18, leading spot fire is 12.5 km from point zero - ROS = 15 kph (= 12/0.8).

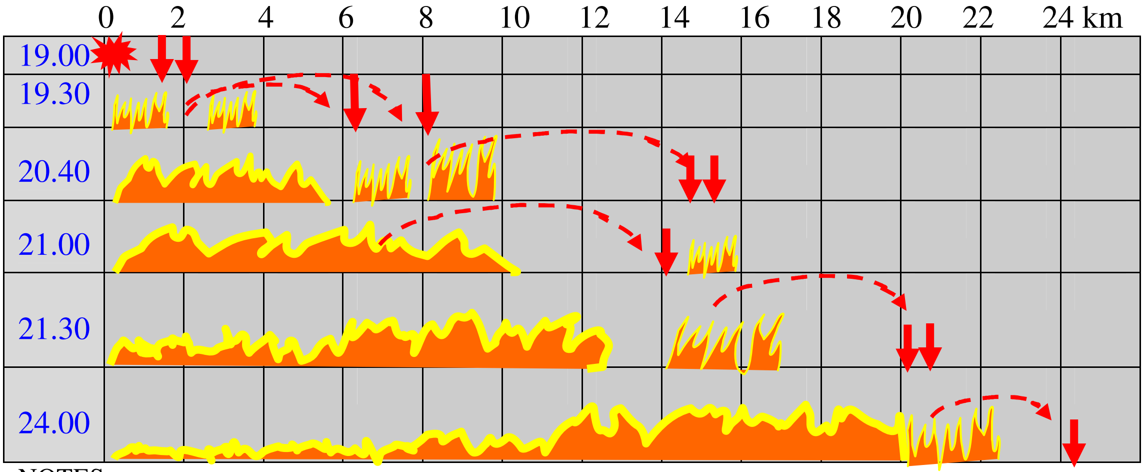
Weather / site details:
Weather at nearby Gellibrand is 40^0C and 11% RH but they quote mean wind speed of 50 kph at Avalon, which is over 60 km away.

Authors' observations
Rawson et al (1983) report that a spot fire reached Lorne at 16.18 (point C), and state the fire's average rate of spread from point A to point C through the forest was 10 kph. They are referring to the leading fire front, but I question how they calculated it. Chart 6A clearly shows the distance between A and C is 12.5 km is jumped in 48 minutes, meaning the leading spot fire had a rate of spread of 15 kph.

Vesta interpretation
Vesta use this weather 40^0C, 11% RH and 70 kph*, and quote 10 kph ROS between 3.55 and 4.37pm. On their Fig 8.6, the Vesta model predicts ROS approx 15 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 21% (= 15 / 70), which is approx ten times expectation for a wind driven mechanism in forest.
*70 kph is the peak wind gust at Avalon.

My explanation
Vesta does not point out that the fire's spread is a spot fire driven mechanism whereas their model is based on a wind driven mechanism. Their use of this data cannot be regarded as scientifically valid.

Chart 6B - SW wind phase – after the wind change



NOTES:
Point zero is 18.15 isochrone. Wind change occurred at 19.00 hrs.

Types of rate of spread
I can distinguish three distinct rates of spread in Chart 6B:

Rate of spread of original fire front
Original flame front probably travels at approx 1 kph.
At 19.30, fire front is probably 0.5 km from point zero.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front travels approx 1 kph

Rate of spread of leading fire front
At 19.30, leading spot fire is 8 km from point zero - ROS = 16 kph, (= 8/0.5), but there is an unburnt gap behind it.
At 20.40, leading fire fronts are 16 km from point zero - ROS = 8 kph, (= 16/2), but there is an unburnt gap behind it.
At 21.30, leading spot fire is 20 km from point zero - ROS = 8 kph (= 12/2.5).

Weather / site details:
The SW wind change arrives at 19.00 with gusts of up to 100 kph.

Authors' observations
They say average ROS just after the change is 10 kph. Chart 6B shoes the leap frog spot fire rate of spread is initially 16, and falls to 8 kph later.

Vesta interpretation
Vesta do not use this part of the fire.

My explanation:
As before, this fire is driven by the spot fire mechanism

Bushfire Case Study 7   East Trentham / Macedon 16 Feb 1983   Ash Wed
(Rawson et al, 1983)

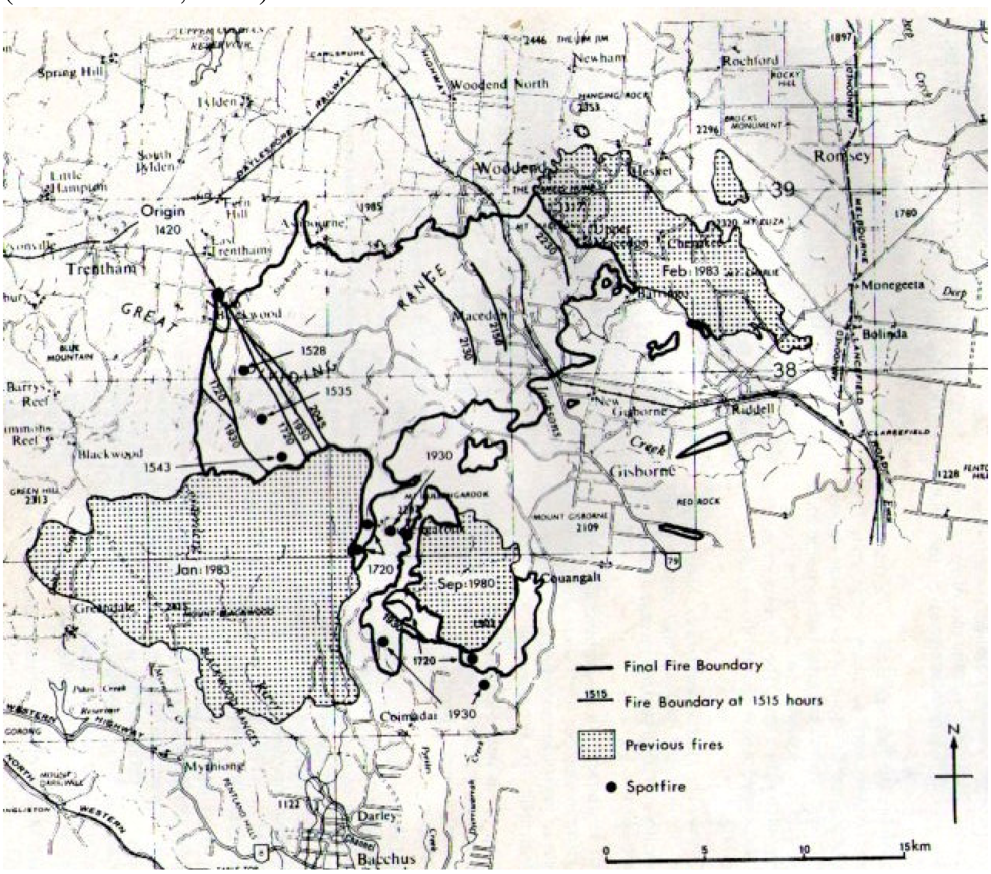
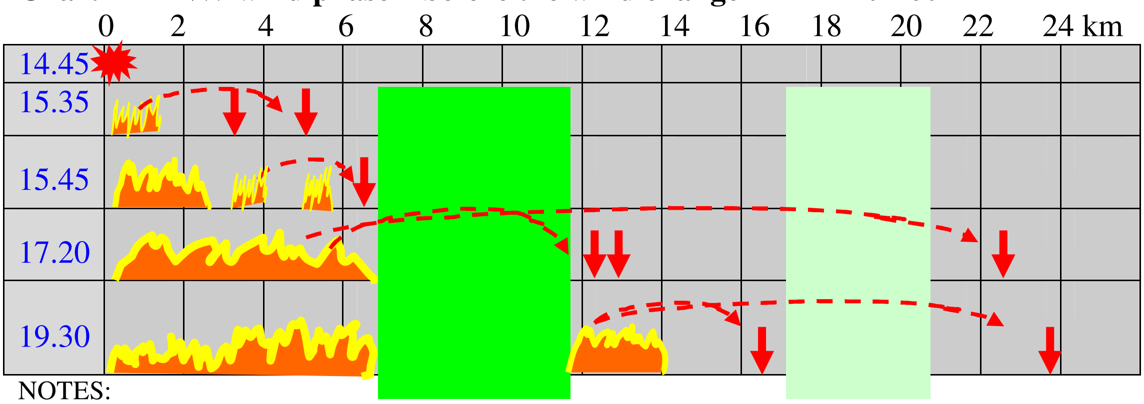


Figure 26   Map of Trentham / Macedon fire isochrones, from Rawson et al (1983)

Chart 7A and 7B describe the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 7A - NW wind phase – before the wind change   FDI 40 - 60



NOTES:
Point zero is measured from 14.45, the approx time the grass fire reached the forest boundary. It is 1.5 km from fire origin.
Lime green is area burnt 1 month before. Pale green was burnt 3 years earlier.
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 7A:

Rate of spread of original fire front
Original flame front probably travels at approx less than 1 kph.
Eg, at 15.35, fire front is several hundred metres from point zero.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front travels approx 1 kph

Rate of spread of leading fire front
At 15.45 leading fire front is 5 km from point zero - ROS = 5 kph, (= 5/1), but there is an unburnt gap behind it.

Rate of spread of leading leap frog spot fire
At 15.45, leading spot fire is 6 km from point zero - ROS = 6 kph (= 6/1).
At 17.20, leading spot fire is 22 km from point zero - ROS = 9 kph (= 22/2.5)

Rawson et al (1983) also report spotting up to 25 km from the fire in Deer Park.

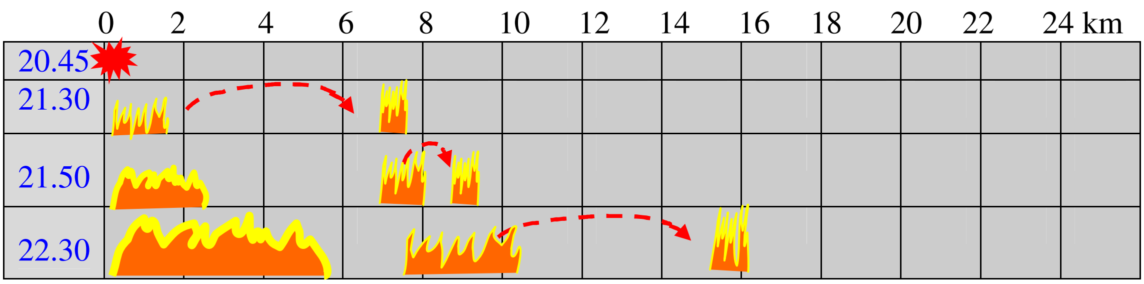
Weather / site details:
Weather at Trentham is 38^0C, 18% RH and 20 – 40 kph winds, FDI 40 – 60.

Authors' observations
Southerly fire spread stopped at 16.00 when it reached the area burnt in the previous month, but an hour or so later, spot fires developed down wind.

Vesta interpretation
Vesta uses this weather 29^0C, 24%, 40 kph, and quote 5.4 kph ROS between 2.20 and 4pm. On their Fig 8.6, the Vesta model predicts ROS approx 4 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 10% (= 4 / 40), which is approx 4 - 5 times expectation for a wind driven mechanism in forest.

My explanation:
This ROS is clearly the leap frog spot fire ROS. Vesta does not point out that the fire's spread is a spot fire driven mechanism whereas their model is based on a wind driven mechanism. Their use of this data cannot be regarded as scientifically valid.

Chart 7B - SW wind phase – after the wind change



NOTES:
Point zero is measured from 20.45 isochrone, Wind change occurred at 20.45 hrs

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 7B:

Rate of spread of original fire front
Original flame front probably travels at less than 1 kph.
Eg, at 21.30, fire front is probably a few hundred metres from point zero.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front travels approx 1 kph

Rate of spread of leading fire front
At 21.50 leading fire front is 9 km from point zero - ROS = 9 kph, (= 9/1), but there is an unburnt gap behind it.
At 22.30 leading fire front is 16 km from point zero - ROS = 9 kph, (= 16/1.75), but there is an unburnt gap behind it.

Weather / site details:
The wind change arrives at 20.45 with winds in excess of 40 kph, possibly peaking at 100 kph (gust speed)

Authors' observations
Within 1.5 hours of the wind change, spot fires engulf Macedon township.

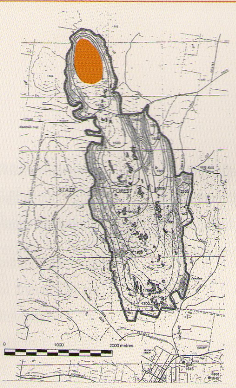
Vesta interpretation
Vesta uses this weather 35^0C, 20% RH and 70 kph, and quote 10.5 kph ROS between 8.45 and 9.20pm. On their Fig 8.6, the Vesta model predicts ROS approx 7 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 10% (= 7 / 70), which is approx 4 - 5 times expectation for a wind driven mechanism in forest.

My explanation:
This ROS is clearly the leap frog spot fire ROS. Vesta does not point out that the fire's spread is a spot fire driven mechanism whereas their model is based on a wind driven mechanism. Their use of this data cannot be regarded as scientifically valid.

Bushfire case study 8 Linton bushfire 2 December, 1998 (CFA, 1999)

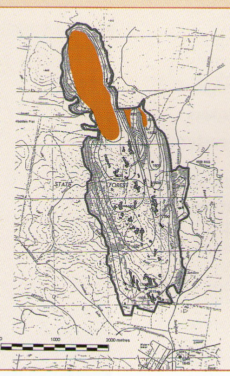
14.00	2.00 p.m.
Temperature.:	28°C
Rel. Humidity:	24%
Wind Speed:	44 km/h
Wind Direction:	N
Fire Spread:	N/A.
Intensity:	N/A.

Fire Area



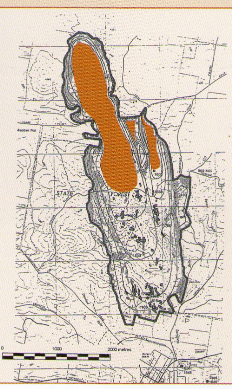
15.00	3.00 p.m.
Temperature.:	27°C
Rel. Humidity:	24%
Wind Speed:	43 km/h
Wind Direction:	N
Fire Spread:	1.6 km/h
Intensity:	13 100 kW/m

Fire Area



16.00	4.00 p.m.
Temperature.:	29°C
Rel. Humidity:	24%
Wind Speed:	33 km/h
Wind Direction:	N
Fire Spread:	1.1 km/h
Intensity:	9400 kW/m

Fire Area



18.00	6.00 p.m.
Temperature.:	28°C
Rel. Humidity:	24%
Wind Speed:	10 km/h
Wind Direction:	N
Fire Spread:	0.2 km/h
Intensity:	600 kW/m

Fire Area

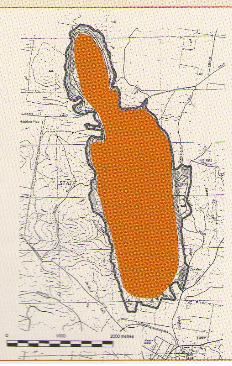
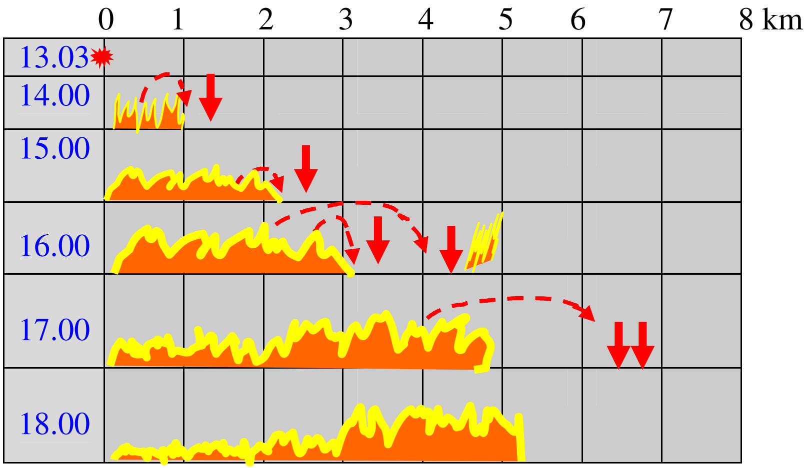


Figure 27 Copy of Linton fire progression map (CFA, 1999)

Chart 8 Linton bushfire FDI 40



Notes: The documented time periods are in blue on left side
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 8:

Rate of spread of original fire front
ROS of original flame = 1 kph.
Coroners Report (2002) concludes average ROS is 1 kph, maximum to 1.5 kph.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front in forest potentially travels approx 1 kph

Rate of spread of leading fire front
At 16.00 leading fire front is 4.5 km from origin – ROS = 1.5 kph, but there is very little unburnt gap behind it.

