Manual of Bushfire Behaviour Mechanisms in Australian Vegetation: Flame Spread and Flame Height

Version 2, August 2016

Denis O'Bryan, Red Eagle Bushfire Protection Services

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Abbreviations

Hc	Heat of combustion	kJ / kg
FMC	Fuel moisture content	% of moisture by weight
ROS	Rate of spread	m / sec or kph
MLR	Mass loss rate – in dry fuel, MLR measures fuel supply rate	kg / sq m / sec

INTRODUCTION

The purpose of this manual is to document known bushfire spread and flame height mechanisms in Australian vegetation in a way that transparently shows how fire behaviour derives from scientific fundamentals. This will give bushfire managers confidence that their diagnoses, analyses, explanations and predictions are based on scientific foundations and will provide them with a framework to assess whether observations, opinions and fire behaviour models meet high scientific standards. The description of each mechanism explains how flame spread or flame height occurs and provides the seeds of how spread and height can be managed or eliminated from any site.

It picks up from the observations of the pioneers – "progress in the use of models for predicting the behaviour characteristics of full-scale fires has been slow. Possibly this has been due to the lack of knowledge of the basic physical mechanisms of fire spread' (Byram et al, 1966). It also hopes to redirect the disappointing direction taken by bushfire behaviour research over many years, as outlined by Finney et al (2013). "Although fire scientists now obsess with how well spread models fit macro scale observational data (e.g. spread rate), there should be equal concern over whether the models are actually based on a physical understanding of fire spread processes".

To the bushfire manager, the development of bushfire research in Australia is a good example of the Finney et al (2013) description – "Fire spread research has historically been motivated by needs of fire suppression operations. Australia is also a vibrant exemplar of the dangers perceived by them – (1) "Because of the desire for practical tools, fire modelling or model engineering was seen as the foundational science", (2) "judging model success based only on agreement with observations can lead to an illusion of understanding", (3) the focus on models matching observations rather than seeking knowledge of how fire behaves "may even be misleading", and (4) "models (and the knowledge behind them) will inevitably be tasked with uses beyond their original range of association and thus reliability".

The Manual encourages bushfire managers and researchers alike to understand that a model must be based on a specific mechanism and a specific fire behaviour theory within specific design criteria and that it cannot be or amalgamated with data from another mechanism or extrapolated beyond its design criteria without losing reliability and scientific credibility.

The Manual presents the core underpinning theory for the Red Eagle series that document aspects of severe fire behaviour in Australian vegetation, much of it observed and recorded during the East Kilmore bushfire on 7 February, 2009.

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 some introductory 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
7 Effect of FMC on flammability of forest fuels
8 Predicting spread rate of leap frog spot fires

SUMMARY of bushfire behaviour mechanisms in Australian vegetation for Flame spread, Firebrand spread and Flame height

Tables assume severe weather conditions. Numbers refer to text sections.

Summary of Flame Spread Mechanisms

Category - Spread mechanisms are influenced by fuel bed factors

Flame spread mechanism	ROS, flame size and firebrand activity
2.1 Radiation	ROS slow Flame height variable, No live firebrands in fuel bed within one flame length
2.2 Tall flame / piloted ignition	ROS fast Flame height tall, Live firebrands in fuel bed within one flame length
2.3 Wind driven continuous spread	ROS proportional to wind speed Flame tilts, stretches, slaps onto and into unburnt fuel bed
2.3A Wind driven intermittent spread	ROS varies according to balance between wind and convection strengths When flame height is tall, ROS is slow, when flame short and tilted, ROS is faster
2.4 Backing fire	ROS slow Flame height variable
2.5 Upslope spread, Low to moderate slope	ROS correlated with slope Flame height variable
2.6 Upslope spread, Very steep slope	See 3.1 below
2.7 Down slope spread	ROS slow, unless driven by wind from upslope Flame height variable

Category - Spread mechanisms are influenced by non fuel bed factors

Flame spread mechanism	ROS and flame size
3.1 Trench effect	ROS fast Flame height is low to moderate because upslope flame attaches to fuel bed
3.2 Merging flame	Local ROS can vary from medium to a sudden surge Flame height mod to high
Convection column related: 3.3 Atmospheric downburst 3.4 Below canopy convection	 ROS is proportional to downburst speed ROS is variable - slow and fast See 2.3A above

Summary of firebrand spread mechanisms

Spot fire spread mechanism	Firebrand activity
4.1 Short distance spotting (Wind assisted)	Firebrands travel up to a few hundred metres from mother fire ***Source area:*** Flame height medium to tall. Plentiful firebrands
4.2 Medium to long distance spotting (Wind and plume assisted)	Aerodynamic firebrands travel several km from mother fire ***Source area:*** Flame height tall, rising into tree tops. Plentiful supply of aerodynamic firebrands
4.3 Leap frog spotting (Wind and plume assisted)	Aerodynamic firebrands travel several km from successive rapidly developed mother fires ***Source areas:*** flame height tall plentiful supply of aerodynamic firebrands ***Sink areas:*** flammable fuel bed that allows firebrands to ignite and grow rapidly into tree tops and generate a fresh supply of plentiful aerodynamic firebrands
4.4 Wandilo effect (wind and plume assisted)	Firebrands travel in concentrated area within 1 km or more from source area ***Source area:*** Flame height tall, rising into tree tops. Plentiful aerodynamic firebrands. ***Sink area***: If flammable, multiple firebrands ignite simultaneously

Summary of flame height mechanisms

Category – flame height mechanisms are influenced by fuel bed factors

Flame height mechanism	Influencing fuel bed factors	Flame height expectation
5.1A Single layer mechanism Litter bed	Fuel bed has high bulk density Fuel bed ignites on upper surface. Flammability level of volatiles too rich Flame height rises for dilution and combustion	Flash flame is above fuel bed Free flame height is up to two orders of magnitude (= 100X) times fuel bed depth
5.1B Single layer mechanism Grass	Fuel bed is low bulk density, Fuel bed ignites mid height, Volatiles are at flammability level. Flame height rises as lower and taller fuel particles pyrolyse	Flash flame is within and above fuel bed Free flame is up to 10X grass height
5.2 Multi layer / Vertical layer mechanism	Prerequisite: flame exists in surface layer Ignition of upper layer from below by direct flame contact Total flame height is correlated to pyrolysis height	Flash flame is within and above fuel bed Free flame is up to 3X fuel bed layer depth

Category – flame height mechanisms are influenced by non fuel bed factors

Flame height mechanism	Influencing Factors	Flame height expectation
6.1 Flame merge mechanism	Prerequisite: flame exists in surface layer of adjacent fires. Pressure deficit between fires causes plumes to deflect and merge into one flame, Flame height increases because air supply to flame body is restricted.	The merger can express itself as rapid lateral flame in-fill or 2X – 3X flame height expansion or flame filled vortex – many X expansion
6.2 (1) Trench effect flame - attachment	Prerequisite: flame exists in surface layer. Hill steepness causes one sided entrainment and rapid air flow uphill across fire area causes low air pressure at surface of slope	Flame height is low because it is attached to slope due to air pressure deficit along slope
6.2 (2) Trench effect flame - detachment	Prerequisite: flame exists in surface layer. Flame lifts up within low pressure parcel at top of slope.	Flame height large Flame height is independent of fuel or surface flame at break of slope.
6.3 Vortex flame height mechanism	Prerequisite: flame exists in surface layer. A trigger factor causes angular air flow entry into flame, which then spins. Parallel flow within the whirl slows air-fuel intermixing, causing flame height to increases.	Flame spike is several times original flame height. Flame height is independent of fuel Flame vortex height growth stops when all volatiles combust

Chapter 1
THE BASICS OF BUSHFIRE BEHAVIOUR MECHANISMS

The following mechanisms are based on a first principles approach - linking how flame ignites and behaves at the molecular level within the flame to how the flame impacts the unburnt fuel bed.

A **first principle** is a foundational, self-evident proposition that cannot be deduced from any other proposition.
In science, a calculation is from first principles if it can be linked directly to established laws of physics or chemistry and specifies reasonable assumptions and parameters.

Stoichiometric combustion and heat release
Byram (1959) was one of the first to explain the combustion process in forest fires. Woody fuel oxidises under heat to produce water vapour, CO_2 and more heat. This is achieved through three phases of combustion - the **preheating** phase which pyrolyses the volatile gases, the **tall flash flame** phase which consumes the volatiles (typically the thinnest fuel particles burn rapidly with a yellowish flame) and the **smoulder** phase, when charcoal burns with a low blue flame.

Under heat, the cellulose polymer splits into the levoglucosan monymer $C_6H_{10}O_5$ which requires 6 moles of oxygen for complete combustion, as follows:
$\mathbf{C_6H_{10}O_5 + 6O2 \rightarrow 6CO_2 + 5H_2O}$
Mass oxygen to mass fuel ratio = 192 gm air to 162 gm fuel = 1.185 to 1

Because oxygen is 21% of air (by mass), the complete reaction requires consideration of molecular mass and volume of air.
$\mathbf{C_6H_{10}O_5 + 6(O_2 + 2.76\ N_2) + \text{input energy} \rightarrow 6CO_2 + 5H_2O + 22.6\ N_2 + \text{output energy}}$
Thus the stoichiometric air-fuel ratio is 28.6 to 1.
Mass air to mass fuel ratio = 828 gm air to 162 gm fuel = 4.1 to 1

The heat released during combustion (H) is proportional to the oxygen mass consumed. Most fuels generate approximately 13.1 MJ of energy per kg of oxygen consumed. The constancy is due to energy release from breaking either carbon-carbon or carbon-hydrogen bonds which have similar bond strengths (Steckler 2001).