Rate of spread of leading leap frog spot fire
At 17.00, leading spot fire is 6.5 km from start - ROS = 1.5 kph (= 6.5/4).

Weather / site details:
Weather 28C, 24%, 44 kph from N FDI 40
CFA report says the fire starts at about 1pm. "The day was hot (28^0) with light northerly winds". However, the CFA report says that at 2pm, the wind is 44 kph, at 3pm it is 43, at 4pm it is 25 and at 6pm it is 10 kph.

The forest is densely stocked with advanced saplings and occasional mature trees up to 10m tall – predominantly messmate, but also peppermint and gum. Understorey is predominantly litter bed and continuous light understorey < 0.5m tall.

Authors' observations
The CFA Linton report documents ROS at 1500 as 1.6 kph, but their map shows head fire travels 1 km consistently each hour until 4pm. Coroners Report (2002) concludes average ROS is 1 kph, maximum to 1.5 kph. It also says flame height was generally less than 6m. The CFA document comments about numerous short distance spot fires and occasional longer distance ones.

Vesta interpretation
Vesta uses this weather 29^0C, 24%, 40 kph, and quotes 2 kph ROS between 2.45 and 3.45pm.
On their Fig 8.6, the Vesta model predicts ROS approx 2.7 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 12% (= 2.7 / 40), which is approx three times expectation for a wind driven mechanism in forest.

My explanation:
This fire was an authentic wind driven mechanism. I inspected the entire length of the fire shortly afterwards. The entire canopy was scorched. Even up hill runs were scorched. The only place where the crown was consumed was where the tanker caught fire. This means flame height due to surface fuel was barely 3-4 m tall. The trunks were blackened, indicating they burnt vigorously. A reasonable estimate of litter bed and surface fuel is 10 – 12 t/ha.

Summary:
Average reported ROS is 1 kph, which is 2.5% of wind in open (= 1/40)
McArthur Meter under predicts ROS: ROS is 0.45 kph and flame height 7m for FDI 40, DF 10 and 10 t / ha.
The Vesta model seriously over predicts ROS: ROS = 2.7 kph.

Bushfire case study 9 Berringa 25 February 1995
(Tolhurst and Chatto, 1999)

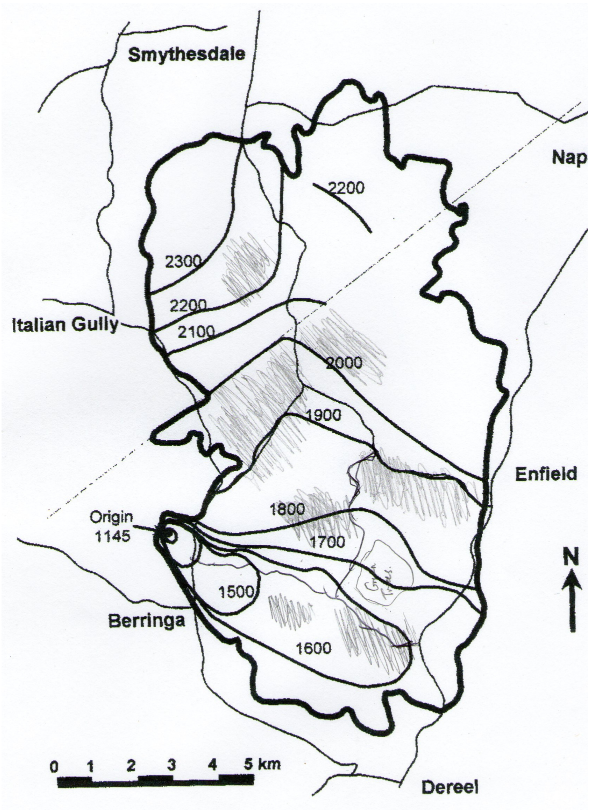
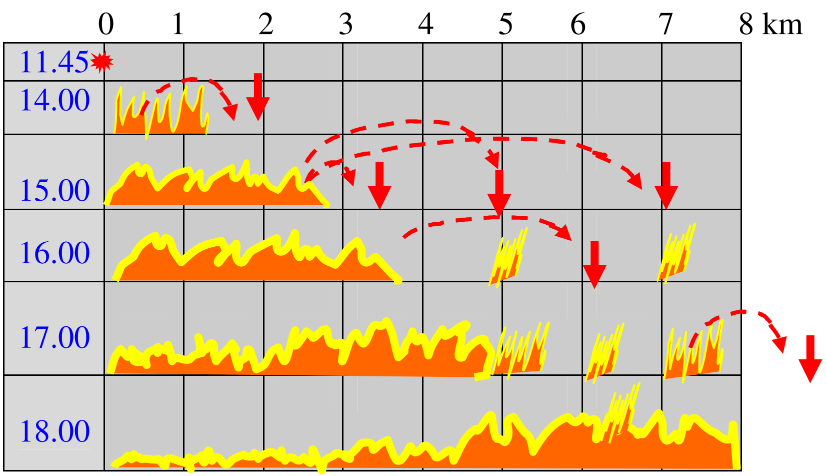


Figure 28
Copy of Fig 4 from Tolhurst and Chatto (1999), who say they do not know if isochrones show the main fire or the leading spot fire. At 1400, distance of isochrone from origin is 1.2km, at 1500 - distance is 3km, at 1600 - distance is 7km and at 1700 - distance is 8km = edge of forest. During that time there is no significant change in weather. I conclude isochrones are lead spot fires, initiated by up slope runs. This is reflected in Chart 9. I have pencilled in approx areas of crown fires (which may have been the upslope runs) from post fire aerial photos.

Chart 9 describes the progress of the main fire, the advanced fire fronts and the spot fires in sequential format.

Chart 9 Berringa NW wind phase FDI 70



Notes: The documented time periods are in blue on left side
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of fire brand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of a fire front from its origin at start of period

Types of rate of spread
I can distinguish four distinct rates of spread in Chart 9:

Rate of spread of original fire front
ROS of original fire front = 1 kph.
Eg, at 15.00, fire front is 3 km from origin.

Rate of spread of each new flame front ignited by spot fires
I expect each new spot fire front travels approx 1 kph

Rate of spread of leading fire front
At 16.00 leading fire front is 7 km from origin – ROS = 1.75 kph (= 7/4), but there is an unburnt gap behind it.

Rate of spread of leading leap frog spot fire
At 15.00, leading spot fire is 7 km from start - ROS = 3.3 kph (= 7/3).

Weather / site details:

Weather Sheoaks		
11.45 to 16.00	35 - 37^{0}C, 6 – 10%	25 – 35 kph, NNW FDI 70
16.00 – 18.30	35 - 37^{0}C, 6 – 8%	10 - 15 kph, NNW – NW FDI 45

The report uses 12 t/ha for litter bed fuel load. McArthur Meter predicts approx 1 kph for FDI 70 and 0.6 kph for FDI 45. I use DF 10 and zero slope. The report uses DF 7 or 8. Thus the McArthur Meter provides a reasonable estimate of the actual moving line of head fire.

The southern part of the fire area is moderately dissected with slopes from 5^0 to 20^0 Forest is 15m tall, red stringybark / peppermint, with a predominantly litter bed and low height, medium density understorey. High tree density.

The northern part is less dissected. Forest is 25 m tall, messmate / peppermint / gum, with a predominantly litter bed and low height, medium density understorey. High tree density.

Most of the burnt area is scorched. Typically the western slopes or higher fuel load patches crowned when the wind was from NW and the southern slopes or higher fuel load patches crowned after the wind became southerly.

Authors' observations
The authors declare the fire has a convection driven phase during which it is driven by the plume rather than by wind. They diagnose this phase as an increased high rate of spread when the weather becomes milder, ie, after a sea breeze increases moisture and remains low wind speed.

ROS evidence:
The authors say this about the isochrones - "it is unknown whether this is the fireline of the main fire or the fireline of a spot fire. It is therefore assumed that the firelines shown are actually the firelines of the main fire. Forward rates of spread were

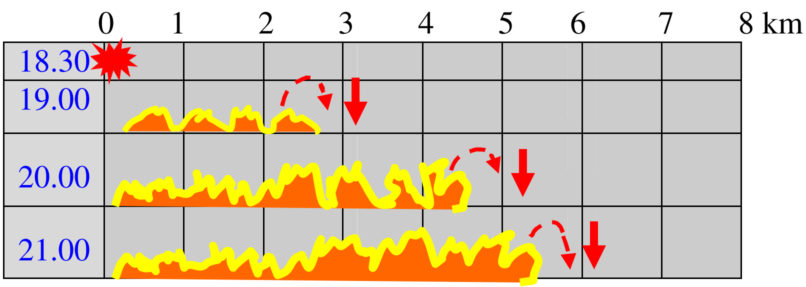
calculated from the isochrones". In addition, their Figs 5 and 6 shows a different distance vs time chart to the isochrone map in their Fig 4.

They are aware of spotting. Spotting is estimated as 300 - 500m ahead of fire front during afternoon run. The report says "at 15.10, a spot fire was reported to the SE of the main fire front, which most likely led to the forward rate of spread of 4 kph … between 1500 and 16.00 hours".

Vesta interpretation
Vesta use this weather 36^{0}C, 6% RH, 25 kph, and quote 2.5 kph ROS between 2.30 and 4.30pm.
On their Fig 8.6, the Vesta model predicts ROS approx 3 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 12% (= 3 / 25), which is approx five times expectation for a wind driven mechanism in forest.

My explanation:
This fire was probably a combination of the wind driven mechanism and the tall flame / piloted ignition mechanism. I inspected a large proportion of the fire area shortly afterwards. The canopy scorch areas were in similar short dense messmate forests as Linton. This suggests a low flame height in undergrowth and high density of flaming trunks.
It is inappropriate for the authors to conclude the isochrones are the true fire fronts without analysing the possibility that they are spot fire fronts. Their construction of Figs 5 and 6 to vary inputs into the McArthur Meter until predicted matches observed are consistent with McArthur's extrapolation technique in the McArthur bushfire case studies 3 and 4, but just as unscientific.

Chart 9B Southerly wind phase FDI 25
There is insufficient evidence to distinguish different rates of spread. I suspect the isochrones are leading spot fires and that the fire cross section may have looked like Chart 9B.



Weather / site details:
Weather at Sheoaks
18.30 wind change to 15 kph, from South
At 20.00 30C, 20% 13 kph, SW FDI 25*
The report uses 12 t/ha for litter bed fuel load. McArthur Meter predicts 0.4 kph for FDI 25.

Authors' observations
The sudden southerly change converts the northern flank of the afternoon fire into a 7 km wide front.

18.00 – 19.00 fire isochrone moves 2.5 km maximum	ROS = 2.5 kph max
19.00 – 20.00, fire isochrone moves 2 km maximum	ROS = 2 kph max
20.00 – 21.00, fire isochrone moves 1 km maximum	ROS = 1 kph max

Vesta interpretation
Vesta does not use this data

Other Vesta case studies include …
Examples of usage of selective data, bizarre short run data and unashamed use of leap frog mechanism fires to justify a wind spread mechanism model.

Andrew fire
Vesta uses this weather 43^{0}C, 15% RH, 30 kph, and quotes 1.8 kph ROS between 3.20 and 4.00pm.
On their Fig 8.5, the Vesta model predicts ROS approx 1.6 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 5% (= 1.6 / 30), which is above two times expectation for a wind driven mechanism in forest.

Bemm River
(1) Vesta uses this weather 28^{0}C, 30% RH, 95 kph, and quotes 2.3 kph ROS between 11.45 and 1.30pm.
On their Fig 8.6, the Vesta model predicts ROS approx 16 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 17% (= 16 / 95), which is approx 8 times expectation for a wind driven mechanism in forest.
(2) Vesta uses this weather 24^{0}C, 40% RH, 75 kph, and quotes 3.7 kph ROS between 1.30 and 3.30pm.
On their Fig 8.6, the Vesta model predicts ROS approx 8.5 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 11% (= 8.5 / 75), which is approx 5 times expectation for a wind driven mechanism in forest.

Rocky Gully
Vesta uses this weather 40^{0}C, 10% RH, 70 kph, and quotes 6.4 kph ROS between 2.30 and 4.30pm.
On their Fig 8.6, the Vesta model predicts ROS approx 10 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 14% (= 10 / 70), which is approx five times expectation for a wind driven mechanism in forest.

Lake Muir
(1) First day: Vesta uses this weather 34^{0}C, 24% RH, 20 kph, and quotes 1 kph ROS between 12.30 and 3pm.
On their Fig 8.6, the Vesta model predicts ROS approx 2 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 10% (= 2 / 20), which is approx five times expectation for a wind driven mechanism in forest.
(2) Next day: Vesta uses this weather 35-37^{0}C, 29% RH, 30 kph, and quotes 2.3, 1.4 and 2.5 kph ROS for three periods between 11am and 7pm .
On their Fig 8.6, the Vesta model predicts ROS approx 1, 1 and 3.5 kph respectively for this weather. Vesta data calculates a ROS to wind speed ratio of 3% (= 1 / 30) which is a bit above and 12% (=3.5/30), which is approx six times expectation for a wind driven mechanism in forest.

Daylesford
Vesta uses this weather 35^{0}C, 34% RH, 45 kph, and quotes 3.2 kph ROS between 2.30 and 5.30pm. McArthur (1967) clarifies that leap frog spot fire rate is 3.2 kph and line of flame runs at 1 kph.
On their Fig 8.6, the Vesta model predicts ROS approx 1.5 kph for this weather. Vesta data calculates a ROS to wind speed ratio of 3.3% (= 1.5 / 45), which is approx 1.5 to 2 times expectation for a wind driven mechanism in forest.

Conclusions:
Vesta predictions lack consistency. They are occasionally close, they sometimes over predict, they sometimes under predict. This is frustrating for the bushfire manager.

Compare this observation to this sales pitch statement from Vesta proponents:
"The models developed here would be reliable to predict the potential rate when fires are started by line-ignition or when fires coalesce together to form a wide head early in the day while burning conditions are relatively severe." (Cheney et al 2012)

The ratio of Vesta-predicted ROS to wind speed has a tendency to increase into the teens when wind speed in the open is above 40 kph. This is the opposite for a wind driven litter bed mechanism, where the ROS to wind ratio remains around 2%. The Vesta model is founded on a wind driven mechanism. The prediction ratio suggests it has veered from its roots.

Project Vesta has collected very valuable data. It will be a tragedy if this data is not stratified into two ROS mechanisms and reanalysed accordingly. If this Vesta output remains unchanged, this means Vesta has generated a prediction model for the "apparent" ROS of the leap frog spot fire mechanism by extrapolating from research in the wind driven spread mechanism. This has not only breached the rules of scientific validity, it has distorted the bushfire manager's understanding of bushfire spread in a forest fire. As such, it is a double tragedy. It will grossly overestimate ROS of the running fire front in the forest and has no empirical credibility in predicting apparent ROS of leap frog spot fires.