There are two basic types of flame in a bushfire – the taller yellow flash flame and the small blue flame. They can be replicated in the Bunsen burner. The small blue flame combusts at the fuel source with stoichiometric ratio of oxygen, and the taller yellow flame is like the Bunsen burner with the air hole closed (Drysdale, 2011). The fuel supply is too rich for mass ignition at the source and as the flame body rises, it draws in air that dilutes volatiles to flammability level, and continues to rise until the fuel molecules can find enough oxygen. It is similar with the bushfire flame. The higher the fuel supply rate or lower the oxygen supply rate, the taller the flame has to rise. This Manual focuses on fire spread and height during the tall flash flame phase.

The buoyant, diffusion, turbulent flame
The tall flash bushfire flame is classified as a buoyant diffusion turbulent flame (McCaffrey, 1979) - **buoyant** because its uplift velocity is due solely to buoyancy caused by flame temperature, **diffusion** because air must diffuse (= entrain) into the

flame body for combustion and **turbulent** because of the eddies that that are Nature's method of efficiently mixing volatile gases and oxygen within the flame body (Drysdale (2011). Because oxygen is limited within the diffusion flame, a proportion of C atoms amalgamate into soot particles. They heat to incandescence (eg, 800 - 1000^0C) and produce the yellow flame before cooling to become smoke (Atkins, 2003).

A typical diffusion bushfire flame has considerable turbulence, which is a very important feature. Because the interior of a solid flame is low in oxygen and has a high proportion of unburnt fuel volatiles (Thomas et al, 1964), combustion can only take place at flame surfaces, where the fuel meets oxygen in the right concentration. Turbulence increases the area of such flame surfaces. It is therefore a major influence on air entrainment rate and flame height.

The turbulence includes high frequency vortices (mini oscillations at multiple points at 10 cycles per sec) and large scale eddies that rise from the base along the edges and rotate inward. The large scale eddies cause the flame height fluctuations. McCaffrey (1979) identified a solid flame zone and an intermittent zone. The outer large eddies produce a vortex which rises through the solid flame zone and keeps rising above it until the fuel burns out, thereby extending the flame upwards. Meanwhile a new eddy series forms at the base, coalesces and rises up through the solid zone, carrying the flame tip to its former height. And so the flame height fluctuates at a measurable frequency. ***Frequency = 1.5 / sq rt D*** Where D = diameter of the fire.
Eg, a 10 cm fire sheds eddies at 5 / sec, a 100 m fire at 1 per 10 sec (Quintiere, 1998).

McCaffrey (1979) incorporated the eddy phenomenon into his two flame zones. The **solid flame zone** is 800^0C above ambient (delta T = 800^0K = 1100^0K flame temp less 300^0K ambient) and the **intermittent zone** temperature falls from 800 to 300^0C above ambient at the tip. The intermediate zone is where eddy turbulence is most visible. Successive flame tips rise to approx double the height of the solid zone. Quintiere (1998) explains that these temperatures are averages with a wide range due to turbulence and air pockets, eg, delta T of 800^0K is the average of fluctuations between delta T's of 500 and 1500^0K. If a parcel of solid flame were to be followed, its delta T would be around 1300^0K. McCaffrey's research derives from diffusion flames in a flat fuel bed, but is a useful reference point for understanding more complex flame structures. McCaffrey's flame heights are correlated with mass loss rate to the power 0.4.

The flames generate an updraft velocity that is directly correlated with flame height and flame temperature. Updraft velocity enables upward mass flow rate through the flame tip to be calculated, which allows convection power to be calculated. The temperature of the flame body generates radiation power, which can also be calculated and measured. Upward air flow draws an equal volume of air into the flame body. All of these fundamentals help to understanding flame behaviour mechanisms, whether lateral spread or flame height.

Thus the forest flame is unique world of vigorously combusting gases that is being fed by the fuel particles in its path, but is also influencing its surroundings and is being influenced by its local environment. It expresses itself by how tall is grows, how long it burns and how fast it moves across the landscape.

Heat transfer and ignition mechanisms
Flame spread and flame height in a fuel bed are achieved by combination of heat transfer mechanisms and ignition mechanisms.

- There is an initial phase of flame development:

Heat transfer mechanism causes preheating, preheating causes fuel particles to pyrolyse (gasify) at a variable fuel supply rate, ignition mechanism ignites volatile gases when diluted within flammability levels.

- Then there is a subsequent phase of flame influence:

The flash flame develops its own heat transfer and ignition mechanisms.
Flame spread rate is determined by combination of flash flame, fuel bed and environmental factors.
Flash flame height and duration are determined by fuel supply rate and pyrolysis height, which are in turn determined by fuel bed factors and environmental factors.

There are **four heat transfer mechanisms** (Byram, 1959), Morvan and Dupuy (2001)

Conduction	heat transfer through the fuel particle
Radiation	heat transfer to unburnt fuel particles through air
Convection	heat transfer to unburnt fuel particles by flame contact or heated air
Spotting	transport of burning firebrands through air; ignition of unburnt fuel

particles occurs by firebrand occurs by piloted ignition = convection and / or radiation

There are **five ignition mechanisms** (Babrauskas, 2001):

Flame contact	
Piloted ignition in pre-heated fuel bed	= Hot firebrand ignition
Piloted ignition in un-heated fuel bed	= Cold fire brand ignition
Radiation only - external heat source	= Auto ignition
Radiation only - internal heat source	= Spontaneous combustion

Fuel bed influences include surface fuel bed factors, vertical fuel bed structure, fine fuel loading and bulk density in each layer, ratio of dead to live fine fuel in each layer, quantity of firebrand source material (eg, Project Vesta, 2007)

Environmental influences on fire spread and flame height (eg, Byram, 1959 and McArthur, 1967) include RH (relative humidity), wind speed, slope and direction of slope, and atmospheric pressure differentials.

Models for flame spread and height
The following models assume the flame originates in and is carried by flammable fine dead dry fuel at ground level. They also assume a continuous surface fuel bed, zero slope (unless otherwise specified) and low air moisture (which means the thin fuel particles (< 2 - 3mm) are very dry).

Simplified fire spread model:
Consider a bushfire flame that is moving through an area whose fuel is a checkerboard of fuel bed units. Flame ignites in one unit and while burning, attacks the "next" unburnt fuel bed unit with flame and / or live firebrands. That unit ignites and while burning, attacks another unit of unburnt fuel bed. Whether the "next" fuel bed unit is adjacent or at a distance depends on the spread mechanism. This Manual describes the mechanisms within **two bushfire spread categories** - spread by continuous moving flame and spread by leaping firebrands.

Simplified flame height model
Consider the surface fuel bed as the origin of the flame. When preheated, it pyrolyses as fuel-rich vapour, and both ignition and combustion rely on the volatiles rising due to buoyancy and simultaneously entraining air into the flame body to dilute the fuel-air mixture to flammable levels. This is how the diffusion flame of the bushfire rises up from the surface fuel bed. If surface flame ignites elevated fuel, flame height rises higher, with concomitant increases in vertical velocity, radiation levels and firebrand production.

This Manual describes **two bushfire flame height categories** – one determined by fuel bed factors and the other determined by non fuel bed factors. Each has a number of specific height mechanisms.

The relative influence of radiation and convection on bushfire behaviour
The influence of the radiation mechanism on fire behaviour may have been overestimated by some bushfire researchers in the mistaken belief that the influence of convection power was negligible. This misunderstanding may have distorted models which were extrapolated to predict bushfire behaviour in severe weather.

Early researchers focused on radiation as the foremost heat transfer mechanism, particularly in ROS. Byram et al (1966) described how some investigators believed the tilting of flame by the wind increased radiation onto the fuel bed which "may explain the effect of wind on the rate of fire spread". Rothermel's (1970) ROS model was based on a zero wind vertical flame that spread by radiation. He incorporated wind as an add-on coefficient that caused this flame model to tilt (which generated a little more radiation) and move across the fuel bed. The role of the convection mechanism in ROS was largely neglected by researchers, with few exceptions, eg Thomas (1970) who demonstrated that both mechanisms were involved, but the flow of wind driven convection flux (flame and heated air) into the adjacent unburnt shrub fuel bed was the predominant cause of ROS increase. Recent attempts to incorporate convection as a leading heat transfer mechanism (eg, Morandini and Silvani, 2010) have been met with some apparent resistance (Nelson 2015).

Yet a simple example clearly shows that the heating power of radiation is a fraction of the true heating power of peak convection from combustion zone in the fuel bed and advection due to movement of the heated flame fluid (also called advective flux). Consider a wide flame face of 2m height and a 1 kg timber object with a 1 sq m face at 1m or so from the wall of flame and a windless day. If the object receives incident radiation of 50 kW / sq m, it takes 20 seconds to raise it to ignition temperature (300^0C above ambient), based on the Thomas (1970) figure of 1,000 kJ per kg (it may be 500 kJ / kg for fine fuel particles). The Thomas (1962) equation suggests the centre line of this flame has an upward velocity of 4.5 m/sec. Using a temperature above ambient of 800^0C and accounting for lower density air (0.33 kg / cu m), the advective flux (Thomas, 1970) is around 1,200 kW / sq m. [Peak heat release rate from combustion in the fuel bed generates 750 kW / sq m assuming peak MLR of 50 gm / sq m / sec provides heat source for this upward blast of superheated air]. This means it now takes 1 second to raise the same object to ignition temperature.

Now consider the same scenario with a strong wind of 10m / sec. The early researchers would say that the flame tilt increases net incident radiation onto the object, meaning it might take 10 - 15 sec to raise it to ignition temperature. What they overlooked was the convective (= advective) flux that pushes parcels of the flame body laterally at 10 m/sec, delivering a massive convection flux of 2,400 kW / sq m. The object now reaches ignition temperature in less than 1/2 second. Clark et al (1999) calculated convective heat fluxes of up to 3,000 kW / sq m at 12m high in crown fires where updraft winds were 20 m/sec and above.

Hopefully, this example highlights the importance of accurately identifying flame spread and flame height mechanism. Such wind speeds and lateral convective fluxes are commonplace in severe bushfire scenarios.

Atmospheric pressure mechanisms
In hilly terrain, wind streamlines compress at the hill tops and ridge tops, causing an increase in air speed, thus creating pressure gradients. Wind speed can increase up to 50% on a hilltop (Stangroom, 2004). As airflow is deflected over a hill, air pressure is significantly lower on the crest by a few millibars, and this pressure drop is coincident with accelerating airflow on the upwind slope and decelerating air flow on the lee side. (Finnigan and Belcher, 2004). When rapid, leeward deceleration causes flow separation and turbulence on the lee slope, including the formation of large eddies (Simpson et al, 2013). If a fire occurs on such a lee slope, it is likely to generate flame vortices and fire whirls (eg, Countryman, 1971). If a fire occurs on the windward side of such an upslope, a wind shear develops between the rapid upslope air flow within the fire and the slower air outside and generates flame filled vortices in the flanks that also run uphill. Dupuy et al (2011) reproduced this in the lab in litter fuel bed. Fire filled flank vortices (up to 1.5m tall x 30cm diameter) were intermittent on 20^0 slopes but frequent on 30^0 slopes, where they ran along both flanks reaching the head fire alternately at 1 to 2 seconds apart. Head flame heights were 50cm.

Lower pressure can also be enhanced by terrain shape, as explained by Euler's equation. When wind crosses a ridge line, air streamlines change direction and accelerate as they rise up along the slope and then follow a curved path across the ridge top. In cross section, this resembles the airfoil mechanism of an aeroplane wing. Euler's equation states that pressure difference is a function of ***Air density X air speed^2 / Radius of curvature***. The pressure gradient is perpendicular to the flow direction with higher pressure on the outside of the curve and lower pressure on the inside.

Passing air exerts a downward force on the airfoil shaped hill top. According to Newton's third law, the air must exert an equal and opposite (upward) lift force from the airfoil shaped hilltop. Lift force is a function ***of Air density x air speed^2 x area*** of wing or ground surface equivalent**.**

Simpson et al (2013) added a bushfire to the airflow / air pressure regime on a windy hill top and modelled how the fire's pyro-convection upset the balance. They saw a reversal of airflow on the leeward side to a strong upslope flow that fed into the plume. The uplift created vertical updraft-down draft flow circulations pattern around the convection column that interfaced at ground level to generate a moving inflow-outflow interface. If the fire was hit by a downdraft outflow, it could spread laterally very fast, albeit short lived.

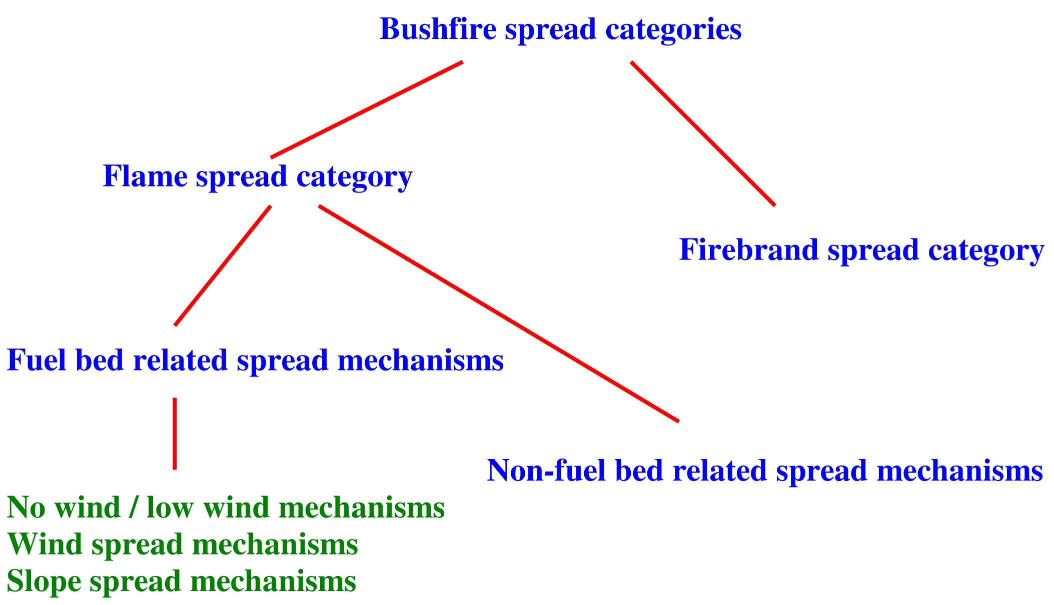
BUSHFIRE SPREAD MECHANISMS

This Manual now documents flame spread and firebrand spread mechanisms as stand alone processes, so that the diagnostic features of each can be clearly identified. It is axiomatic that understanding of each mechanism is a pre requisite of scientific validity and assurance that the pathway to first principles remains transparent and therefore verifiable.

Each spread mechanism is a unique combination of core causal processes that defines how the flame spreads. Each spread mechanism has a spread algorithm specific to it. Neither the combination of processes nor the spread algorithm cannot be transferred or extrapolated to another mechanism.

Because each spread mechanism derives from first principles that are identifiable and transparent, this allows the observer to predict or explain fire spread from first principles. And the corollary also applies. Each description provides the insight to manage fire spread, eg, slowing or preventing fire spread by denaturing that mechanism.

Having stressed their individuality, the Manual also recognises that bushfire behaviour is not always black and white, and that different mechanisms combine to produce a net fire behaviour outcome. Eg (1) a severe bushfire attack can deliver concurrent flame spread and firebrand spread mechanisms; (2) the Project Vesta fire trials were a mixture of wind spread mechanism and tall flame / piloted ignition spread mechanism (refer videos provided by Wotton et al (2012). Hopefully, the Manual facilitates effective diagnosis and identification of their relative influences.



Chapter 2
FLAME SPREAD MECHANISMS - FUEL BED RELATED

Flame spread mechanisms assume continuous horizontal fuel bed because the mother flame moves from a burning fuel bed unit into the adjacent unburnt fuel bed unit. This section excludes spread with help from firebrands. Two types are recognised – fuel bed related and non fuel bed related

This chapter refers to flame spread that is attributable to fuel bed factors. Three categories can be identified, based on wind speed at fuel bed level and slope –

- no wind / low wind mechanisms
- wind spread mechanisms
- slope spread mechanisms

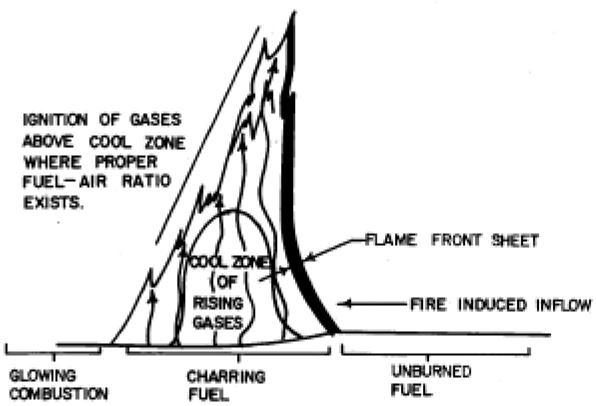
These mechanisms occur within the flame body or within about one flame length of it. They apply to any vegetation type and structure, eg, grass, heathland, forest, or combination. Eg, Burrows (1999) identified two wind related flame spread mechanisms in litter fuel. At wind speeds below 3-4 kph (at fuel bed level), the dominant mechanism of flame spread was radiation. At higher wind speeds, the dominant mechanism was convection. The former was slower, dependent on fuel load and flame height. The latter was linear with wind speed. The same mechanisms have also been confirmed in grass fires (Cheney and Sullivan, 1997), forest undergrowth (Project Vesta, 2007) and an excelsior flame trial (Morandani et al, 2012).

Low or zero wind spread mechanisms

2.1 Radiation spread mechanism

Documented description: Rothermel and Anderson (1966), Burrows (1999)

Identifying features: Mechanism occurs when wind speed at fuel bed is zero or low (< 5 kph); mother flame is vertical or nearly so, flame is typically low (up to a metre or so), firebrands are absent (ie, spread occurs without firebrands), ROS in hot dry weather is slow, of the order 100m per hour. Flame length to depth ratio is high, ie, tall vertical flame and narrow flame depth. Flame length increases with fuel bed depth.



Mechanism:
Preheating of unburnt fuel occurs by radiation at base of mother flame. Ignition mechanism is auto ignition along interconnected unburnt fuel particles, ahead of flame base. The incipient flame assumes into the mother flame and so the flame base advances.

Figure 1 Copy of Fig 8 in Rothermel and Anderson (1966).

Note: Convective heating flux can be more than 10 times lateral radiation flux, but because it rises vertically, it does not influence ROS.

ROS of mother fire front
ROS = [furthest distance from leading base of mother flame that surface fuel bed rises to ignition temperature (eg, 300^0C)] ***divided by*** [time to preheat to that temperature]
OR = Furthest distance to reach ignition temp / time to raise it to ignition temp

Influences on spread rate: ROS is directly correlated with flame height and width. This is because incident radiation increases as either separation distance reduces or width of flame increases or flame height increases (Byram, 1959). Flame height increases with fuel loading, which also increases flame depth.

2.2 Tall flame, piloted ignition spread mechanism

Documented description Taylor et al (2004)

Identifying features: Wind speed is low but ratio of ROS to wind speed is very high; mother flame is a vertical or nearly so; typically a tall wide wall of flame, short distance firebrands are in abundance, often dropping from adjacent tall burning fuel. ROS in hot dry weather is up to 2 – 3 kph and can equal or exceed in-forest wind speed. Flame length to depth ratio is high, ie, tall vertical flame and narrow flame depth.