Summary of the rate of spread analyses

Where does their research leave us?
They each did some excellent research, but neither Vesta, Burrows and McArthur models **explain or predict the variation** in eucalypt bushfire ROS. Of the three models, the most consistent is McArthur's but only if it is limited to its designer forest – litter bed in tall forest. There are many other types of eucalypt forest, but the McArthur model is a durable benchmark.

Vesta and McArthur tried to include the influence of spotting within their models, despite the fact that their research was based on wind driven lines of flame where spotting had negligible influence on ROS. McArthur tried to account for short distance spotting by boosting his wind and FMC exponents. Vesta and Burrows unashamedly verified their inflated wind speed models against severe bushfires that were driven by leap frog spotting mechanisms, and despite their scientific transgression, proclaimed them as reliable.

So what is my answer to this question - **what is expected ROS in a forest on a worst case fire weather day, eg, FDI 100?**

1 In tall forest, long distance average ROS of mother fire front is 2 – 3% of prevailing wind speed. Thus for 40 kph wind speed, ROS in tall forest averages around 1 kph.

2 In forest, long distance average ROS of individual spot fire fronts is 2 – 3% of prevailing wind speed

3 In shorter open forests, we still have to guess as McArthur did, eg, 2 – 4 kph.

4 ROS of leading leap frog spot fire fronts is unknown, but can be between 5 and 20 kph.

Answers 1, 2 and 3 derive from McArthur's writings and his model for 10 – 20 t / ha. Burrows and Vesta's research add nothing to improve the answer. In fact, Vesta's model predicts double McArthur's in-forest ROS, but only if forest has been recently burnt. For older forest fuel, the Vesta model predicts up to 12 kph. These predictions are meaninglessly excessive to be contemplated by the bushfire manager.
Answer 4 derives from my analysis of Black Saturday spot fires in a companion paper.

Where does this analysis leave us?
The body of research adds useful bits of knowledge about observed fire behaviour, eg, oscillating ROS and surface fuel consumption during wind driven fires, but the major finding arose from what each research work neglected – the importance of fire spread mechanisms. I repeat – the value of this analysis is identifying what the researchers did not consider.

As the four above answers indicate, we still have trouble estimating ROS in a forest fire. At best, if we observe actual ROS to be significantly different from in-forest rule of thumb estimates, we can make a hindsight judgement about the likely mechanism. This highlights the fact that knowledge of the various mechanisms is the most important foundation for understanding bushfire fire behaviour:

- If we understand the pre-requisites of each spread mechanism, we can make predictions for ROS on a given site in given weather, and we can undertake works to mitigate ROS on a given site.
- If we understand that the common pre-requisite for all rapid spread mechanisms is a large flame, the bushfire manager must understand how to predict flame height. I examine flame height research in eucalypt forests in the next section.

I can now present a brief summary of the four ways that bushfires spread in severe weather and what their pre-requisites are, and from this, the bushfire manager can apply defensive mitigation strategies before the bushfire attack.

Wind driven mechanism
Pre-requisites for severe bushfire attack: continuous bed of highly flammable fuel on the ground or near the ground, high wind speed.

The preferable wind to use for the ROS to wind ratio is at fuel bed level. For the driest fuel bed, the correlation between wind and ROS is linear. The ratio varies by surface fuel bed type. Rules of thumb:

- ROS in litter bed is slowest at approx 10% of wind at fuel bed
- ROS in driest heath is approx 15%
- ROS in the driest grass fuel is approx 45%

Tall flame / piloted ignition mechanism
Pre-requisites for severe bushfire attack: tall flame in forest, multi-layered old fuel bed to ensure flame up-lift and ample ember supply, continuous fuel bed. Occurs when wind speed at forest floor is relatively low .

Probably has a maximum ROS of 3 – 4 kph.
Potential ratio of ROS to in-forest wind speed = 20 to 100% or more

The Vesta data and accompanying videos allow me to identify this bushfire spread mechanism in eucalypt forests. This mechanism explains the rapid rates of spread that Vesta observed in low winds.

Spot fire mechanism
Mass short distance spotting Maximum localised ROS = 2 – 4 kph.
Features: one off, up to 1 km ahead of fire front,
Pre-requisites for severe bushfire attack: tall flame in a patch of old fuel is required to generate mass ember supply, flammable surface fuel bed downwind is required to allow ignition, high wind speed. Mass ignition can occur when fuel bed is discontinuous.

Leap frog spotting ROS of leading spot fire = 5 – 15 + kph
Features: long distance hops, each can be up to 5 to10 km ahead of fire front,
Prerequisites for severe bushfire attack: tall flame in a succession of old fuel beds, high wind speed. Can occur when fuel bed is discontinuous

For more details about spread mechanisms, see Paper 1 of this series.

Flame height

Mitigation of flame height in a severe bushfire attack is critical for successful damage prevention. There has been a huge body of research into flame height and its influences in both the industrial and bushfire areas. In this section, I examine what researchers have discovered about flame height in materials and situations relevant to flame height scenarios in eucalypt forests. I distil the key principles into working mechanisms that I can use as a bushfire manager to understand flame height in eucalypt forests - to explain it, to predict it and to mitigate it to prevent bushfire damage.

There have been three flame height models published for eucalypt forests, the McArthur, Burrows and Project Vesta models.

What the bushfire manager wants to know is how can I predict or explain flame height on any site and especially in severe weather.
In each of the flame height chapters, I ask these questions: What is flame height in a pure litter bed on a worst case day? What are the influencing variables and which ones can we manage to mitigate or eliminate flame height.

Chapter 5 McArthur – flame height

2.1 Introduction

McArthur's writings have scant reference to flame height. They tend to report flame height as an afterthought, rather than analyse it. His work is unable to answer to my first question - What is flame height in a pure litter bed on a worst case day? And struggles with the second question - What are the influencing variables and which ones can we manage to control flame height?

2.2 McArthur's theories

McArthur (1967) declares flame height is primarily determined by rate of spread, fuel quantity and wind velocity, but other influences include fuel distribution and atmospheric stability. He is well aware of its importance of FMC. He separately describes findings for combustion rate in litter and grass fuel beds. He makes no connection between it and flame height, but contemporary researchers in industrial fires were developing consistent correlations.

2.3 McArthur's data

McArthur's nominal working lab was the "McArthur forest" – tall forest with litter bed and sparse shrub layer. This suggests that his flame height data would refer to litter bed flame height, but reported tall flame heights suggest shrub and tree trunk involvement. Individual reference data from McArthur about flame height in litter bed is rare. Instead, his flame height data is incorporated into smoothed charts. His base line data for flame height is missing in action.

His writings refer to research in forests with predominantly litter layer and scattered shrubs, but his prediction models include shrub layers. He accounts for flame height in them by adding their fuel load to that of the litter bed.

2.4 McArthur's findings

(1) Flame height

McArthur (1967) does not define flame height. Does he mean average height or maximum height? Does he mean McCaffrey's continuous flame zone or intermittent zone? McArthur's Meter predicts total flame height, but its meaning is unclear.

In each of the flame height chapters, I ask the question. What is flame height in a pure litter bed on a worst case day? After reviewing accessible McArthur writings, I am unable to answer this question. I try the McArthur Meter , but it does not distinguish a litter bed only forest. I can interpret that it might be 5 or 10 t/ha fuel load. When I apply severe weather, say FDI 100 to 5 and 10 t / ha, the Meter tells me flame height is 6m or 14m respectively. But I cannot accept either as credible.

Is this finding useful? No, definition is unclear

(2) Flame length

McArthur disregards the Byram - flame length equation, even though it derives from a litter bed in pine forest in southern USA. **Flame length (m) = 0.0775 x BFI^0.46** Instead, he calculates fire intensity and matches it with observed flame height rather than calculated length.

For example, Luke and McArthur (1978) quote a medium intensity fire as ROS = 13.7 m / min (= 0.23 m / sec = 0.82 kph) in 17.5 t/ha (1.75 kg / sq m) and a flame depth of 27m and flame height of 15m. They do not quote BFI, but it calculates to 6500 kW / m (= 16,000 x 1.75 x 0.23). Byram's equation calculates flame length as 4.4m. [Note: Luke and McArthur (1978) use H = 16,000 kJ / kg]

They quote a fully developed crown fire as ROS = 30 m / min = 0.5 m/sec = 1.8 kph in 25 t/ha (= 2.5 kg/sq m) and a flame depth of 60m and flame height of crown fire, ie, 20m+. They do not quote BFI, but it calculates to 20,000 kW / m (= 16,000 x 2.5 x 0.5). Byram's equation calculates flame length as 7.4m

They also quote a low intensity fire as 450 kW / sq m, which has 1.2m flame height and 2.7m depth. Byram's equation calculates flame length as 1.3m.

Figure 29 shows that the difference is substantial. It is tempting to think that Byram's line refers to litter bed flame and McArthur's line refers to multi-layer flame height. But no such statement is ever made.

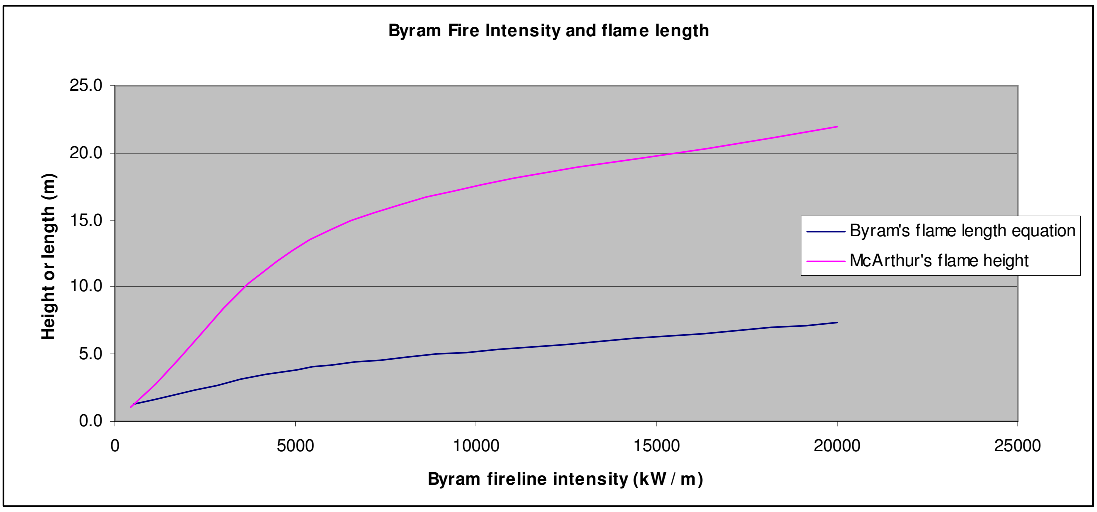


Figure 29 McArthur's flame height observations compared to Byram's flame length equation. Flame height = 5.4*Ln(BFI) – 32 Flame length =1.67*Ln(BFI) - 9.4

Is the finding useful? No because BFI is not an independent variable

(3) Effect of wind velocity on flame height

McArthur is possibly using ROS as a proxy for wind speed in his flame height chart which uses ROS (which is a dependent variable) along with fuel load to calculate flame height. Figure 30 re-orders McArthur's data to plot flame height against wind speed as the true independent variable. It shows that for a given ROS, flame height increases parabolically with wind speed. It raises the question - how can a flame front maintain a constant ROS as wind increases and flame height increases? If the fuel bed remains the same, it cannot. If FMC decreases, ROS would also increase. Therefore this chart and its parent chart must be flawed. See (5) below.

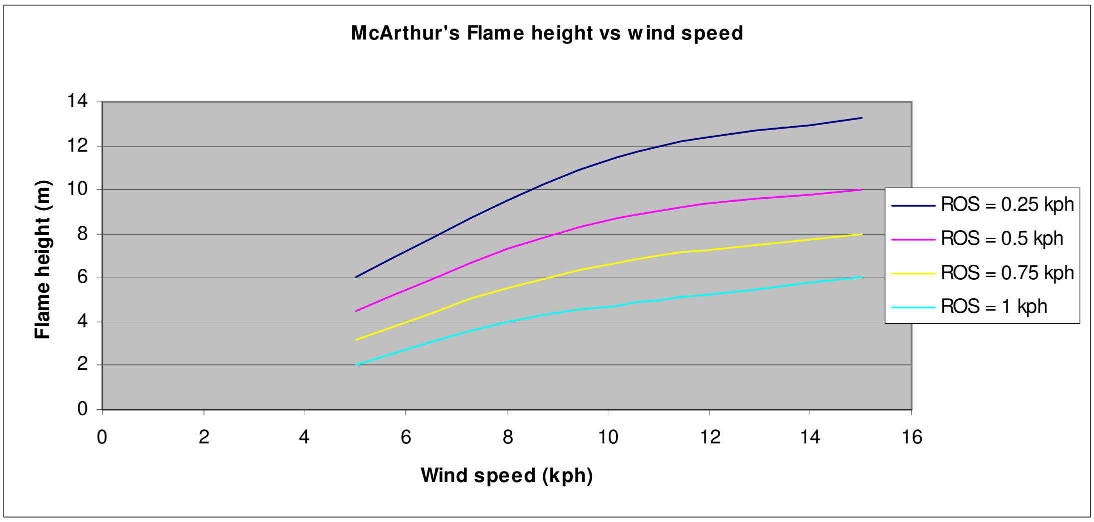


Figure 30 This is a re-ordered version of Fig 6.15 (Luke and McArthur (1978) with wind speed on the X axis. What causes ROS to reduce at a given wind speed in a given fuel bed? The likely answer is higher FMC. But this contradicts lab findings of Roth and Anderson

By comparison, the expected effect of wind speed on a litter flame height in a litter bed, as deduced from Rothermel and Anderson (1966) data in Figure 31, is a slight increase with wind speed when wind exceeds 1m/sec.

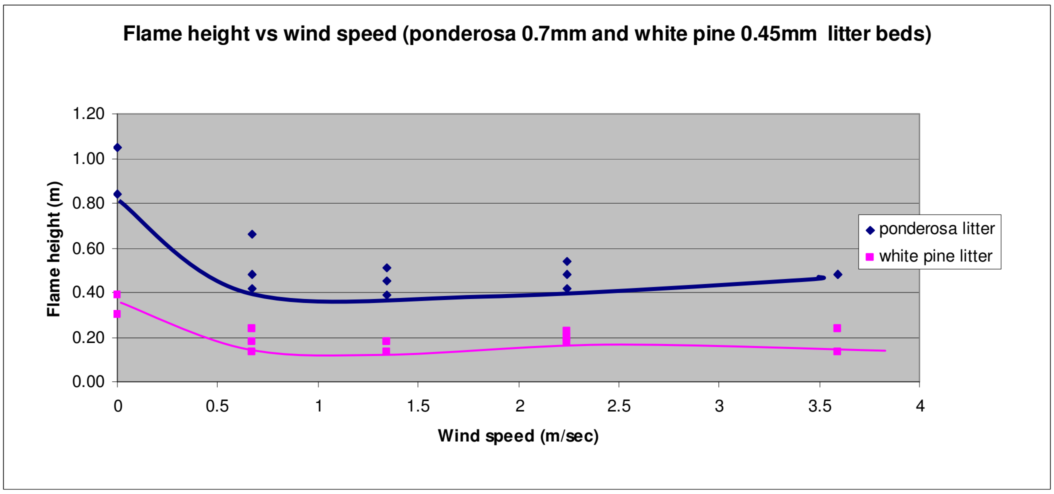


Figure 31 Data from Rothermel and Anderson (1966). For a given wind speed, highest dot is lowest FMC

Is the McArthur finding useful? No. The shape of the re-ordered chart is more consistent with known flame height theory that air flow has a direct influence on peak MLR, which in turn generates taller flame in mat fuel beds at ground level. But the stratification would appear more accurate if it was by FMC rather than ROS. Then, the tallest flame height would correspond with the lowest FMC. But on this chart, the tallest flame corresponds with the lowest ROS, which suggests a higher FMC. Thus there are too many contradictions.

(4) Effect of fuel moisture content (FMC) on flame height

McArthur (1962) identifies two types of fuel moisture content and assigns them different influences. One is the combination of temperature and RH. It determines the equilibrium FMC of fine fuel particles (this section). It can be deduced that McArthur (1962) used this correlation $\mathbf{FMC}^{-2.44}$

The other is time since last rain and rain amount. It determines available fuel load after recent heavy rain (see section (6)). These theories are the basis for fuel reduction burning, and they are incorporated into the McArthur Meter.

McArthur's 1962 leaflet presents a comprehensive description of McArthur's input variables for flame height. In this leaflet, he is concerned about predicting maximum flame height for low intensity fuel reduction burns so that scorch height can be managed. The maximum flame height he deals with is 3.6m. The maximum FMC he deals with is 6%.

Is the McArthur finding useful? Not really. The inverse correlation conforms to known theory, but its accuracy needs testing. Recent flame height research says that when high moisture fuels pre-heat, MLR increases initially without flame action because water vapour evaporates first. When fuel particle begins to release volatile fuels, flame action can start.

(5) Effect of rate of spread on flame height

McArthur's 1967 paper presents his Fig 12 chart showing flame height as a function of rate of spread and wind speed. Same chart is repeated in Luke and McArthur (1978). I now reproduce his chart in Figure 32.

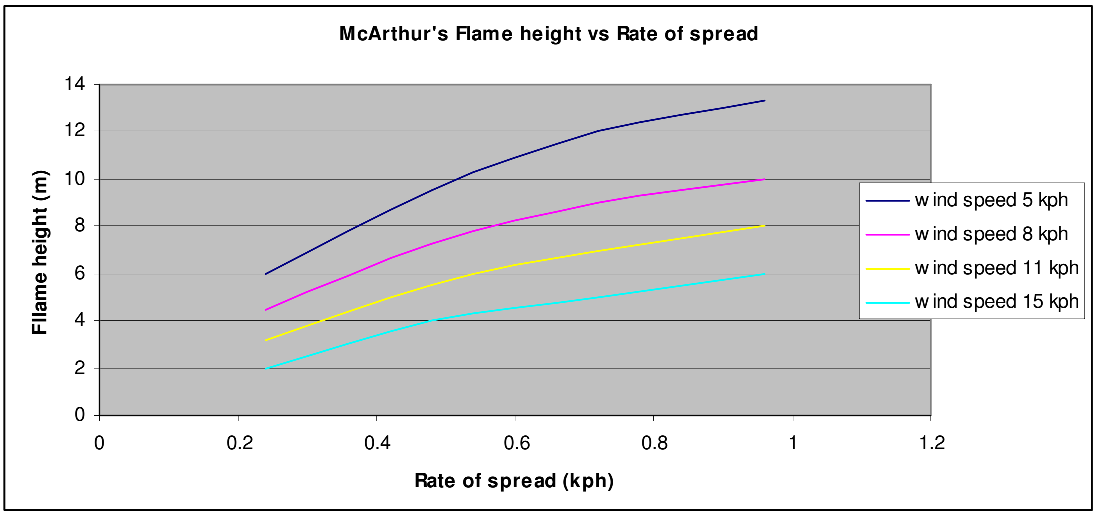


Figure 32 Chart extracted from Fig 12 in McArthur (1967) and repeated as Fig 6.12 in Luke and McArthur (1978). Wind speed is at fuel bed level. Fuel load is constant – 20 t / ha.
For a given wind speed, flame height increases as ROS increases
How can ROS increase if wind stays constant? FMC must decrease
For a given ROS, flame height increases as wind speed increases
How can a flame front maintain a constant ROS as wind increases and flame height increases? If FMC decreases, ROS would also increase

The McArthur chart shows that flame height has a parabolic correlation with ROS and he concludes that flame height reduces as ROS increases because high winds prevent crown fires. But he is seriously incorrect on two levels. Firstly, he presents ROS on the X axis, but it is not an independent variable. I am also concerned that this error has now been has been emulated in peer reviewed publications by recent researchers.

Secondly, the format of the chart suggests rate of spread has a causal influence on flame height, but this probably only applies in short litter bed fires, not in 10m flames.

Nevertheless, McArthur (1967) used this chart to explain why crown fires were uncommon in the Hobart bushfire. He said the stronger wind prevents crowning by keeping the flames height low. But he was totally incorrect. What the chart shows is that to maintain the same flame height, the wind has to blow harder. What causes flame height to reduce if all other input factors are constant? FMC must be higher. McArthur had forgotten his own theory of five years earlier that there are two input variables that contribute to flame height at a given wind speed – fuel load and FMC. Because his Fig 12 chart is for a fixed fuel load, about 20 t / ha, the only input variable remaining is FMC. This is the true meaning of McArthur's Fig 12.

The expected effect of ROS on a litter flame height in a litter bed is reproduced from Rothermel and Anderson (1966) data The encircled dots are zero wind speed. Figure 33 shows that ROS had no influence on flame height.

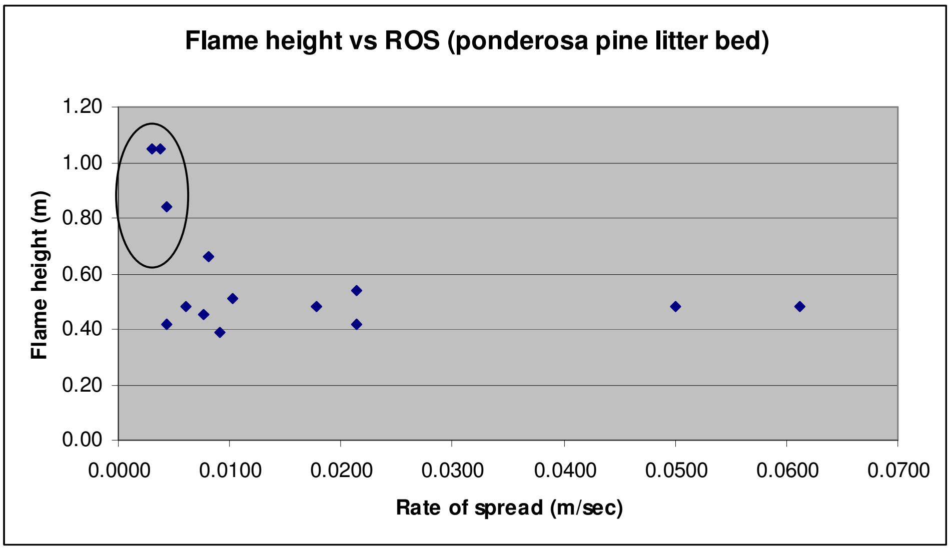


Figure 33 Data from Rothermel and Anderson (1966).

Is the McArthur finding useful? No, it wrongly assigns ROS as an independent variable. Fuel bed flammability is the independent variable that influences two dependent variables - rate of spread and flame height. The dependent variable ROS has no causal correlation with flame height, but they may be coincidentally related.

(6) Effect of fuel quantity on flame height

McArthur lists fuel load as an influence on flame height. It can be deduced that for higher intensity fires in Figure 32, the approx correlation with flame height is fuel load to the ¾ power. **Flame height = 0.55 x fuel load $^{0.75}$ x ROS $^{0.5}$**

Is this finding useful? Not really, because flame height theory links flame height to peak mass loss rate, not total fuel load.

Effect of shrub layer on flame height

McArthur is aware that ladder fuel contributes to flame height, eg, says a litter bed forest will not produce a crown fire because of the large gap between ground and crown, but rough barked eucalypts with a well developed shrub layer will crown when FMC <4%.

Is this finding useful? Qualitatively

Influence of recent rainfall on available fuel load
Flame height theory says that ignition is delayed as fuel particles evaporate water vapour, but flame height is not necessarily reduced

McArthur's (1962) theory is that recent rainfall causes less fuel to be available for combustion. He includes a table that converts days since rain into net available fuel load. For example, if 12.5 mm of rain falls on day zero, after 1 day, 35% of fuel load will burn, after 3 days, 70% will burn and after 5 days, 90% will burn.

Is this finding useful? Not really. The concept of fuel load not burning due to recent rain has no backing evidence and has dubious scientific merit (O'Bryan 2005). Besides, there may be other reasons. Eg, Rothermel and Anderson (1966) found that less fuel per unit area burns in litter layer as wind speed increases.

(7) McArthur's prediction system
McArthur Meter estimates flame height from fuel load and FDI, which is a combination of four independent variables, temperature, RH, wind speed and slope. At low FDI, doubling fuel load triples flame height. At high FDI, doubling fuel load increases flame height by 2.4.
When FDI is low and fuel load is constant, flame height doubles as FDI doubles. When FDI is high and fuel load is constant, flame height increases by approx 1.7 times when FDI doubles. McArthur provides no explanation.

The Meter's highest specified flame height is 14m, and taller flames are unhelpfully labelled "crown fire". Noble et al's (1982) peer reviewed equation compounds the misunderstanding. It calculates flame height precisely from the Meter using rate of spread and fuel load, even though the Meter's correlation between flame height and rate of spread is coincidental, not causal, and even though ROS is not an independent variable.
Flame height (m) = 13 x ROS (kph) + 0.24 x fuel load (t/ha) - 2
This equation is now used to fearlessly calculate flame heights of 50m or more, well above its true design capability of 14m, by extrapolating ROS above McArthur's 3 kph and fuel load above his 25 t/ha. The embedded contradiction is that when fuel load is held constant, the formula suggests flame height is directly proportional to ROS, yet in McArthur's Fig 12, it is parabolic.

Flame heights on the Meter are extremely high for forest fires that are derived from litter bed fires. For example, 5 t / ha fuel load predicts 3.5 m flame height at FDI 50 and 6 m flame height at FDI 100, yet such a low litter bed load would barely reach 1 or 2m flame height in very severe fire. Another example is the 12.5 t/ha loading, which is the Meter's designer forest - tall forest with predominantly litter and scattered understorey. The prediction table shows that flame height at FDI 30 is approx 6.5m, and at FDI 50 is 11m. Again, litter bed alone generates flame at a fraction of this height. I therefore cannot deduce what McArthur's predicted flame height is based on, but I assume it includes an unknown allowance for shrub height.

Is the McArthur finding useful? Not really. The predicted flame height is not obviously rooted to litter bed as the base, and seems to have an unknown factor for presumed rather than actual shrub height.

(8) Residence time

McArthur seems to regard residence time as equivalent to burnout time, ie, the time for the litter flame to self extinguish. McArthur and Cheney (1967) define available fuel as the quantity that burns during the burnout time. McArthur's burnout time is the sum of the flash flame phase and the longer smoulder phase.

McArthur regards a nominal residence time for each 10 t / ha consumed of eucalypt litter fuel is around 60 sec. His records include:
For 20 t / ha fuel load, Tr = 120 sec (McArthur, 1967).
For 25 t / ha litter, Tr = 178 sec (McArthur and Cheney, 1966)

Is the McArthur finding useful? Not really. Residence time needs to be ties with flash flame phase and peak MLR phase

(9) Combustion rate = Heat release rate (HRR)

McArthur (1967) provides measurement of HRR for loosely packed litter (10 t/ha) – 1011 kW/sq m for FMC 3%, 602 kW/sq m for FMC 5% and 250 kW/sq m for FMC 10%, but does not relate it to flame height. Nor does he identify it as average or peak HRR.

Is the McArthur finding useful? Not really. The definition of HRR as peak or average is missing

Summary

McArthur believes flame height is influenced by FMC, available fuel load and rate of spread, which he probably regards as a proxy for wind speed. He presents negligible data. His Meter predicts total flame height. He does not identify flame height by layer or the interaction between layers. In this regard, the basis of his flame height predictions is a mystery. His explanation that canopy fires are prevented by strong winds keeping the tilted flame low is shown to be incorrect.

His work is unable to answer to my first question - What is flame height in a pure litter bed on a worst case day? I cannot find anywhere what flame height will be on a severe day in a litter bed forest and what its residence time is. Nor can I find anywhere how to estimate additional flame height due to shrub layers and ladder fuel in eucalypt forest and what its residence time is.

His work leaves me struggling with the second question - What are the influencing variables and which ones can we manage to control flame height? Fuel load is the only variable mentioned, but its precise influence is not defined.

In short, the McArthur prediction model is technically unhelpful with regard to flame height.

Chapter 6 Project Aquarius – flame height

Only one flame height record was reported during the Aquarius study in the following narrative - 28 February 1983, FDI of 14.
"Shortly after ignition the fire averaged 7080 kW per metre of fire front (kW m^{-I}) over a 7 minute interval and travelled at more than 1300 metres per hour. Flames were commonly 5-6 m high, intermittently extending into the tree crowns more than 25 m above the ground, and numerous spot fires were ignited up to 300 m down-wind of the head fire" (Budd et al, 1997)

A rule of thumb approximation for Byram's Intensity can be used, as follows:
BFI = 500 x W x ROS, where BFI = kW / m, W = t / ha and ROS = kph.
This means a 7000 kW / m fire produced a 6m flame and the consumed fuel load for this fire was estimated at 11 t / ha. This relatively low fuel consumption refreshingly corresponds with the later Burrows and Vesta findings about partial fuel load consumption during the wind driven tall flash flame phase. For example, Burrows (1999) uses the Andrew bushfire as a data point, which McCaw et al 1992) quote as 9 t / ha fuel consumption, ROS 1 kph and flame height up to 6m. Byram's intensity calculates as 4,500 kW / m. Vesta's (2007) Fig 6.21 shows their highest intensity BFI = 8300 kW / m had a 14m flame length. This indicates W = 8300 / (500 x 1.2) = 13.8 t / ha consumed.

Figure 34 presents pictures that were taken around the Aquarius era – reproduced in Burning Issues: Sustainability and Management of Australia's Southern Forests by Mark Adams and Peter Attiwill, CSIRO Publishing, 2011. They are shown here to demonstrate how correct application of consumed fuel leads to reasonable calculations of Byram's fireline intensity, and to show how forest flame heights may visually correspond with BFI. Of interest to me is the relatively low fuel consumption in each, which refreshingly corresponds with the Burrows and Vesta findings, and the wide divergence of flame heights or lengths for similar calculated BFI's, which indicates how poor a predictor BFI can be.

Plate 2. Fire burning with an intensity of 1000 kilowatts per metre; the flame height is 1–2 metres, and the rate of spread is 0.2 kilometres per hour. This intensity is about the limit for suppression by ground crews using hand tools (photo: AG McArthur, Blackmountain, ACT).

Flame ht 1 – 2m

A BFI = 500 x W x ROS Therefore, W = 1000 / (500 x 0.2) = 10 t/ha

Plate 3. Fire burning with an intensity of 2500 kilowatts per metre; the flame height is 4–6 metres, and the rate of spread is 0.4 kilometres per hour. This intensity is about the limit for suppression by bulldozers and aircraft (photo: NP Cheney, Nowa Nowa, Victoria).

Flame ht 4 - 6m

B BFI = 500 x W x ROS Therefore, W = 2500 / (500 x 0.4) = 12.5 t / ha

Plate 4. Fire burning with an intensity of 7500 kilowatts per metre; the flame height is 20–35 metres, and the rate of spread is 1.2 kilometres per hour. This intensity is beyond the lim for direct suppression by any means (photo: J Cutting, McCorkhill Block, WA).

Flame ht 20 – 35m

BFI = 500 x W x ROS Therefore, W = 7500 / (500 x 1.2) = 12.5 t / ha

Plate 5. Fire burning with an intensity of 10 000 kilowatts per metre; the flame height is 40 metres, and the rate of spread is 1.6 kilometres per hour. This intensity is beyond the limits for direct suppression by any means (photo: J Cutting, McCorkhill Block, WA).