Mechanism: As tall flame of advancing front preheats litter bed to pyrolysis and bark surfaces to auto-ignition temperature, live firebrands from adjacent tall fuel drop into pyrolysis gases on ground. Litter bed gases ignite in small patches like a match in a petrol spill. Trunks ignite by auto-ignition. Embryonic litter bed flame rapidly grows in height and assumes itself into the mother flame and so the flame base advances.

ROS of mother fire front
ROS = [furthest distance from leading base of mother flame that surface fuel bed rises to 250 - 300^0C] divided by [time to preheat to that temp]
Or = Furthest distance to reach pyrolysis temp / time to ignite at that distance
(Figure 2 shows that ROS = 1.2 - 1.8 kph when wind at fuel bed = 1.5 kph)

Influences on spread rate: Prerequisite is a tall shrub layer or vertical ladder fuel complex with a ready supply of fire brand material. ROS is directly correlated with flame height and width (because incident radiation increases as either separation distance reduces or width of flame increases or flame height increases (Byram, 1959)). Flame height is directly related to vertical height of shrub layers or ladder fuel.

Figure 2 Copy of Fig 3 in Taylor et al (2004). They reported this camera sequence for Plot 3 as follows, noting in-forest wind speed was 1.5 kph. “The fire approached from behind the camera at a spread rate of about 20–30 m/min (1.2 - 1.8 kph). The sequence shows glowing and flaming embers starting numerous spot fires approximately 10–20 m ahead of the flame front; gasses coming off tree boles about 7 m ahead of the flame front, presumably because of radiant heating”
(A) Time 15:08:26, spot fires ignite from ember rain about 10 - 20m ahead of the flame front.
(B) 15:08:40, vapour release from bark on tree trunks at about 6 m ahead of the flame front.
(C) 15:08:48, ignition of forest floor patches and tree boles about 3–4 m ahead of the flame front.
(D) 15:08:52, embryo flame grows in height and becomes new flame front
Ie, flame front arrives at camera

Wind spread mechanisms

2.3 Wind spread mechanism – continuous forward spread

(= Wind assisted heading fire)

Documented description: Rothermel and Anderson (1966), Burrows (1999)

Identifying features: Mechanism occurs when wind speed at fuel bed > 3-4 kph and flame spread responds proportionally to wind speed; flame in litter fuel bed is pushed along surface; flame within a porous fuel bed shoots into adjacent unburnt fuel bed; free flame above fuel bed stretches or flaps onto adjacent unburnt fuel bed; ROS is much faster than zero wind conditions when radiation spread is dominant mechanism.

Mechanism of continuous spread: Spread occurs by convection (heat transfer by flame engulfment or superheated gases, ignition by flame contact). Wind at fuel bed level causes flame base to shoot flame jets across and into unburnt fuel bed. Taller free flame above tilts and slaps onto downwind unburnt fuel bed, as if hinged at the flame base. Embryonic flame grows quickly and becomes new flame base, and so the flame front progresses. [It is possible that a taller free flame can cause a slightly faster spread rate. If so, height of free flame is determined by single layer flame height mechanism.]
"The flames and convection column were tilted at an appreciable angle from the vertical. For a short distance downwind from the leading edge of the burning zone the flames appeared to be in contact with, or very close to, the upper surface of the crib (= fuel bed). For a somewhat greater distance, random fingers of flame would descend from inner surface of the tilted flame front to make momentary contacts with the upper surface of the crib. Also, unburned gases appeared to flow in a horizontal direction within the crib and would well up through the surface openings ahead of the burning zone. At the higher wind speeds these gases would ignite and form a small secondary fire about 10 to 16 inches (0.3 – 0.4m) ahead of the main burning zone"
"The horizontal speed of the flames in this region may he greater than the speed of the wind. If so, then wind converts a flame front into a form of jet."
"The nearly continuous envelopment of the surface fuel for some distance ahead of the leading edge of the active burning zone plus random flame contacts at greater distances ignite the surface fuels. This effect would be magnified for fuels such as brush or tall standing cured grass which would be penetrated by the jet-like flames." (Byram et al, 1964)

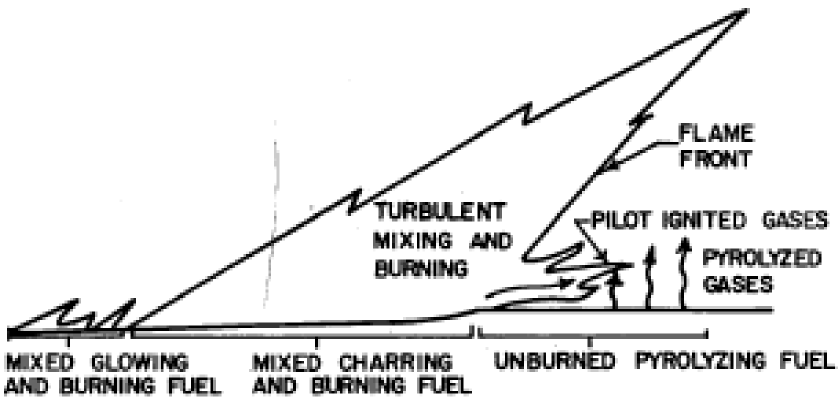


Figure 3 Copy of Fig 9 in Rothermel and Anderson (1966).
Note that the flame body continues to radiate at around 100 – 150+ kW/ sq m, according to its temperature, but its influence is overwhelmed by convective heat flux of 10X higher.

ROS of moving fire front
ROS = distance from base of mother flame to furthest ignition point / time to ignite

Influences on spread rate: ROS in surface – near surface layers is directly correlated with wind speed at fuel bed and inversely related to FMC of dead fuel. Overall spread rate in severe weather is characteristically proportional to wind speed according to fuel type (eg, ROS in dry litter bed is of the order 10% of wind speed at fuel bed level, in shrub fuel 25% and in dry grass is 40% (O'Bryan, 2005).

ROS in multi layer fuel bed: flame spread rate in surface – near surface layers typically determines spread rate in entire elevated fuel bed

2.3A Wind spread mechanism – intermittent forward spread

Documented description: Project Vesta (2007)
Note: The Vesta mechanism occurs where prevailing wind does not change. However, it differs from the reports of buoyancy / wind driven fires of that were directly caused by change of wind speed (eg Morandini et al, 2012). Morandini and Silvani (2010) report similar variations in flame speed and height variation in shrub fuel on steep slopes but they are on different days and in different fuel structures.

Identifying features:
In a continuous forest fuel bed at a given wind speed, a flame front can spread on a cycle of fast and slow. The cycles (duration of 1 to 3 minutes) occurred below the canopy in all fuel bed ages. The updraft phase had dense dark smoke, vigorous vertical flames and slow ROS and was the source of longer distance spotting. The downdraft flames leant forward, had less smoke and rapid ROS resumed, and they were the source of short distance spotting.

Mechanism of intermittent spread:
Project Vesta (2007) believed the cycle was caused by feedback mechanism between the fire and sub canopy ambient wind (p129).
Lateral flame spread phase: Continuous spread mechanism as above
Vertical updraft phase: Forward spread mechanism is by radiation spread mechanism. Presumably, a strong low pressure cell develops above flame that draws flame vertically, thereby overriding prevailing sub canopy wind force.

ROS of moving fire front
ROS = distance from base of mother flame to furthest ignition point / time to ignite

Influences on spread rate: ROS in surface layer is directly correlated with wind speed at fuel bed and inversely related to FMC. Vesta's ROS data was the average of these fluctuating phases. Vesta diagnosed the occurrence of intermittency when the ratio of peak ROS to mean ROS was 2 – 3 (p 122).

2.4 Backing spread mechanism

Documented description: Burrows (1999) and Rossa et al (2015)

Identifying features: Flame perimeter burns down slope or backs into wind; flame is vertical or leans away from unburnt fuel, entire fuel bed depth is consumed.

Mechanism: Similar to radiation spread mechanism. Radiation is the means of heat transfer and the cause of ignition.

ROS of flame
ROS = furthest distance from leading base of mother flame that surface fuel bed rises to auto-ignition temperature (eg, 500^{0}C) / time to preheat to that temperature

Or = Furthest distance to reach ignition temp / time to raise it to ignition temp

Influences on spread rate: ROS is directly correlated with flame height and width; flame height is directly related to vertical height of ladder fuel.

Slope spread mechanisms

2.5 Upslope spread mechanism Low to moderate slope (< 20^0)

(Assume zero wind)

Documented description: Rothermel (1972), Byram et al (1966)

Identifying features: Upslope is low to moderate; compared to flat terrain in zero wind, flame is taller with a wider flame depth, angle between slope and flame face is smaller, and ROS is higher.

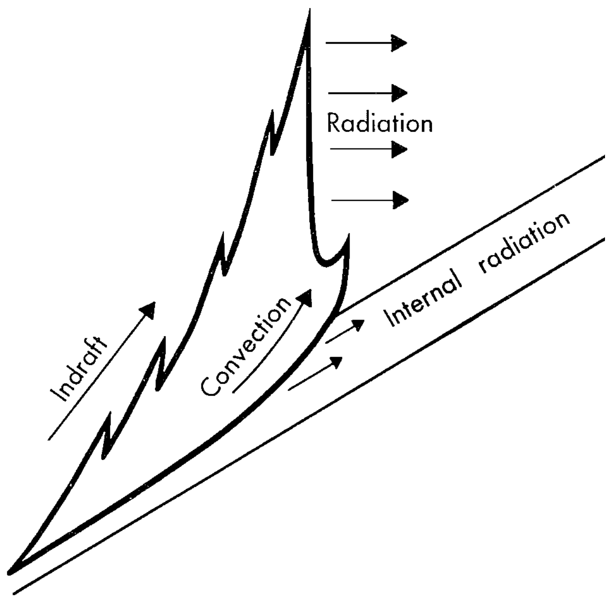


Figure 4 Copy of Fig 4 in Rothermel (1972)

Mechanism: Flame is vertical, but slope means flame face is closer to fuel bed, meaning radiation preheats at greater distance from flame base. Spread mechanism is same as radiation spread mechanism. Flame tilts and stretches onto or through uphill fuel bed, preheating and ignition is caused by combination of radiation and direct flame contact (= convection). Ignition of unburnt fuel bed is rapid.