Flame ht 40m

D BFI = 500 x W x ROS Therefore, W = 10,000 / (500 x 1.6) = 12.5 t / ha

Figure 34 Visual evidence of BFI and flame height reproduced from Adams and Attiwill (2011)

Chapter 7 Burrows – flame height

2.1 Introduction

Burrows recorded flame height systematically in the lab and in the field. His work provides the best yet answer to my question - What is flame height in a pure litter bed on a worst case day? But is unhelpful in answering the second question - What are the influencing variables and which ones can we manage to control flame height?

2.2 Burrows' theories

Burrows explains flame height using three variables. Flame height increases as wind speed and fuel quantity increase and fuel moisture content decreases.

2.3 Burrows' data

Burrows (1999a) lab experiments were done on a 4 x 2 m table with leaves and small diameter twigs (< 6 mm) from a jarrah forest. Bulk density is typically 47 kg / cu m, FMC, wind speed and fuel load are varied respectively as follows: 3-18%, 0 – 8 kph, up to 20 t / ha.

His field trials (Burrows, 1999b) were done in tall forests with predominantly litter fuel bed and sparse low understorey, Young one area had 0.3m shrubs with 10% cover, another area McCorkhill had 0.5m shrubs with 15% cover, and Harrington another had 0.6m (0.2 – 1.5m) shrubs with 20 - 35% cover
He bundled the data together
He assumed that all the fine fuel was consumed by the flash flame phase.
He measured FMC of surface litter at each burn site

Weather: His field trials were up to FDI 25, which is typically, 30^0C 30% RH, 30 kph at 10m height, making fine fuel EMC = 5%. Lower fuel particle dryness could be achieved by 35^0C 25% RH, 15 kph (EMC 4.5%) or 35^0C 20% RH, 10 kph (EMC 4%). His data range has been skewed a little by the McCaw bushfire 43^0C 15% RH, 30 kph at 10m height

(1) Flame height

Burrows lab studies

Backing or stationary fire: The tallest flames are approx 0.6m

Moving fire front: Very few fires have complete details. Some taller flames are traceable. Figure 35A shows that the tallest flame height was 1m, produced in 5 kph winds in 3% FMC fuel bed, when flame spread was 0.17 kph. The average tallest trial flames were approx 0.6m, two of which were generated in low FMC fuel beds with low winds and spread at approx 0.03 kph and the other was generated in 7kph winds in 6% FMC litter, spreading at 0.22 kph.

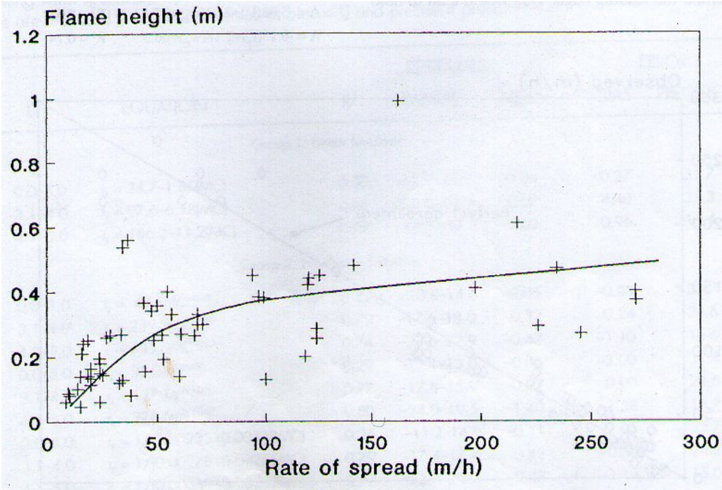


Figure 35A Copy of flame height lab data chart Burrows' 1999a, Fig 7.

Field studies

Figure 35B shows Burrows' flame height – ROS chart. Several of the data points were traceable to FMC. Figure 3 shows that the four tallest flames are approx 6m, which occurred when FMC was lowest (3 and 4%) and wind speed at fuel bed was 6 – 8 kph.

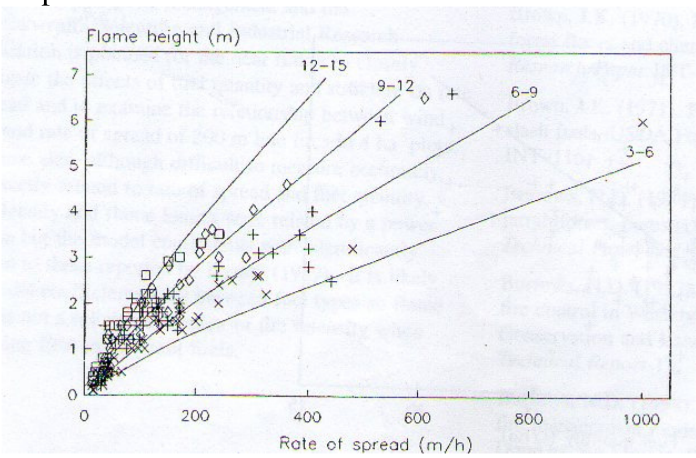


Figure 35B Copy of flame height field data chart Burrows' 1999b, Fig 18. The annotations on each curve refer to fuel load range in t / ha.

The next tallest are up to 4.5m. Several identifiable trial fires are summarised in Table 6

Table 6 Some identifiable trial fires gleaned from Burrows' field trial data

FMC	**Flame height**	**Wind speed**	**ROS**
3	6	8	1
4	6.5	6.5	0.65
4	6.5	6.5	0.6
4	6	6.5	0.55
4	1.5 – 3.5 (2.5)	5	0.2
5	3 - 4.5 (3.7)	8	0.4
5	2 – 4 (3)	7	0.3
7	3	9	0.5
7	2.5	7	0.45
7	4.5	7	0.35

Table 6 shows clearly that the range of flames heights is due to variation in height of shrub layers. It is reasonable to expect that taller flames are due to ladder fuels in tall shrubs and flammable trunks and that taller flame heights eg, 3 – 6m are due to presence of litter bed and shrub layer combined.

In conclusion, Burrows' findings suggest that a bone dry litter bed flame in moderate weather with low to moderate winds can produce a 1m flame height. It provides a partial answer to my question about flame height in a litter bed. Perhaps a flame height of 1 - 2m in a pure litter bed may be a useful rule of thumb on a worst case day.

Is this finding useful? A rule of thumb flame height of 1 – 2m for a pure litter bed in severe weather is useful. It would have been useful to link flame height in field trials to shrub height.

(2) Flame length

Burrows measured flame length from flame tip to mid way along base of flame. In his field trials, he assumes fine fuel load is fully consumed in the flame zone. Using his flame length measurements, he re-calibrates Byram's fireline intensity / flame length equation as follows

Flame length (m) = 0.0147 x BFI^0.767

Figure 36 shows that Burrows' measured flame lengths are taller than Byram's original equation. Burrows' data extends to 3,500 kW/m and 10m flame lengths. He finds that BFI of 3000 kW/m corresponds with flame length of 6m, whereas, Byram found in pine litter bed that the same BFI produced 3m flames.

Data anomaly: Burrows' case study example of the Andrew fire (ROS 1 kph and fuel load 9 t / ha) has a 4 – 6m flame height and BFI is approx 4,500 kW/m. This is closer to Byram's equation than Burrows'.

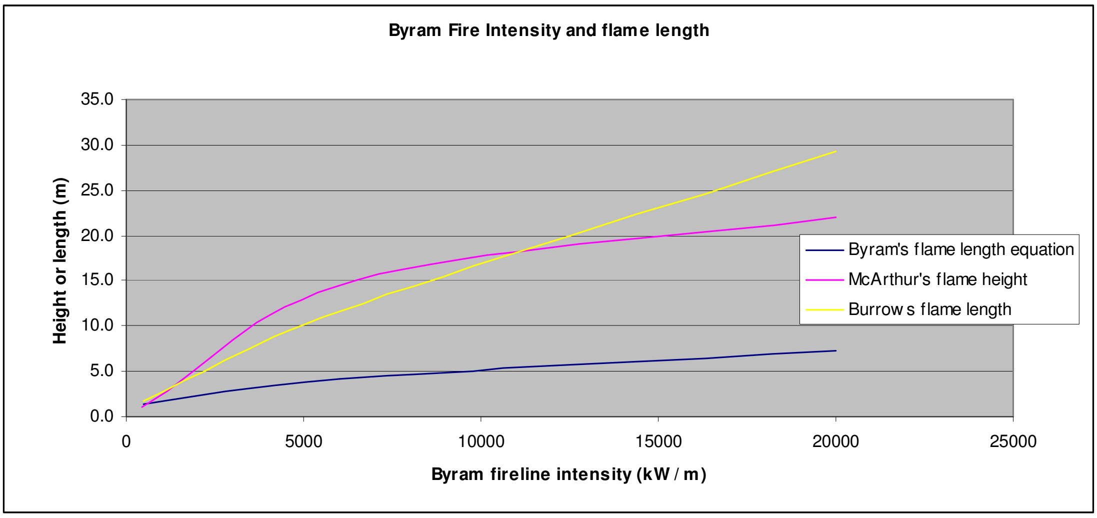


Figure 36 Burrows' measured flame lengths

Is this finding useful? No it is confusing to present an equation that does not match his own data without some explanation

(3) Effect of wind velocity on flame height

No wind

Burrows (1999a) Fig 10 shows that for zero wind and backing flames, peak flame height in the lab is 0.65m, and it has a positive linear correlation with fuel load consumed. I have reworked recognisable Burrows lab data and now plot his flame height data against wind speed, the true independent variable, on Figure 37. It shows tall flame at zero wind and a wide range of flame height as wind speed increases.

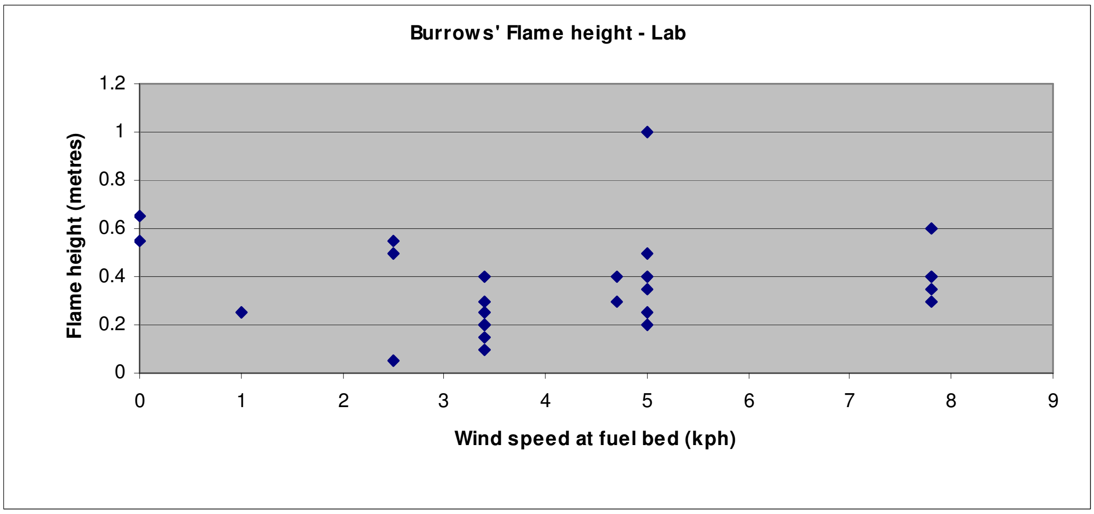


Figure 37

For a given wind speed, the vertical dots indicate that flame height increases as FMC reduces.

Wind

Burrows finds that most variation in flame dimension (length, depth) is due to wind speed. He said because ROS is mainly a function of wind speed and FMC, it can be substituted for them and used with fuel load consumed to predict flame dimension. This may be true for a given FMC, but he does not specify this condition.

I have reworked recognisable Burrows field data and now plot it against wind speed on Figure 38. It indicates a trend that flame height increases with wind speed

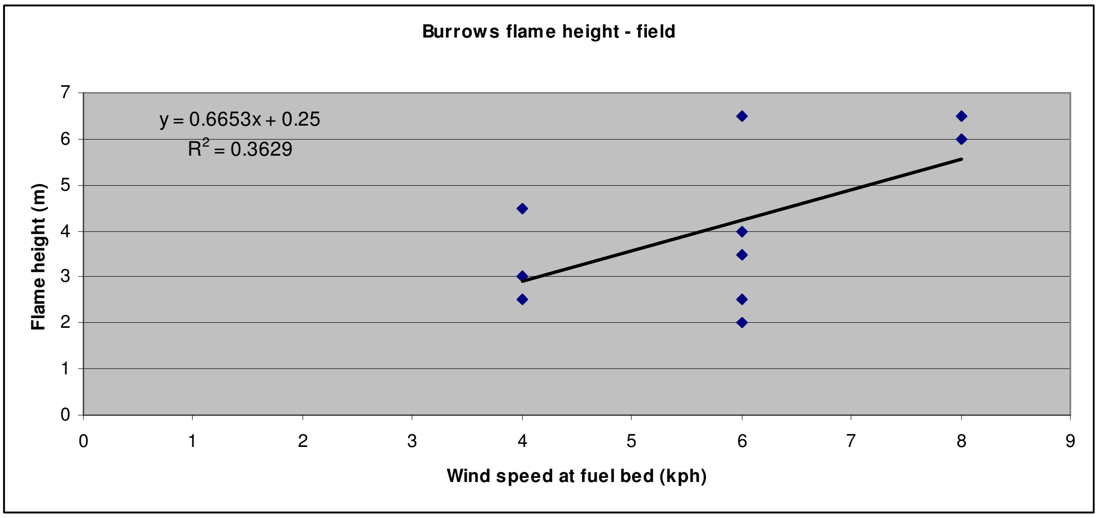


Figure 38 Burrows field data for flame height vs wind speed at fuel bed

Comparing lab and field flame heights for the same wind speed shows an order of magnitude difference. Forest flame heights can be 10 times lab flame heights. The lab fuel bed is pure litter, ie, leaf and small twigs. In field trials, however, the forests are predominantly litter bed with scattered understorey of low shrubs and scattered taller sapling sized shrubs. One forest had up to 30% cover of shrubs up to 1.5m high. The most feasible explanation for the difference is that shrubs and elevated fine fuel in the forest have added extra flame height.

Is this finding useful? Yes it confirms wind tends to increase flame height in a given fuel bed.

(4) Effect of fuel moisture content (FMC) on flame height

Burrows presents no direct link between FMC and flame height. The closest linkage is via the damping effect that is indirectly incorporated into the flame height / ROS equation. **Flame height = 0.062 x ROS ^0.687**

Is this finding useful? No

(5) Effect of rate of spread on flame height

Similar to McArthur, Burrows' plots rate of spread on the X axis and flame height on the Y axis, yet there is no causal correlation. Burrows states that because ROS is mainly a function of wind speed and FMC, it can be substituted for them and used with fuel load consumed to predict flame dimension. This may be true for a given FMC, but he does not specify this condition.

Burrows' lab data charts (see Figure 35A) show that "flame height and length tended to plateau beyond rate of spread of 100 m/hr, supporting the observation that flames were driven across the surface of the fuel bed and that sub strata fuels contributed little to the flame front at higher wind speeds".

In startling contrast, his field data charts show an almost linear correlation (see Figure 35B):

Flame height = 0.062 x ROS ^0.687 Where flame height = metres, ROS = m / hr

Is this finding useful? No because there is no causal correlation between ROS and flame height and the contrast between lab and field findings is too great to confer reliability.

(6) Effect of fuel load on flame height

Burrows (1999b) says the above correlation with ROS is improved with the addition of fuel loading as follows:

Flame height = 3.35 x ROS x W Where flame height = m, ROS = kph, W = t / ha.