"The flame over a fuel bed burning on a sloping surface is displaced upslope along the surface and tilted toward the surface in the same manner as the flames for a wind-driven fire on the horizontal." Byram et al, 1966)

ROS of moving fire front

ROS = distance from base of mother flame to furthest ignition point / time to ignite

Influences on spread rate:

ROS increases as slope increases and / or as flame height increases

2.6 Upslope spread mechanism Very steep slope > 25^0

Refer to **3.1 Trench effect flame attachment mechanism**

2.7 Down slope spread mechanisms

For zero wind conditions, refer to **2.4 Backing fire mechanism**

For down slope winds, eg, katabatic winds, refer to **2.3 Wind spread mechanism**

Chapter 3
FLAME SPREAD MECHANISMS - NON-FUEL BED RELATED

Flame spread in this category is controlled by atmospheric pressure or convection column influences, whereby flame flows towards air parcels of lower pressure (eg, Baldwin et al, 1964).

3.1 Trench effect flame attachment mechanism

Documented description: Sharples et al (2014) Sharples et al (2010), Dupuy et al (2011)

Identifying features: low flame on steep uphill slope (> 25^0); faster ROS than upslope spread mechanism, tall fleeting flame flash at top of slope

Mechanism When a fire burns up a steep slope, it draws air from one direction, ie, downslope, and air flow rate along fire is very high. High air flow generates lower pressure due to a combination of Bernoulli's equation and Coandă effect, and this pressure differential causes airflow and flame to attach to the slope.
Flame attachment phase: The flames stay low on the surface and preheat the fuel ahead, and the flame progresses along the slope, igniting fuel by convection (ie, flame contact).
Flame detachment phase: At the top of the slope, air flow and flame detach as air entrains from lee side of fire and a jet of flame shoots skyward until the fuel depletes.

ROS of flame attachment phase = distance moved by flame front / time interval

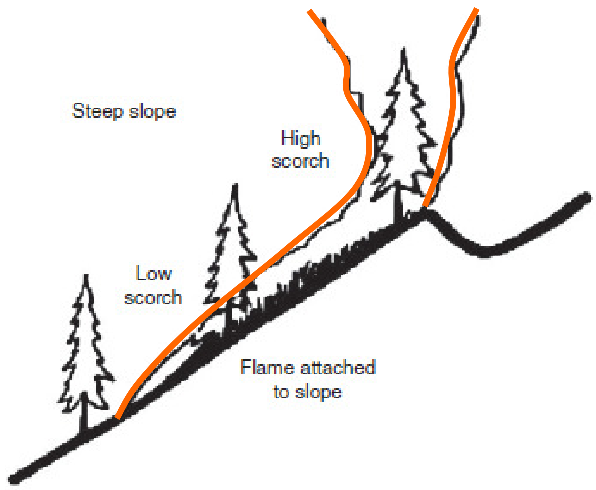


Figure 5

Alexander and Cruz (2012) displayed Rothermel's 1985 description of the two key components – low rapid flame along the slope and tall flash flame at the top of the slope.

3.2 Merging flame spread mechanism

Documented description: Cheney et al (2012), quoting observations in a 1996 report about grass fire trials

Identifying features: two adjacent parallel fronts in close proximity; ROS of both increase up to three times during merger within zone of interaction; after merger, ROS resumes to previous
Note: Wide fire fronts often develop similar parallel tongues and the intervening unburnt area is known to be the source of rapid flame in-fills, tornado development and the origin of mass spotting - all due to low pressure areas associated with parallel plumes.

Mechanism (deduced): plumes are downwind of flame fronts; air pressure falls in gap between plumes of adjacent fires (Bernoulli's law); plumes lean towards lower pressure and join and some spiral; low pressure area descends towards ground ahead of flame zone and draws flame into it. Heat transfer mechanism = convection. Ignition mechanism = direct flame contact.

ROS of merged flame
ROS = distance moved by flame front / time interval

Convection column influences

3.3 Atmospheric downburst spread mechanism

Documented description: Tolhurst and Chatto (1999)

Identifying features: Plume rises strongly until a pressure equilibrium point, then a sudden collapse; sudden unexpected wind downburst from fire-caused convection column.

Mechanism
Atmospheric mechanism: Tolhurst and Chatto (1999) quote Rothermel observations from 1991 that a fire generated convection column can rise to the point of equilibrium and then reverse flow, causing a downburst that hits the ground and sends wind speeds radiating at up to 100 kph. If these winds hit a fire edge, ROS suddenly increases and the fire runs in the direction of the wind, according to wind spread mechanism.
Fire spread mechanism: Flame spreads by wind spread mechanism, refer 2.3

Note: Presumably, highest risk occurs when plume site more or less vertically above the fire ground, meaning winds are low at fire ground and in upper atmosphere.

Also refer to ***6.4*** ***Convection column updraft mechanism***

3.4 Below canopy convection spread mechanism

Refer to ***2.3*** ***Intermittent spread mechanism***

Summary of Flame Spread Mechanisms

Flame spread mechanism	Heat transfer mechanism	Ignition mechanism	Environmental influences	Flame size and firebrand activity
Fuel bed related				
2.1 Radiation	Radiation only	Auto-ignition	Zero wind, low wind	flame height variable, no live firebrands within one flame length
2.2 Tall flame / piloted ignition	Radiation plus very short distance spotting	Hot firebrand ignition	Zero wind, low wind	flame height tall, live firebrands within one flame length
2.3 Wind driven continuous spread	Convection	Flame contact	Wind speed variable	flame tilts, stretches, slaps onto and into unburnt fuel bed
2.3A Wind driven intermittent spread	A cycle of convection then radiation	A cycle of flame contact then radiation	Prevailing wind speed constant	Flame behaviour changes from tall and slow ROS to short and high ROS
2.4 Backing fire	Radiation only	Auto-ignition	Flame backs into wind	flame height variable
2.5 Upslope, Low to moderate slope	Convection and radiation	Flame contact	Up slope	flame height variable
2.6 Upslope Very steep	See 3.1 below			
2.7 Down slope	Radiation only	Auto-ignition	Down slope, Wind variable	flame height variable
Non fuel bed related				
3.1 Trench effect:	Convection	Flame contact	Upslope Steep Wind low to moderate	Flame height is low to moderate because upslope flame attaches to fuel bed
3.2 Merging flame	Convection	Flame contact	Wind speed high Terrain variable	Flame height mod to high, fire size medium to large
Convection column related 3.3 Atmospheric downburst 3.4 Below canopy convection	Variable (see text) See 2.3A above	Variable (see text)	Variable (see text)	Variable (see text)

Chapter 4

FIREBRAND SPREAD MECHANISMS

It has been long known that there are three categories of spotting distance in eucalypt forest, short, medium and long (eg, McArthur, 1967). They can be characterised respectively as a few hundred metres ahead of the fire front (eg, up to 500m), a few km ahead (eg, 1 – 3 km) and several km ahead (5 to 25+).

Recent research (eg, Project Vesta, 2007 and Hall et al, 2015) has confirmed spotting distance is a function of aerodynamic nature of the fire brand, duration of burning while aloft and wind speed in upper atmosphere. For example, messmate bark firebrands tend to generate short distance spotting because they is heavy and burn out in a few minutes, whereas gum bark firebrands tend to generate very long distance spotting because they are light and tubular and burn for many minutes.

The Byram et al (1966) description of "blow up" fires appears to fit within this category. "Their sustained rates of spread are usually from 1.5 to 6.0 feet per second (= 1.5 to 8 kph) but many (are) considerably greater during erratic surges. One of their most prominent features is the convection column which may tower to a great height or it may be terminated, or fractured, by a layer of high-speed winds several thousand feet above the earth's surface. In either case the column appears to be of the free convection type. Another feature is airborne burning material which "is carried aloft by the strong updrafts in the convection column (or columns). On a large scale, embers falling from the convection column may reach the proportion of an ember shower which can ignite extensive areas well ahead of the advancing fire front".

Four firebrand spread mechanisms can now be described – short distance spotting, medium to long distance, leap frog spotting and the Wandilo effect. The first mechanism is wind driven and the other three are plume driven and carried by wind.

4.1 Short distance spotting spread mechanism (Wind assisted)

Documented description: McArthur (1967), Hall et al (2015)

Identifying features: Firebrands are thrown a short distance ahead of advancing flame (< 200 - 500m); mother fire tends to overrun or retard development of these spot fires

Mechanism: Strong head fire updraft lifts loose firebrands several hundred metres upward and upper winds carry them downwind as they fall at terminal velocity. Figure 6 illustrates that spotting distance is the sum of horizontal distance travelled during uplift (Du) and Horizontal distance travelled during free fall (Df).

ROS of leading spot fire occurrence
ROS = furthest distance from defined origin to spot fire ignition point / time from lift off to ignition
ROS of leading spot fire front
ROS = furthest distance from defined origin to spot fire ignition point / time to grow to viable size (eg, 5m diameter)

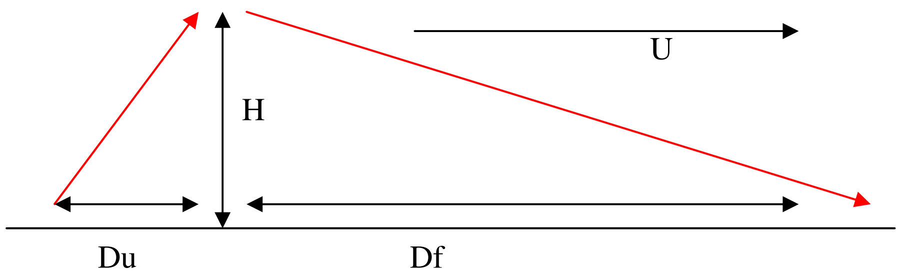


Figure 6 Spot fire distance theory - the firebrand rises to a maximum height H, and then falls at terminal velocity to the ground. Spotting distance = Du + Df
The following equations apply:
Du = Horizontal distance travelled during uplift = H x U / Vplume
Df = Horizontal distance travelled during free fall = H x U / Vterm
Where U = wind speed, Vterm = terminal velocity, Vplume = upward plume velocity
The following calculations show that the major influence on spotting distance is wind speed.
Say U = 72 kph = 20 m/sec, and Vterm = 5m/sec U / Vterm = 20 / 5 = 4
Say Vplume = 50 m/sec U / Vplume = 0.4
Therefore horizontal distance = H x 0.4 + H x 4 = 3.4 x H
Therefore, if H = 1,000m, spotting distance = 3.4 km

Influences on spread rate: Plentiful supply of aerodynamic firebrands at source area increases density of potential spot fire ignitions at sink areas. Greater wind speed at fire ground means longer throw distances.

4.2 Medium or long distance spotting spread mechanism (Plume assisted)

Documented description: McArthur (1967), Hall et al (2015)

Identifying features: Firebrands are thrown well ahead of advancing flame (> 1km); spot fires ignite in "cold" fuel beds and mother fire has no influence on their development.

Mechanism: Very strong head fire updraft lifts loose firebrands to several thousand metres into the plume and upper winds carry them downwind as they fall at terminal velocity. Distance is determined by spot fire distance theory (Figure 6). Spot fire direction is determined by direction of upper atmosphere wind stream. Figure 7 shows time sequence diagrams of mother fire, long distance spotting distances and spot fires for the Andrew Fire, Manjimup when Fire Danger Index was 65 (McCaw et al, 1992).

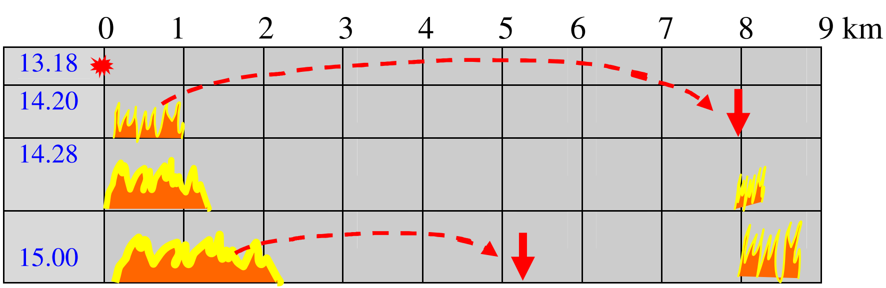


Figure 7 Time sequence of Andrew Fire, Manjimup
The documented time periods are in blue on left side
The numbers across the top are km from origin (0).
Red star is fire origin
Dashed arrow is path of firebrand from source to ignition point
Red arrows are location of spot fire ignition at start of time period
Orange/yellow mass is progressive length of run of each fire front from its origin at start of period

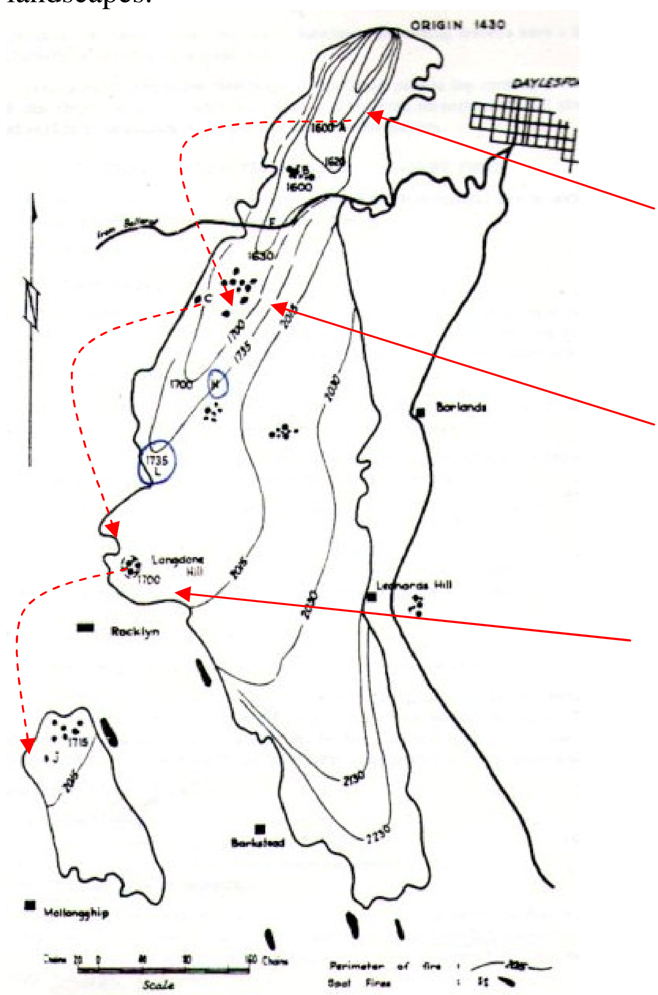
ROS of leading spot fire occurrence
ROS = furthest distance from defined origin to spot fire ignition point / time from lift off to ignition
ROS of leading spot fire front
ROS = furthest distance from defined origin to spot fire ignition point / time to grow to viable size (eg, 5m diameter)

Influences on spread rate: Plentiful supply of aerodynamic firebrands at source area increases density of potential spot fire ignitions at sink areas. A taller flame in long unburnt vegetation at the source area increases the chance of greater plume uplift speed, and therefore a greater uplift height and therefore greater distance of travel. A stronger wind speed in upper atmosphere means longer throw distances.

4.3 Leap frog spotting spread mechanism

Documented description: McArthur (1967)

Identifying features: The gross speed of leaping spot fires is very fast, eg, they can exceed 20 kph. They travel in the direction of wind stream in upper atmosphere, which can differ from wind direction at fire ground. High percentage of area between fresh spot fires is unburnt. This mechanism occurs only in forest or in mixed forest landscapes.



Mechanism:
Strong mother fire updraft lifts loose firebrands a few thousand metres into the plume and upper winds carry them downwind as they fall at terminal velocity.

Firebrands ignite and develop vigorous daughter fires that throw fire brands downwind that ignite and develop vigorous granddaughter fires.

Vigorous granddaughter daughter fires throw fire brands downwind that ignite and develop vigorous great granddaughter fires, etc, etc,

Figure 9 shows time sequence diagram of this fire

Figure 8 McArthur's map of Daylesford isochrones and spot fires (McArthur 1967)

ROS of mother fire and each individual spot fire
ROS = distance moved by flame / time interval
ROS of leading spot fire occurrence
ROS = distance from defined origin to furthest spot fire ignition point / time from lift off at defined origin to ignition at furthest point
ROS of leading spot fire front
ROS = furthest distance from defined origin to spot fire ignition point / time to reach say 5m diameter

Influences on spread rate: plentiful supply of aerodynamic firebrands at first and subsequent source areas increases density of potential spot fire ignitions at first and subsequent sink areas; the taller the flame in long unburnt vegetation at first and subsequent source areas, the greater plume uplift speed and therefore the more leap frog jumps and the greater distance of travel; a greater wind speed in upper atmosphere means longer throw distances.

Daylesford bushfire 16 Jan 1962 FDI > 50

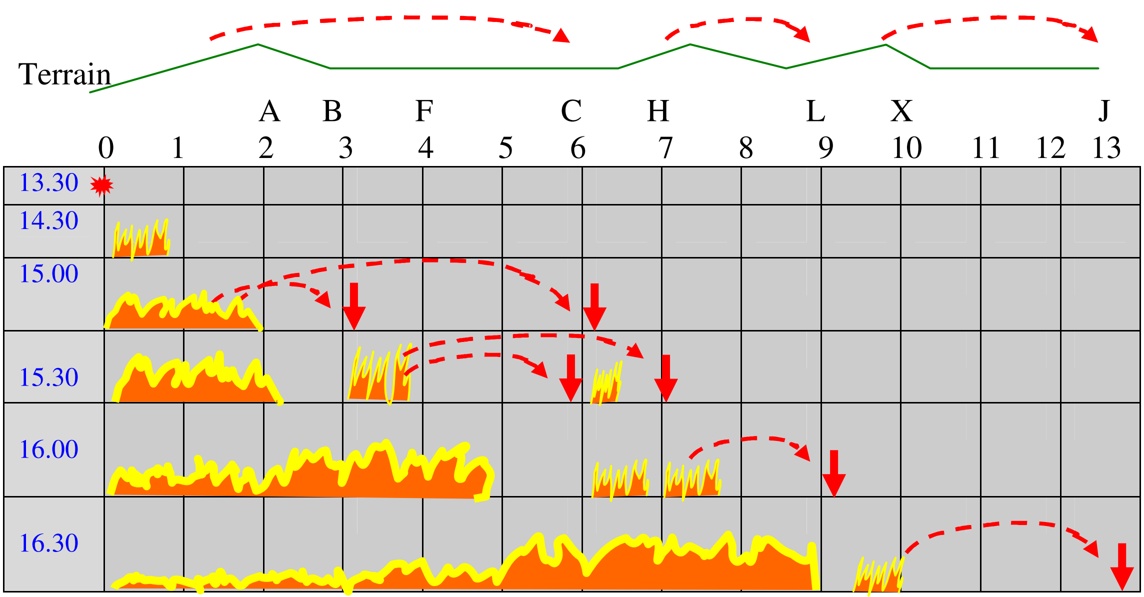


Figure 9 Time sequence of Daylesford Fire
The two lines above this chart are as follows:
Green line is approx terrain diagram (the terrain diagram shows that longer distance spotting is associated with up slope runs). The letters correspond to McArthur's descriptions (Figure 8 above)
The documented time 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 each fire front from its origin at start of period