This is remarkably similar format to Noble et al's (1980) quantification of McArthur Meter prediction model,

Flame height (m) = 13 x ROS (kph) + 0.24 x fuel load (t/ha) - 2

Despite the similar format, Burrows' equation seems to significantly over predict. Eg, using ROS = 1kph and 10 t / ha fuel load, Burrows' flame height is 33.5m and McArthur's is 12.6m.

However, both these formulae reveal two major problems.

- At a given fuel load, flame height is linear with ROS. The expectation from McArthur's data is parabolic.
- They appear to be inconsistent with Burrows' previous finding that there is no correlation between fuel load and rate of spread when wind speed is above 3 – 4 kph.

Is this finding useful? No because the causal influence on flame height is now known to be peak MLR, not fuel load.

(7) Residence time

Burrows clarifies the distinction between residence time and burnout time. This was a useful advance in knowledge because McArthur's residence time was burnout time, meaning time for flame to consume all fine fuel. Residence time is essentially the duration of the tall flame phase.

Burnout time = tall flame duration + smoulder phase duration.

In the lab, he attempts to define residence time by temperature, but does not specify which temperature. He finds he has to supplement temperature traces with visual observations of end of flame phase and start of smoulder phase. For the moving head fire flame, his chart shows a wide range of residence time for a given fuel load, eg, any fuel load up to 12 t / ha can have a residence time ranging between 5 to 22 seconds. Presumably the scatter is due to FMC.

He finds weak correlations with fuel load for moving flame

Residence time = 1.5 x W + 4.55 ($R^2 = 0.32$)

But stronger correlation for the stationary or backing fire

Residence time = 2.08 x W + 2.42 ($R^2 = 0.77$)

Units residence time = seconds, W = fuel load consumed in t / ha.

In the field, Burrows calculates residence time by dividing flame depth by ROS,

[ROS = flame depth / residence time]

He finds a weak but linear correlation between residence time and fuel load but he has no confidence in it because of difficulties measuring flame depth and other factors. The range of most residence times is 15 – 60 sec.

Burrows' (2001) later systematic residence time study defined residence time as "period of flaming combustion". It extends beyond the flash flame phase to the start of the smoulder phase. His study adds to the bank of knowledge about residence time:

Single particles:

Single round wood fuel particles between 1 and 80 mm diameter):

He finds residence time for one particle to **Tr (particle) = 0.871 x D^1.875**

Units: residence time = seconds, D = mm

Single leaf Average residence time in no-wind for the single dead leaf is 11.7 sec, and the single wet leaf is 12.2 sec. He notes that the wet leaf took longer to ignite, but once alight, the residence time is similar to dead leaf.

[Jarrah leaf averages 0.4 mm thick by 110 x 40mm. He reports the surface are to volume ratio (SAV) is 55. The average dimensions calculate to 50 (= 44 sq cm / 1.76 cc)].

This is equivalent to SAV for 0.8 mm round wood, but clearly, for the same length, the leaf has eight times the surface area.

Fuel beds:

Fuel bed of round wood fuel particles of same size (1 kg over 1 sq m, size between 1 and 80 mm diameter):

He finds residence time for fuel bed is **Tr (bed) = 7.36 x D^1.236**

Units: residence time = seconds, D = mm

Fuel bed of dead leaf litter (1 kg over 1 sq m): Average residence time in no-wind and the dead litter bed of leaves and small twigs is 33 seconds.

The litter bed residence time is equivalent to a 1 kg of 3.5 mm diameter twigs on 1 sq m bed. It is of interest that the residence times of the 3.5 mm twig and the bed of such twigs are very similar to the leaf and the bed of leaves – one twig is approx 10 sec and a bed of 3.5 cm twigs is approx. 33 sec.

Is this finding useful? Yes the systematic study is of interest

(8) Mass loss rate Combustion rate

Burrows' 1999 reports, as does McArthur's data before him, use fuel load or fuel load consumed as the indicator for flame height. They do not link flame height to combustion rate or mass loss rate, despite consistent contemporary findings of a correlation. In a later paper, Burrows (2001) records mass loss rate, but frustratingly does not record corresponding flame height.

Burrows (2001) presents mass loss rate data for a bed of jarrah leaves and twigs < 2 mm diameter in his Fig 5, now reproduced in Figure 39. The shape of Figure 39 reflects the method of ignition. Burrows sprays the entire fuel bed with flammable fluid to ensure ignition is simultaneous. This explains the sudden and continuous fall in weight. The entire fuel bed is weighed. Burrows shows that flaming combustion in a no wind fire consumes 75% of the mass of leaves. Initial fuel load is 1 kg / sq m (= 10 t / ha). FMC is 5%.

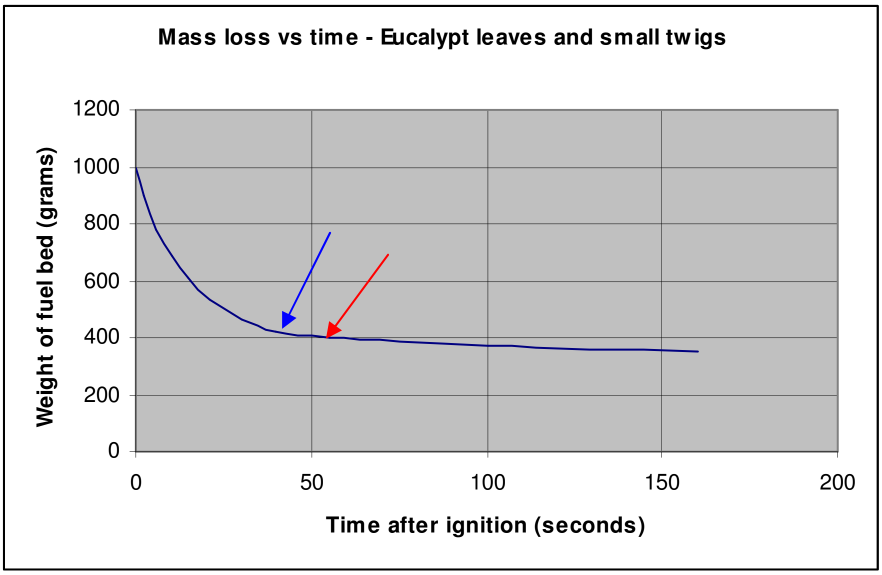


Figure 39 A reproduction of Burrows' (2001) Fig 5, complete with his notations – flame dying (blue arrow) and flame out (red arrow). The fuel load is 1 kg / sq m and fuel bed depth around 3cm. There is no wind.

As later research links flame height to peak MLR, Figure 39 is now converted into mass loss rate vs time in Figure 40.

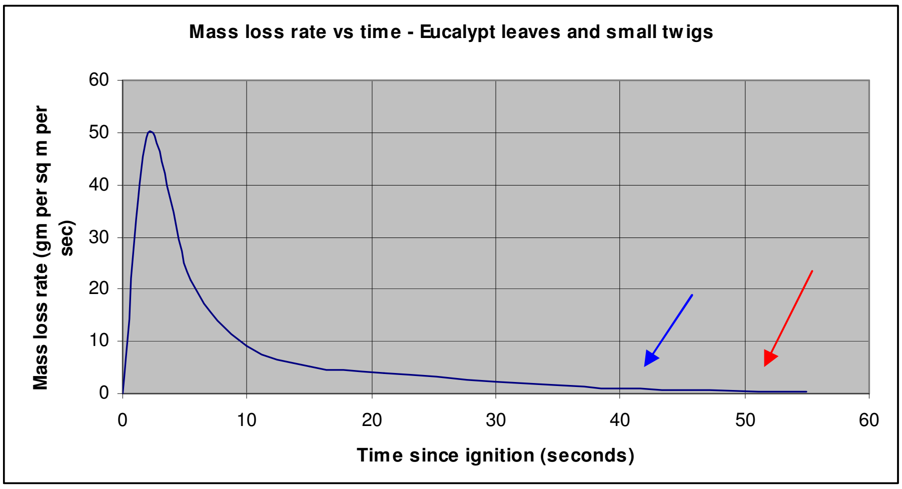


Figure 40 Conversion of Figure 39 into mass loss rate

The peak MLR of 50 gm / sq m / sec converts to a peak HRR of 900 kW / sq m. This is a no-wind flame, so we can expect that peak HRR is high because the entire fuel bed depth contributes to flame height. Unfortunately, Burrows (2001) does not link peak HRR to flame height, nor provide a description of flame height over time.

Burrows also measures average MLR for round wood between 1 and 80 mm diameter: **Average weight loss per 1kg of fuel = 37 x D^-0.910**
Units average weight loss = gm / sec, D = mm
Unfortunately, Burrows does not link average MLR to peak MLR.

Average weight loss ranges from 40 gm / sec for a bed of 1mm diameter twigs to 2 gm per sec for a bed of 20 mm diameter rounds. Burrows finds the average mass loss rate for the litter bed is 17.1 gm / sq m / sec, range 11 – 20. This is approx 34% of peak MLR.

Is this finding useful? The bushfire manager has nothing new to build on because flame height has not been linked to peak MLR.

Summary

Like McArthur, Burrows believes flame height is influenced by FMC, available fuel load and rate of spread. His lab study finds flame height is independent of ROS, but confusingly, he regards field data as different and uses ROS as a proxy for wind speed plotting flame height against ROS, stratified by fuel load. His data is contradictory.

His work partially answers my first question - What is flame height in a pure litter bed on a worst case day? I make an informed guess at flame height on a severe day in a litter bed forest. There is no advice about estimating additional flame height due to shrub layers and ladder fuel in eucalypt forest.

His work provides little help with the second question - What are the influencing variables and which ones can we manage to control flame height? Fuel load is the only variable mentioned, but findings are too contradictory to be helpful.

Chapter 8 Vesta – flame height

2.1 Introduction

Vesta research is targeted at ROS, but some flame height studies are done. Vesta conducts field trials only. Their work is unable to answer my first question - What is flame height in a pure litter bed on a worst case day? And is unhelpful with the second question - What are the influencing variables and which ones can we manage to control flame height?

2.2 Vesta theories

Project Vesta adopt Cheney's 1990 theory, confirmed by Burrows, whereby the moving fire spreads by burning across the top of a fuel surface and then downwards into the fuel bed. Thus there are potentially identifiable parts of the fuel bed, eg, parts that contribute to flame height, to flame depth, to smouldering, and that do not burn.

2.3 Vesta data

Published Vesta data about flame height is provided as output results in charts with rare complete descriptions of respective input data. The most complete sets are given in the spotting studies of Chapter 10 and the associated Appendix VIII, not reproduced in Table 7.

Six fires were conducted over two successive days in the Dee Vee forest. Weather conditions for duration of fires were similar:

Temperature 23.5 and 25.2,
RH 40% and 37%
Wind speed at 10m 16.2 and 12.7 = in forest approx 4-5 kph
FDI 10 and 12
FMC 6 and 6.2%

Table 7 Comprehensive flame height data from Project Vesta (2007)

Fire No.	Fuel age years	Likely initial fuel load* t / ha	Estimated fuel consumed ** t / ha	Bark depth consumed *** mm	Mean rate of spread **** kph	Estimated mean flame height ***** m	Maximum flame height **** m
J	3	9	3.3		0.38	0.5	0.7
D	5	12	10.5	5.4	0.52	3 - 3.5	6
F	22	16	13.1	11.5	0.8	4	6
B	3	9	4.7		0.39	1.5	2
H	5	12	11.3	5.7	0.72	3 – 3.5	5
M	22	16	12.2	11.8	0.72	4	8

NOTES:
* Estimated from Vesta Fig 3.4 – surface and near surface
** Estimated from Vesta mean intensity / mean rate of spread in Table 10.3
*** From Table 10.4. Vesta also estimates that in older fuel, bark consumption is 5 – 8 t / ha
**** From Table 10.3
***** Estimated from Fig 6.18. Vesta notes that most fires had ratio of maximum ROS to mean ROS of 2, but some fires exceeded 3.

Fuel bed height was not recorded, yet it represents pyrolysis height, one of the two influential variables for flame height.

2.4 Vesta findings

(1) Flame height

Vesta measures height as follows (p 75) – they “noted the head fire flame characteristics every two minutes. The flame height was estimated mean vertical height of the flames over the two minute interval and does not take into account the occasional higher flame flashes. Figure 6.18 and 6.19 shows mean flame height for each fire spread interval and the minimum and maximum observed flame height noted for each fire plot”. Each data point has an average ROS and average flame height with ranges. I re-produce this data scatter in Figure 42 (below).

Vesta has developed an equation for flame height that applies to shrubby forest.
Flame height = 0.0193 x ROS^0.723 x exp (0.64 x Ef) Where **ROS** = m/hr, and **Ef** = elevated fuel height (metres)
In each chapter, I ask the question. What is flame height in a pure litter bed on a worst case day? If there is no shrub fuel, there is no elevated fuel height, therefore the exponential function becomes 1 and flame height is determined by ROS. Therefore, to answer the question, I need to know ROS. Thus if ROS = 1 kph, flame height = 2.8m.
If shrub height is 1m, Figure 41 shows the multiplier is 1.9, therefore flame height = 5.3m (= 2.8 x 1.9)

Is this finding useful? Not really, because it cannot be estimated without knowledge of ROS, which is a dependent variable and there is no causal correlation between ROS and flame height. It cannot be confidently compared with the flame height data of Table 7 (above).

(2) Flame length

Project Vesta (2007) plots flame height against Byram’s fireline intensity, not flame length. Burrows (1999b) defines flame length = 1.33 x flame height. Byram’s equation concerns flame length. I reproduce Vesta’s Fig 6.21 in Fig 41.

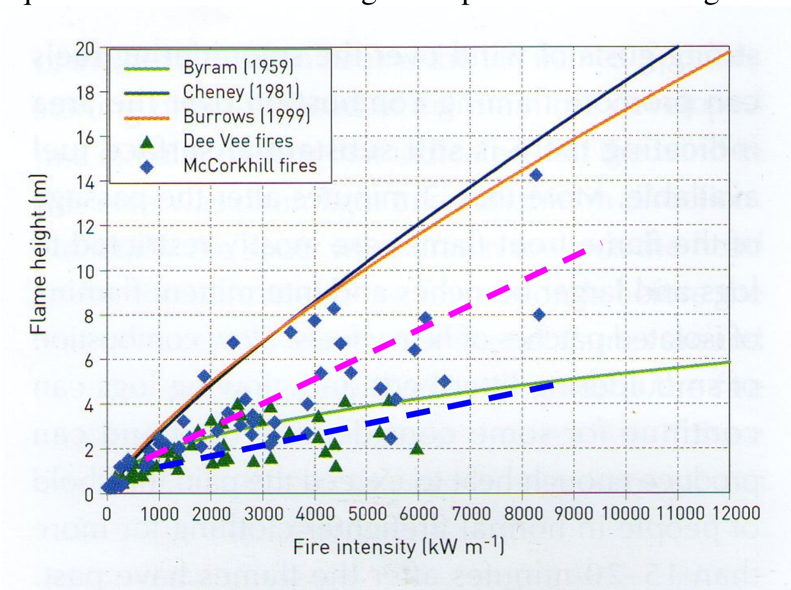


Figure 41. Copy of Vesta’s Fig 6.21. Peak BFI is 9,000 kW/m with peak flame height of 14m. The pink dashed line approximates the trend line for McCorkhill data and the blue dashed line approximates the De Vee data

When the wide scatter of Figure 41 is observed, this statement in the Vesta report seems to be unsupported: "The results of the correlation analysis showed that mean fire flame height was significantly correlated with … Byram's fireline intensity" (correlation value 0.73).

There is a wide scatter. There is no discernable correlation. The Dee Vee data tends to fall along and below Byram's flame length equation, and most of the McCorkhill data scatters in between Byram's and Burrows' equations. The upper limit of data points rarely exceeds Burrows' flame length vs BFI equation. Based on these data points, I estimate the pink dashed line on Figure 41 approximates the trend line for McCorkhill (high shrub forest) data and the blue dashed line approximates the De Vee (light shrubby forest) data

Is this finding useful? No, mean flame height has no significant correlation with BFI, and besides, BFI is a dependent variable and an unsuitable predictor.

(3) Effect of wind velocity on flame height

Vesta plots flame height against ROS on Figs 6.18 and 6.19. Because ROS is a dependent variable, I have reworked recognisable data and plotted flame height against wind speed for both sites (see Figure 42)

Combining Burrows and Vesta data shows that most of Burrows field data points fit within the Dee Vee data range of flame heights and the rest are at the lower end of McCorkhill. Burrows work was done in the Dee Vee forest type. Vesta has higher wind speeds but the flame height does not increase. The McCorkhill flame heights are clearly very different data set.

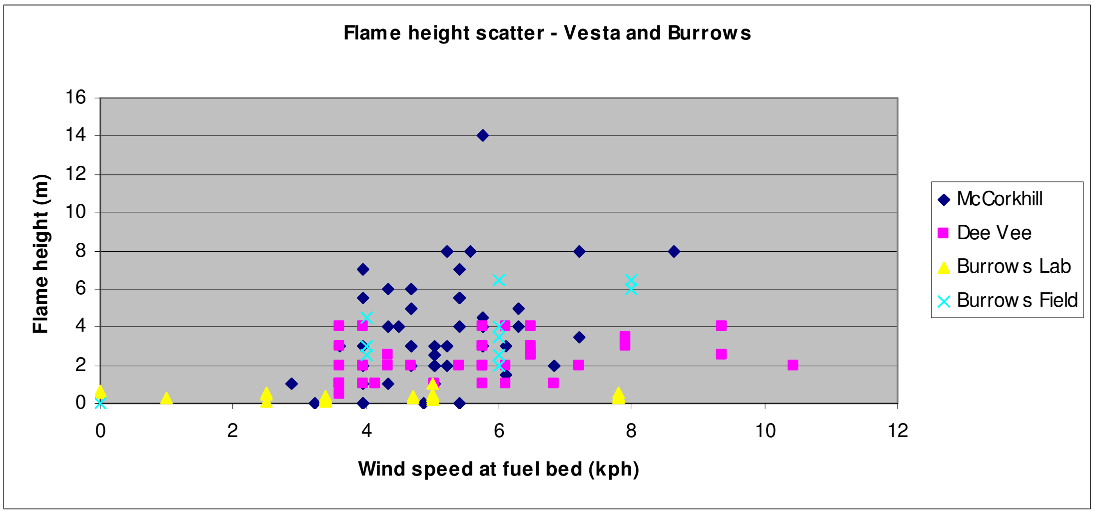


Figure 42 Reworked recognisable flame height and wind speed data from Burrows and Vesta trials

Is this finding useful? Not really, other than the observation that there appears to be no casual correlation between wind speed and flame height.

(4) Effect of fuel moisture content (FMC) on flame height

FMC is a major influence on fuel bed flammability, but Vesta does not examine the effect of FMC on flame height. They assume that ROS takes FMC into account because they believe that flame height and ROS are correlated. But ROS is a poor predictor of flame height because they are not causally related. Section (5) shows that there is a wind scatter when flame height is plotted against ROS.

Most Vesta fire trials are done within FMC range 6 to 9%. Vesta then standardises its data to FMC 7% to remove variability and find other influencing factors. Standardisation uses one of Burrows' five FMC / ROS correlations = FMC $^{-1.49}$, yet he found high correlations for the power range between -1 to -1.56. These correlations were not tested by Vesta. Thus while Vesta believe they are normalising their data to 7% FMC, there is no certainty that it is an accurate conversion. The saving grace of their analysis may be that the variation from a 6 – 9% range to 7% is minor.

After analysis of data at 7% FMC, Vesta then use the untested Burrows' algorithm to estimate ROS and flame height at 3% FMC.

Is this finding useful? No. The FMC correlation was not tested. The companion paper on FMC theory suggest that the Burrows' correlation over predicts the FMC response four fold.

(5) Effect of rate of spread on flame height

Figure 43 now reproduces Vesta's flame height / ROS chart Fig 8.7. Despite the large scatter of flame heights for each ROS, Vesta says (p 75) "The results of the correlation analysis showed that mean fire flame height was significantly correlated with observed rate of spread" (correlation value of 0.67).

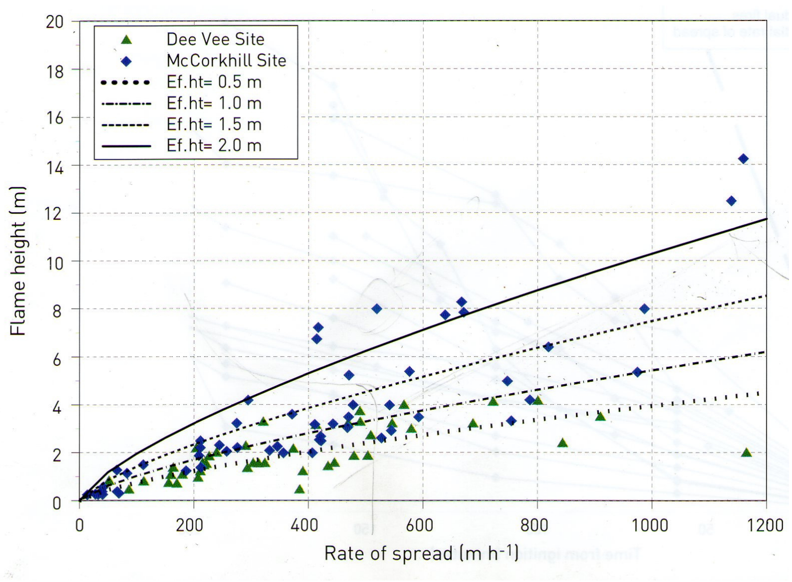


Figure 43 Copy of Vesta's Fig 8.7

The body of flame height vs ROS diagrams is very confusing. If we focus on a flame height / ROS point of say 1.2 kph and 10m flame height, Vesta chart suggests it is due to tall shrub layer of unspecified FMC (Figure 43), Burrows chart suggests it is due to high fuel load (Figure 35B), and McArthur suggests it is due to low wind speed (Figure 23). Yet all charts are similar in scale and shape, eg, starting at zero ROS and zero flame height and peaking at ROS 1.2 kph and up to 8 – 12 m or so flame height. The confusion arises from misunderstanding scientific convention and plotting ROS on the X axis when it is not an independent variable.

Nevertheless, five years later, Cheney et al (2012) re-present this stylised Vesta chart showing the same data points. This chart is reproduced in Fig 45 (below).

Is this finding useful? No because there is no causal correlation between ROS and flame height

(6a) Effect of fuel quantity on flame height

Vesta does not mention any correlation between fuel load and flame height.

(6b) Effect of shrub height on flame height

Vesta (p 101) finds a high level of correlation (0.58 to 0.61) between flame height and near surface (NS) height, near surface hazard (NSH) score and elevated fuel height (El ht), but they present a relationship for elevated height only:

Flame height is proportional to exp (0.64 x El ht)

This correlation is graphed on Figure 44.

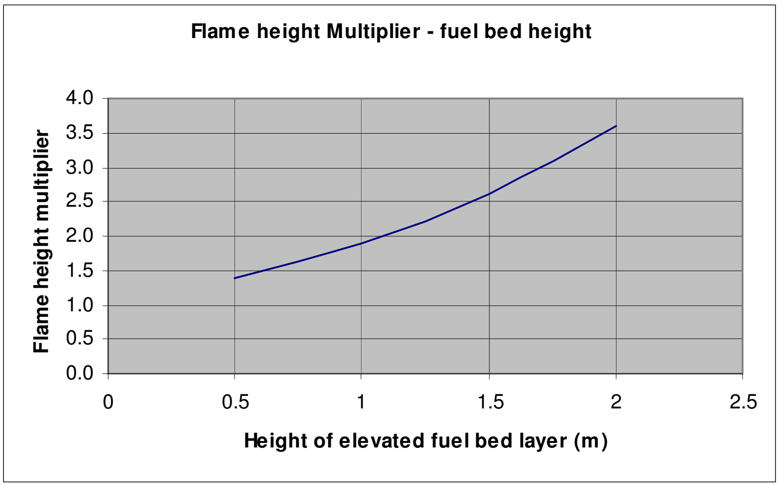


Figure 44 Vesta's elevated fuel height coefficient vs height of elevated fuel bed

The respective flame height multiplier can be read from this Chart. The fuel height data applies to the moderate fire weather conditions. It presumably applies to a mass of shrubs as well as to scattered shrubs. This chart means that in moderate fire danger weather, flame height due to this type of shrub layer is three to four times shrub height. The unanswered question is how much higher will a flame become in severe weather conditions, or will it remain unchanged? Is it six times or ten times shrub height, or is it stable at 4 times? Vesta does not explore this question.

In conclusion, Vesta's unstated theory is that flame height is related to height of shrub layer, all other dependent variables remaining constant.

Is this finding useful? Yes This conforms with pyrolysis height theory

(7) Vesta prediction system

Prediction of flame height

Based on correlation data, Project Vesta (2007) concludes the best predictor of flame height is rate of spread and elevated fuel height.

The prediction formula is **Flame height = 0.0193 ROS^0.723 x exp (0.64 x El ht)**
Units flame height = metres, ROS = m / hr, elevated fuel height = metres

Five years later, Cheney et al (2012) re-present this stylised Vesta chart showing the same data. I reproduce it in Fig 45. It peaks at ROS 1.5 kph and almost 15m flame height. They have included a zero elevated fuel classification, which suggests a peak flame height for the near surface / surface layer of up to 4m.

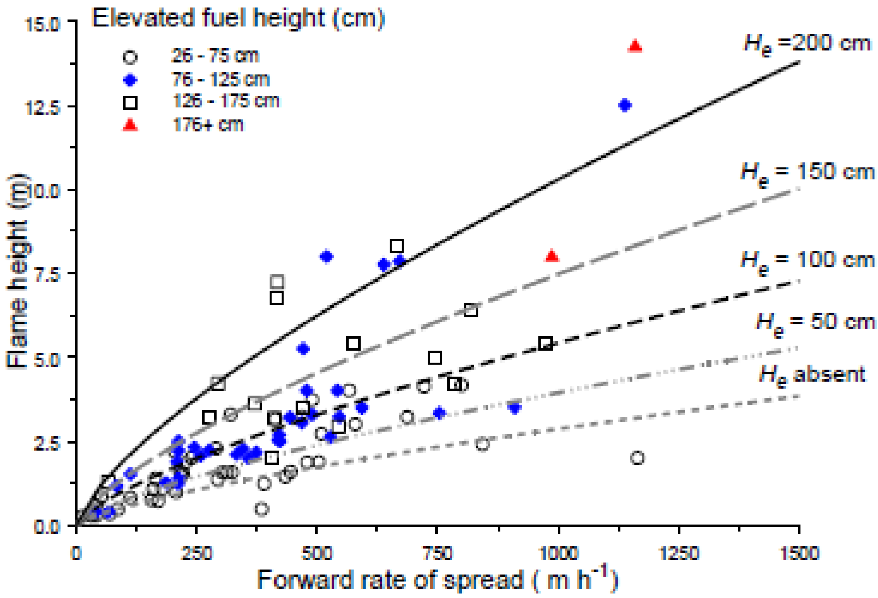


Figure 45 Copy of Figure 7 from Cheney et al (2012)

Their revised formula is **Hf = 0.0193*R^0.723 *exp(0.0064*He)*B3,**
where Hf is flame height (m), R is head fire rate of spread (m h-1) and He is elevated fuel height (cm).
They write: "Flame height is plotted against rate of spread by elevated fuel classes in Fig. 7 with the predicted model overlaid for surface fires, with application bounds *R* ≤ 1500 m h-1 and He ≤ 200 cm. Flame height, although difficult to measure accurately, was related to head fire rate of spread and elevated fuel height. The flame height model predicts reasonably well when flame heights of surface fires are less than 8 m, but not suitable beyond its application bounds of 15 m high flames, or when there is torching or crown fires in the intermittent and overstorey canopies, even in tall elevated fuel structures." (Cheney et al, 2012).

But the prediction has limited application to reality.
Vesta's only predictor variables are rate of spread and elevated fuel height. It does not specify weather conditions, but the model assumes that in severe weather, ROS will increase and therefore flame height rises accordingly. This may happen in some situations, but there are many situations where it does not occur.
It appears to be designed to predict when wind is high and the vertical fine fuel ladder is continuous from ground to upper shrub. It therefore does no allow for prediction of flame height when wind speed is low and vertical fuel is continuous (because it will

predict low ROS and therefore low flame height), when wind is high and there is insufficient surface fuel or ladder fuel or dead fine fuel to ignite elevated layer, and exaggerates the picture when elevated layer is scattered because flame height is in isolated spikes above a low litter bed flame.

Is this finding useful? No. ROS is not suitable as a input prediction variable.

(8) Residence time

Residence time

Vesta's (2007) understanding of residence time is a little confusing. Under the "residence time" heading (p 87), Vesta reiterates their belief that residence time is the period of flaming combustion. They seem to use a thermocouple temperature of 300^0C to define it.

A later publication (Wotton et al, 2012) redefines Vesta's residence time of flaming combustion as the period where temperature exceeds 300^0C at 0.5m height. Flaming residence times are on average 37 sec for both the tall shrub and low shrub sites, despite the differences in fuel load and structure.

Flame duration

Under the "flame duration" heading (p 74-75) of their report, Project Vesta (2007) provide excellent details of flame features at several camera sites. They identify the three phases of the flaming process, based on video evidence - tall flame, short stationary flame and smouldering combustion.

Tall flame phase

The prevailing wind entrains into convection column from behind the tall flames
Bark fuel on trunks ignites some metres ahead of flame face
On all sites, duration of tall flames at camera = 9-13 sec if the fire passes uniformly
On other sites, if violent flame swirls occur or flame stretches from nearby fuel, duration of flame is up to 27 sec

Vesta estimate that the tall flame burns fine fuel less than 2.5 mm. They calculate this using Cheney's formula for a bed of E. sieberi rounds.

Residence time (minutes) = 1.7 x Diameter ^1.686 (diameter in cm)

They say if the flame lasts 10 seconds, this is equivalent to the residence time of a bed of 2.5 mm rounds. Therefore, the flame was produced by twigs less than 2.5 mm and the leaves. They do not verify this statement, eg, they do not estimate what proportion of surface fuel is < 2.5 mm. By contrast, if they had used Burrows (2001) formula for a bed of jarrah rounds, they would have concluded the flame was produced by 1.5 mm rounds.

Smoulder flame phase

After the tall flame passes the camera, flames are pushed low due to down draft winds feeding into the rear of the tall flame.
On all sites, continuous small flames persist for 37 – 74 sec.
From 75 – 127 sec, smoulder phase continues with intermittent flames and receding flame patches
Three minutes after flame phase, flames restricted to logs and larger branches

Fifteen to twenty minutes after flame phase, heat is still too intense for people to bear. Radiation is still above the above pain threshold.

Is this finding usable? Yes

(9) Combustion rate

Vesta does not explore the combustion rate variable

(10) New findings

A Influence of convection updraft

When wind is weak (p 78)

In light winds (< 1 m/sec), wind gust pushes flame onto unburnt fuel bed and then the tall flame causes convection updraft that can block the wind. When it reduces strength, flame height reduces and wind again pushes flame laterally.