4.4 Wandilo effect spread mechanism (simultaneous mass spotting)

Documented description: McArthur et al (1966),

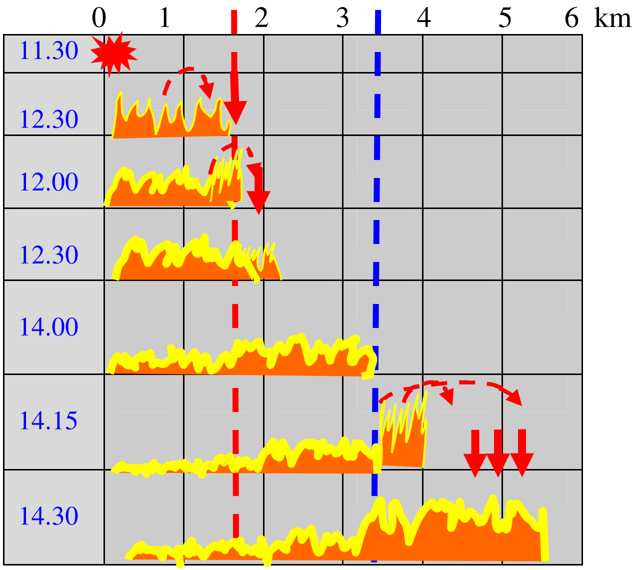
Identifying feature: Massive simultaneous dumping of short to medium distance spotting (eg, up to 2 km or more) into an area. If the landing area is flammable, they ignite more or less simultaneously; mother fire may or may not overrun these spot fires. Keeves and Douglas (1983) report short lived but very high net ROS (12 – 14 kph) associated with flame merging of two parallel flanks in long unburnt short eucalypt forest was due to mass downwind spotting.

Mechanism: Source area develops a substantial area of tall flames that generate rapid uplift and throw a concentrated mass of firebrands skyward into wind streams above the tree tops. The winds carry them downwind as they fall at terminal velocity. They land across an elongated area downwind, the heavier firebrands fall closer to the mother fire and the aerodynamic ones fall further away.
See Figures 10 and 11 for specific Wandilo mechanisms

ROS of leading spot fire occurrence
ROS = distance from defined origin to furthest spot fire ignition points / time for them to ignite
ROS of leading spot fire front
ROS = furthest distance from defined origin to spot fire ignition point / time to reach say 5m diameter

Influences: plentiful supply of aerodynamic firebrands at source area increases density of potential spot fire ignitions at sink areas; a taller flame in the source area increases the chance of greater plume uplift speed, and therefore greater distance of travel; a greater wind speed in upper atmosphere means longer throw distances; the higher percentage of flammable landing area, the more simultaneous ignitions.

Wandilo bushfire, 5 April, 1958 Before wind change FDI 35



Wandilo mechanism:
The merging of two adjacent tongues at 14.15 was the trigger for the tall flame fire storm that threw a concentrated mass of embers skyward. They were dumped over a 1.5+ km swathe, immediately downwind, causing instant ignition and an effective ROS of a few kph.

Figure 10 Time sequence of Wandilo Fire
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
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.
The dashed blue line marks the site of the fire storm
Dashed arrows are 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

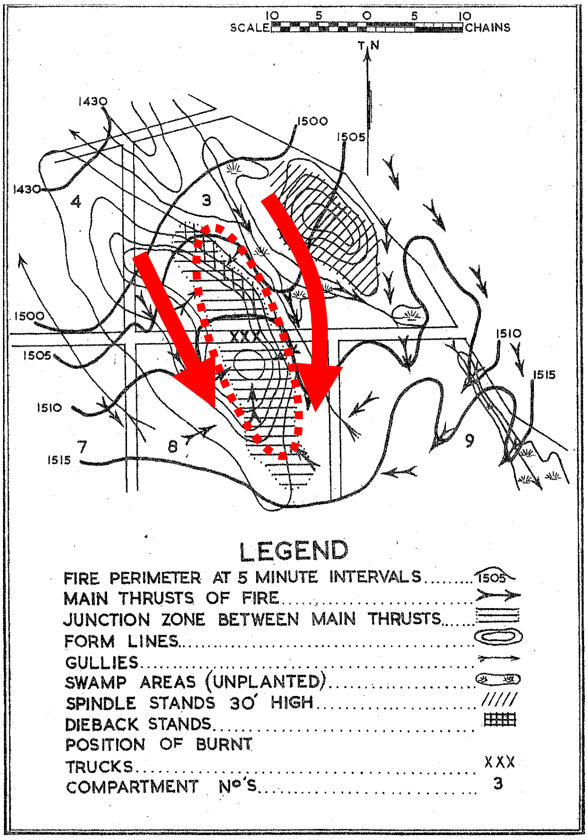


Figure 10 Copy of Fig 12 from McArthur et al (1966)

14.00 – 14.15 The 800 m wide fire front headed SSW towards a long low hill top. Some 400m of the eastern front ran into swampy vegetation along a gully line and increases ROS.
Some 200m of the western front burnt quickly along a gully line.
The central 200m was progressing slower along the unburnt 24 year old hill top pine plantation.
Suddenly, the hill top was flanked by two parallel aggressive fire tongues (red arrows). Just as suddenly, they merged above the hill top, which was instantly engulfed in flame (red dotted area). Fire tankers were on the hill top at the time and 8 of the 11 fire fighters died.

Flame convergence induced crowning on the hill top plantation and the huge convection updraft threw a mass of embers downwind, simultaneously igniting an area of at least 1.5 km downwind by 1 km wide, and "some 600 acres (250 ha) of Pinus radiata plantation was burnt by crown fire within 15-20 minutes"

Summary of firebrand spread mechanisms

Spot fire spread mechanism	Heat transfer mechanism	Ignition mechanism	Environmental influences	Flame and firebrand activity
4.1 Short distance spotting (Wind assisted)	Firebrands travel up to a few hundred metres of mother fire	Cold firebrand ignition	Strong winds at fire ground	Flame height medium to tall. Plentiful firebrands
4.2 Medium to long distance spotting (Wind and plume assisted)	Aerodynamic firebrands travel several km from mother fire	Cold firebrand ignition	Strong winds in upper atmosphere	Flame height tall, rising into tree tops. Plentiful supply of aerodynamic firebrands
4.3 Leap frog spotting (Wind and plume assisted)	Aerodynamic firebrands travel several km from successive mother fires	Cold firebrand ignition	Strong winds at fire ground	***Source area:*** flame height tall, plentiful supply of aerodynamic firebrands ***Sink area:*** flammable fuel bed that allows firebrands to ignite and grow into tree tops. Plentiful aerodynamic firebrands
4.4 Wandilo effect (wind and plume assisted)	Firebrands travel in concentrated area within 1 to a few km of source area	Cold firebrand ignition	Strong winds at fire ground Terrain of source area has potential for flame merging or surging	***Source area:*** Flame height tall, rising into tree tops. Plentiful aerodynamic firebrands. ***Sink area***: If flammable, multiple firebrands ignite simultaneously

BUSHFIRE FLAME HEIGHT MECHANISMS

Two long accepted theories are (1) that flame height peaks where combustion completes, ie, when all fuel is consumed by air entrained into the flame body and (2) that entrainment rate of oxygen controls flame height, ie, higher entrainment rate means higher flame height (Quintiere et al, 1986). The following air entrainment equation (Quintiere, 1998) is useful in explaining reasons for change in entrainment rates and therefore in flame height.
Mass air entrainment rate = N x S x M
Where N = multiple of stoich air required due to inefficient mixing (equivalent to excess air concept), S = stoich air to fuel mass ratio (= 5 for wood flame), M = fuel supply rate or mass loss rate (MLR) of fuel.
Eg, if MLR increases, entrainment rate increases and so does flame height. If the supply of oxygen is reduced (as occurs when flames merge) or ability of oxygen and fuel to diffuse is disrupted (as occurs in a fire whirl), N increases, entrainment rate increases and flame height also rises.

Quintiere (1998) states that ***Hc / S = 3,000 kJ / kg air*** for most hydrocarbons. Eg, if Hc for forest fuels is 15,000 kJ / kg (Nelson et al, 2012), and S = 5, the relationship holds.

Because the flame body is a mass of heated gases, it rises from the fuel bed due to buoyancy but its flow is also subject to laws of fluid physics, eg, its propensity to flow toward low pressure areas, eg, in accordance with Bernoulli's principle (Baldwin et al 1964). This leads to two broad categories of flame height influences, one is **fuel bed related** and the other is **non-fuel bed related**. The two categories each have several flame height mechanisms that will now be described.

Fuel bed related flames have behaviour mechanisms that can be explained by fuel bed factors. Because flame rises due to buoyancy and because all forests have fuel arranged vertically in identifiable layers, these flame height mechanisms can be categorised by fuel bed layers. Non-fuel bed related flames have behaviour mechanisms that are not related to the fuel bed. Their mechanisms relate to how the atmosphere deals with the flame body.