When wind is strong (p 123)

Vesta identifies two types of convection cycles that affect flame height as well as ROS – updraft and downdraft. The convection cycles operate below canopy height.
Duration of cycle is 1 – 3 minutes.
Different parts of fire front are in different cycles simultaneously.
(1) Updraft phase - peak flame height, peak longer distance spotting
Features:
Dense dark smoke and vigorous vertical flames
Rate of spread slows
Spotting occurs over longer distances
Strong inflow of air from ahead of the fire,
(2) Downdraft phase - lowest flame height, peak short distance spotting
Features:
Flames are low - leaning forward,
Rapid rate of spread resumes
Spotting ahead vigorously over short distances

When updraft stage reaches a fire break, it either breaks down and wind blows dark smoke and fire brands across or it remains erect and blows no smoke or embers across.

B Flame temperature

Typically, flame tip is 300 - 400^{0}C and maximum flame temperature is 1000 - 1100^{0}C near the base of the flame.
Maximum temperatures observed are similar at the low shrub and tall shrub forests. (1184 and 1098^{0}C) and are typically recorded on flames several metres in height.
Maximum flame temperature is a function of distance down from the flame tip according to this formula:
Flame temperature = 334 – 258 x Ln (Ht / Hf)
Hf = height of flame, **Ht** = height of temp measurement point.

This is different to McCaffrey's (1979) finding that the solid flame core has a constant temperature and the temperature reduction occurs within the intermittent section.

Summary of flame height studies

The value of the body of research in flame height seem to reflect the secondary status it was given. It is essentially of little practical benefit or technical assistance in answering my two or three indicator questions:
What is flame height in a pure litter bed on a worst case day?
What extra flame height is due to elevated fuel bed height?
What are the influencing variables and which ones can we manage to control flame height?

It is very disappointing scientifically and practically that all three research works report charts of flame height vs ROS. The practice indicates scant regard for scientific convention in using ROS as a dependent variable on the X axis, as well as an input variable in prediction equations. It indicates scant understanding of the difference between causal and coincidental correlation. It may well be that ROS and flame height are both useful indicators of fuel bed flammability, but it is incorrect to assume a casual influence between them without solid evidence.

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Appendix 1

RESPONSE TO SUSTAINED ATTACK ON MCARTHUR METER PREDICTION MODEL BY PROJECT VESTA AND SUPPORTERS

The sustained attack on the McArthur Meter prediction model by Project Vesta and its attempted replacement by the Vesta prediction model has been a very sad and avoidable chapter in the history of bushfire management in Australia. This study shows that the core of the McArthur model remains very relevant and the Project Vesta model is currently scientifically erroneous but not irretrievably so. Its true value can be presented when it data is correctly stratified and reanalysed according to the scientific fundamentals of flame spread mechanisms.

The relentless attack by team Vesta has been belittling, inaccurate, scientifically misinformed, exaggerated, selectively targeted, and yet the actions of team Vesta have been disingenuous and misrepresented documented references to support their claim that the Vesta model is the appropriate national prediction system.

Vesta's attack was **Belittling 1**: The McArthur model "designed primarily to predict the behaviour of low-intensity fires for prescribed burning operations" (Cheney et al 2012)
Reason: Belittling because it was designed initially (not primarily) to predict fire behaviour for control burning and to design a scale for fire suppression difficulty, and later extended to general understanding of fire behaviour and with the knowledge of severe bushfire studies, extended (by unexplained methodology) to predict in-forest ROS under influence of short distance spotting.

Vesta's attack was **Belittling 2:** McArthur and Peet committed experimental error (Project Vesta, 2007)
Reason: Belittling because they wish to disparage their efforts

Vesta's attack was **Belittling 3:** The McArthur Meter model is presented as inadequate (Project Vesta, 2007)
Reason: Belittling because, despite some 60 years of constant usage, they chose to condemn the McArthur Meter model instead of scientifically investigating the differences using core fire behaviour.

Vesta's attack was **Inaccurate 1**: The McArthur model has been "extrapolated to predict the full range of expected fire behaviour (from) observational reports of spread of wildfires" (Cheney et al 2012)
Reason: Inaccurate because it is designed to predict ROS of wind driven continuous line of flame within tall forest, but **not** to predict ROS of leap frog spot fire mechanism, and **not** to predict tall flame / piloted ignition mechanism. Nevertheless, many researchers, including Vesta researchers have used it to predict the "NOTS". Surely, the extrapolation fault lies with the researchers not with the McArthur model in this case.

Vesta's attack was **Inaccurate 2:** Vesta states "fuel load is the only fuel characteristic used in Australian fire danger rating systems to predict fire behaviour in

a particular fuel type." "However there is very little published data to demonstrate a direct relationship between rate of spread and fuel load." (Project Vesta, 2007)
Reason: Inaccurate because fuel load is not an input into the fire danger rating system. The McArthur model uses it (as the only fuel variable) along with FDI to predict ROS. McArthur's theory on the correlation between ROS and fuel load was only correct for the zero wind radiation spread mechanism, but incorrect for the wind spread mechanism.

Vesta's attack was **Scientifically misinformed 1**: For the FMC adjustment to be scientifically credible, the spread mechanisms of low and high intensity fires must be the same. (Project Vesta, 2007)
Reason: Scientifically ill-informed because Vesta does not identify spread mechanisms, and has unknowingly amalgamated and extrapolated data from three spread mechanisms

Vesta's attack was **Scientifically misinformed 2**: The early Peet and McArthur models "consistently under-predict by a factor of 2 or more" the ROS of the Project Aquarius and Burrows trial fires. (Project Vesta, 2007)
Reason: Scientifically ill-informed because the McArthur Meter model was designed to predict ROS for the wind driven mechanism. The under predicted fires generally featured high ROS at low wind speeds in shrubby forests, fires whose ROS was due to a different spread mechanism – the tall flame / piloted ignition mechanism.

Vesta's attack was **Scientifically misinformed 3**: Vesta claimed case studies of severe bushfires under-predict rate of spread and fire intensity, but their sole reference is Rawson et al (1983). It included the Deans Marsh fire spread of 10 kph, but described it as a leap frog spot fire. (Project Vesta, 2007)
Reason: Scientifically ill-informed because Vesta disregarded the fact that the McArthur model was designed for wind spread mechanism, not the leap frog spread mechanism

Vesta's attack has an **Exaggerated implication**: Under predicting the Aquarius' and Burrows and Vesta fires implies the McArthur model will under predict all fires. (Project Vesta, 2007)
Reason: Exaggerated because the Aquarius' and Burrows and Vesta fires were an aberration in a specific fuel type at low wind speeds between FDI 5 and 25 along the FDI scale of 1 to 100.

Vesta's attack was **Disingenuous**: McArthur's data "was obtained from fires of very low intensity and there is very little evidence to suggest that this relationship holds true for fires of high intensity" (Project Vesta, 2007)
Reason: Disingenuous because Burrows and Vesta did exactly the same thing to develop their models. Vesta measured ROS in fire trials at high FMC (6 – 9% FMC) and used a FMC algorithm to convert ROS to 3%, without testing the algorithm for accuracy or relevance and without quoting any evidence that ROS data is adjustable using FMC.

Vesta's attack on McArthur was supported by **Misrepresentations**, meaning selective quoting or mis quoting bushfire references to verify their model:
Reason: Misrepresentation of the facts is indicated by the following examples:

- The Andrew fire (McCaw et al, 1992) Vesta quoted the 1.8 kph run for their verification and disregarded the 1kph run. This fire had two fire runs when wind speed was the same but ROS differed. It may be of interest that Burrows incorporated the 1 kph run as part of his data and disregarded the 1.8 kph run.
- The Daylesford fire (McArthur, 1967) Vesta quoted ROS 3.2 kph for their verification. McArthur pointed out that the mother fire front ran at 1 kph ROS through the forest and leap frog spot fire ran at ROS 3 kph..
- The Linton fire (CFA 1999) Vesta quoted ROS 2 kph from unpublished ref, yet original reference and coroner's report shows average ROS 1 kph
- The Berringa fire Vesta quoted ROS 2.5 kph. The report has four periods with different ROS - 1.2 and 4 kph when wind was 30 kph, and 0.8 and 3.2 kph when wind was < 10 kph. The 1.2 kph run was wind driven, the 4 kph run was spot fire driven, the low wind ROS were probably not a wind spread mechanism.

Vesta's attack on McArthur was supported by **Selective criticism**: Vesta understood that the McArthur prediction model relies on fuel load and FDI
Reason: Selectively criticised because they correctly refute the influence of fuel load on ROS in wind driven fires, but they omit to find fault with the FDI concept of combining two very influential independent input variables into one, and thereby denaturing their predictive power, yet FDI is the basis of Australia's fire danger warning system.

In conclusion, the very strange thing about these attacks is that the McArthur model has serious scientific errors, but, apart from his fuel load theory error, they were not exposed by the Vesta critique as such. Instead, they focused on differences between prediction and observation, reasoning that McArthur committed procedural errors by extrapolating from low to high intensity fires and making experimental errors.

Appendix 2
UNBIASED SUMMARY OF FEATURES, FINDINGS, OVERSIGHTS AND ERRORS – McArthur, Burrows and Vesta.

The following section now presents an unbiased summary the features, the findings, the oversights and the errors of each of the research works – McArthur, Burrows and Vesta.

McArthur Meter prediction model
Features:
The first Australian benchmark study of forest fire behaviour in the "McArthur forest"
Findings were presented as charts and observations based on theories, but very few field studies were documented
Detailed benchmark investigations of many severe bushfires, integrating fire behaviour observations and explanations with suppression responses.

Input variables: Wind, FMC, slope, fine fuel load
Output variables: ROS of line of flame, flame height, burnout time, depth, influence of spotting on fire spread
Output product: McArthur prediction model for "McArthur forest", guidelines adjustments for shrub layer and tree height and density.

Scientific findings and revelations
His charts of ROS vs wind speed and ROS vs FMC, and his observations about flame height and spotting issues were revelatory and educational for many decades from the 1960's in Australia.
He extrapolated his findings from low intensity in-forest fires to high intensity in-forest fires using measured ROS of continuous fire fronts. Eg, he used the Daylesford fire to confirm that actual ROS was close to predicted, and he reported the leap frog mechanism spread rate of 3 kph, but made clear it was not predicted by the Meter model.

Scientific oversights
Recognition of tall flame / piloted ignition as a significant in-forest spread mechanism that causes high ROS at low wind speeds.
Misunderstanding of residence time vs burnout time
Failure to emulate his contemporary Thomas and associate flame height with peak MLR and pyrolysis height

Scientific errors
His theory on fuel load was correct for a radiation spread mechanism, but incorrect for the wind spread mechanism, but he held firmly to the belief (without evidence) that ROS was proportional to fuel load in all in-forest fire spread mechanisms.
He assumed the entire fine fuel load contributed to ROS when driven by wind, despite evidence from contemporary research that the faster the wind in a litter bed, the less depth was burnt by the flash flame.
He extrapolated his litter bed findings (high density compact layer) to a different fuel bed type (low density, porous layer) by adding the fuel load of the shrub layer to inflate the ROS prediction

He did this knowing that ROS would be systemically under predicted because an extra 3 t / ha of aerated shrub layer was substantially faster than ROS in an extra 3 t / ha of dense litter bed
Although his prediction model was based on the wind spread mechanism in the McArthur forest (tall forest with litter bed fuel and sparse shrub layer), he
(1) extrapolated it to account for another spread mechanism (short distance spotting spread mechanism) by inflating exponents of FMC and wind speed to account for the booster effect of both on ROS in a secretive and unexplained way.
(2) incorrectly tried to extrapolate it to explain high ROS in shrubby woodland fires by adding shrub load, and he lamented when he could not match actual observations.
He was scientifically incorrect to combine two core influential variables (wind speed and fuel bed dryness) into one (FDI) as a prediction tool.

Conclusion: His findings remain relevant as guidelines for continuous running line of flame in a forest provided they do not exceed their design criteria and they ignore fuel load as an input variable. Now that we know only the top litter layer burns in a wind driven fire, and that flame in a very dry litter bed runs at close to the benchmark 10% of wind speed at fuel bed level, McArthur's prediction model remains very relevant as a guideline for wind driven ROS in forests for all FDI when fuel load is held at 10 t / ha.

Burrows
Features
The first recorded Australian benchmark lab fire trials with litter fuel bed
Input variables: wind, FMC, slope,
Output variables: ROS, flame height, residence time, flame depth

The first recorded systematic field fire trials in tall forests with litter bed and variable shrub height and cover
Input variables: wind, FMC,
Output variables: ROS, flame height, residence time,

Scientific revelations
There are two mechanisms in a litter fuel bed - radiation driven and wind driven
ROS in radiation driven flame is proportional to fuel load and flame height
Wind driven mechanism becomes dominant when wind at fuel bed exceeds 1 m/sec
Only the top 15 – 20mm of litter layer burns during the tall flame phase of a wind driven fire
The flame of a low intensity fire consumes fuel up to 2mm diameter, and a higher intensity fire consumes fuel up to 4mm diameter
Wind pushes flame front rapidly across the surface while the fire front within the litter bed descends slowly.
Wind speed increases ROS and flame depth, which increases local rate of heat and energy generation, thereby increasing supply of volatile fuel which increases flame height. (Thus large flames are a consequence of an increasing ROS, not the cause)
Aerial fuel does not influence ROS of a wind driven fire
Correlation between ROS and wind speed in wind driven flame is linear
Fuel load has no influence on ROS in wind driven flame
Clarified difference between residence time and burnout time

Scientific oversights
Non recognition of tall flame / piloted ignition as a significant in-forest spread mechanism that causes high ROS at low wind speeds.
Failure to investigate unmistakeable bifurcation of ROS chart (Figure 6, Burrows 1999b) as a different spread mechanism
Failure to associate flame height with peak MLR and pyrolysis height

Scientific errors
His fire trials were done in zero wind where he stated the radiation mechanism was dominant and in wind, where he stated the wind spread mechanism was dominant. He found linear and power correlations, both with high correlation coefficients between ROS and FMC and ROS and wind speed, but inexplicably decided on a very high power exponent for wind speed (2.7) and the highest power exponent for FMC (1.5) for his wind spread mechanism algorithm.
He then committed a scientific error by extrapolating his inflated algorithm to very high speed fires under the influence of the leap frog spread mechanism. His inflated algorithm predicted twice the ROS of a well documented bushfire he used as data.
He correlated flame height with ROS which is a dependent variable

Vesta
Features
Significant systematic body of in-forest fire trials in tall forests with litter bed and variable shrub height and cover
Input variables: wind, FMC, slope. Large range of fuel bed variables, including fuel age
Output variables: ROS, flame height, residence time, spotting distance
Output product: Vesta prediction model for all dry sclerophyll forests

Incomplete data records were published

Scientific revelations
Correlation between ROS and wind speed in wind driven flame is linear
Fuel load has no influence on ROS in wind driven flame
In-flame photography
Clarified realistic duration of residence time and burnout time
Insights into spot fire generation, spread patterns and throw distances
Description of cyclical oscillations between in-forest flame spread mechanisms – radiation and wind driven
Useful in-forest wind data

Scientific oversights
Non recognition of tall flame / piloted ignition as a significant in-forest spread mechanism that causes high ROS at low wind speeds.
Adoption of Burrows' FMC correlation without testing or investigation
Failure to associate flame height with peak MLR and pyrolysis height

Scientific errors
They assume that all forest fires are caused by the wind spread mechanism. They would have realised that the benchmark for driest litter beds was ROS is up to 10% of wind at fuel bed.

When they record high ROS at low wind speeds, eg, ROS = 20% of wind speed, they fail to explore the option of another mechanism.
They use input variables that have no traceable causal correlation with ROS, eg, height of low shrub layer
Their algorithm combined all fire trial data and yielded a high ROS that is impossible to occur in-forest
They knowingly verified their wind spread mechanism model with the high ROS of leap frog spot fire mechanism and inflated some in-forest fire speeds.
They correlated flame height with ROS which is a dependent variable