These flame height mechanisms are relevant to any vegetation type and structure, eg, grass, heathland, forest, or combination. Each flame height mechanism is a unique combination of core processes that defines how tall the flame grows and how long it lasts. Each flame height mechanism has a spread algorithm specific to it that cannot be transferred or extrapolated to another mechanism.

Each flame height mechanism will be seen to derive from first principles that are identifiable and transparent. This allows the observer to predict or explain flame height from first principles. And the corollary also applies. Each description provides the insight to manage flame height, eg, reducing or eliminating flame from a given area by denaturing that mechanism.

Measurement of flame height

Be aware that researchers have a range of definitions. Eg, maximum height of fluctuating tip, average height of fluctuating tip, height of flame > 50% of time, average or maximum height on successive photos or recording instruments . There is no right or wrong, but it can be confusing. This Manual prefers average peak flame tip height because extremities are more identifiable, but assumes reported heights are typically indicative and never exact, and come with ± 20% variation. Observed flame height in a 0.5m homogeneous grass fuel bed tends to be consistent, but in multi layer fuel beds, flame height on a given area depends on the fuel bed structure on that area. Thus a patch of litter bed in a forest has a general flame height of 1.5m, but flame height in a patch of 2m tall shrubs can be 6m, and flame height on a trunk with flammable bark height of 10m will be 10m. Many people tend to report the flame height in this forest as 10m high, whereas it is much more accurate and educational to describe flame height of each layer.

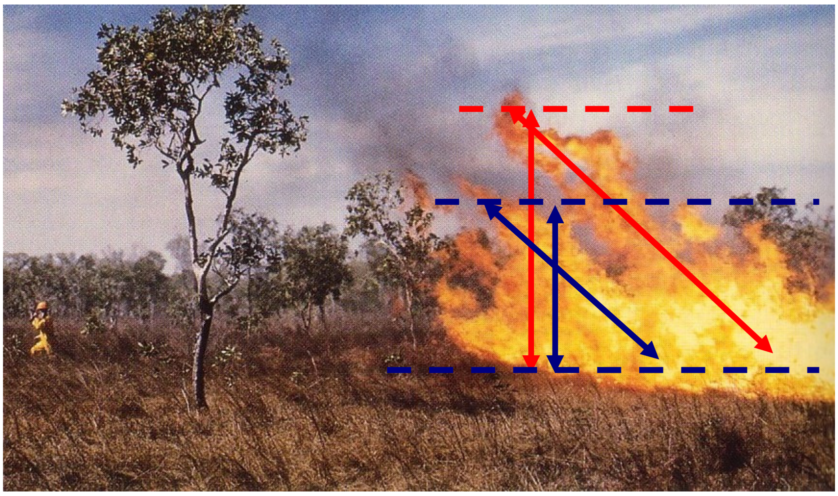
Figure 11 Identifiable flame heights in a forest fire – white arrow is flame height generated by litter bed and low shrubs (1m), green arrow is flame height generated by flammable trunks (8m+). Photo by Ballarat Courier in CFA publication "Reduce risk of entrapment in wildfires a case study of the Linton Fire", CFA Victoria Australia, 1999.

Flame height and peak MLR

It is important to understand the confusing concept that average flame height in a continuous fuel bed is caused by peak MLR of the fuel bed, not average MLR. This can be explained with fuel basket theory. If a small square of fuel bed is isolated and ignited, its MLR rises rapidly to a peak and then falls, and the flame height simultaneously rises to a peak and then subsides. Peak flame height is caused by peak MLR. If a few baskets are set in a line, and the end one ignited, the first one rises to peak MLR and peak flame height, then the second, and so on. Each peak flame height is the same, so that when the observer measures the average flame height along the line of baskets, he is in fact measuring the flame's peak height at the fuel bed's peak MLR.

Flame height and flame length

Researchers differentiate flame height and flame length. There is a range of possibilities, as Figure 12 shows. This means the bushfire manager must be able to clarify their definitions.



Flame height 4m
Flame length 6m

Height of tallest flash 7m
Length of tallest flash 10m

Flame angle 45^0

ROS 4.5 kph

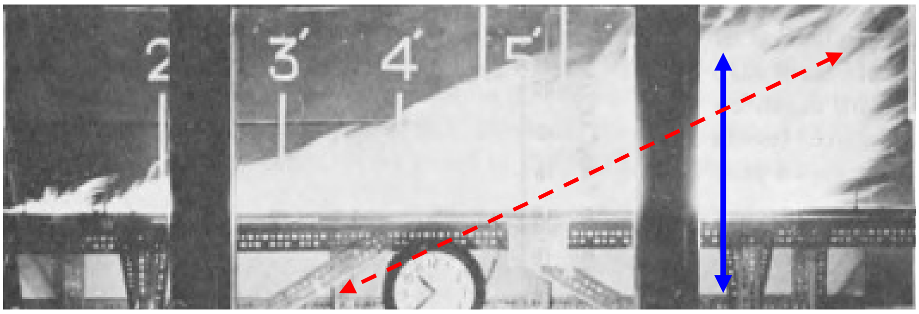
Figure 12 Copy of Fig 2.7 Cheney and Sullivan (1997)

Essentially, flame height is the vertical distance between average flame tip and basal fuel bed. This Manual regards it as the most meaningful variable with which to estimate the ability of the leading flame face to generate radiation or to stretch in the adjacent unburnt fuel bed or into a fuel free gap and inflict damage by direct flame contact by rollover, stretch or slap.

Length of a tilted flame has had a specific definition since the days of Byram (1959) – from flame tip to centre of flame's depth. In scenarios where flame depth is narrow, flame length is a reasonable representation of true flame length. In scenarios where flame depth is high, as in litter bed or grass with a strong wind, flame tends to be low and flame length is a proxy representation of flame depth.

In fire trials with stationary lines of flame, flame length in wind was found to be similar to flame length in no wind because two processes tend to cancel each other out (1) wind generates higher MLR which means taller flame and (2) increased air flow improves mixing rate within flame body, which means faster reaction rate and therefore shorter flame length (Thomas, 1962). He measured flame length from the downstream base of the flame face. Flame height reduced with wind speed as tilt increased.

In trials of a moving line of flame across a litter fuel bed, flame depth expanded substantially with increasing wind speed but flame height tended to remain more or less constant. The measurement of flame length depends on the definition. Figure 13 shows how the Rothermel and Anderson (1966) trials measured flame length. They defined flame length as distance "from midpoint of flame depth to tip of flame" but their data diverged from this definition as wind speed increased above 2m/sec. Thus at 2.2 m/sec wind speed, depth was 2m, but length was 0.6 to 0.8m, and at 3.5m/sec, calculated depth was 6m, but length was 1.1m. By definition, length should have been at least 1m and 3m respectively. The recorded flame dimensions for the photo in Figure 13 were height 0.5m, depth 6m and length 1.1m.



Ponderosa pine needle bed flame at 3.5 m/sec wind speed. The fuel bed was only 2.4m long, but they calculated flame depth as 6m. By definition, flame length should be at least 3m, but it was recorded as 1.1m (shown as dashed red arrow). Clearly, either the calculation or the definition were not consistent with visible data. Blue arrow is flame height (0.5m). Copy of Fig 6 Rothermel and Anderson (1966).

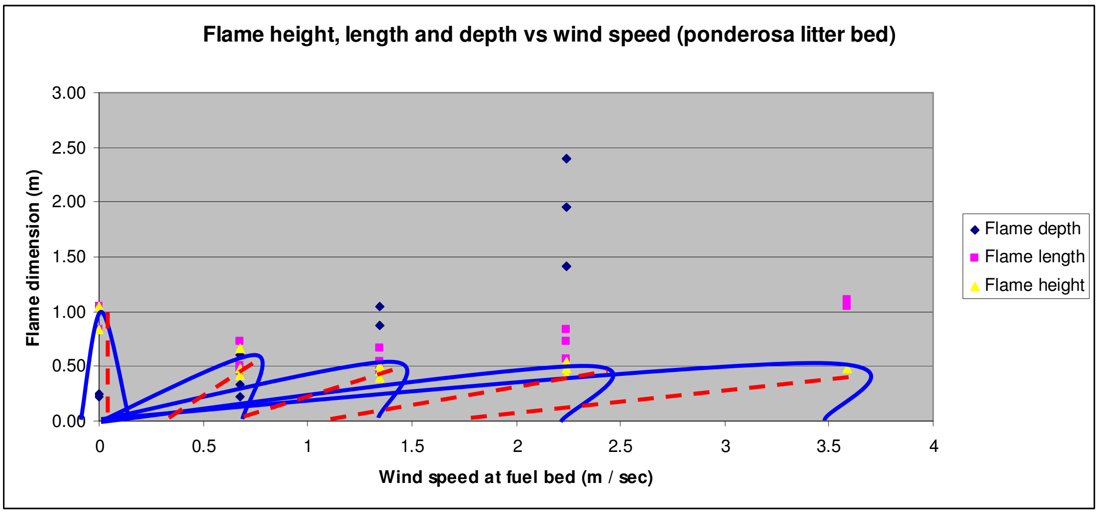


Figure 13 Chart of effect of wind speed on flame dimensions in Rothermel and Anderson (1966) trials. Solid blue line is actual flame cross section; dashed red line is theoretical flame length by definition. Flame height diagram is scaled against Y axis scale and flame length and depth diagrams are scaled against X axis scale. Flame depths for 3.5m wind speed not included, because they calculated them at 6m, but shown here as 3.5m for purposes of illustration.

The montage of flame cross sections shows that wind extends flame depth and that flame length by definition is approx half of flame depth. If the depicted flames stop at a fuel free barrier, the tongue of flame that rolls into it approximates flame height, not flame length. Catchpole et al (1993) suggested the flame length definition be reviewed because of its dependence of flame depth, but the old one still continues with its confusing significance.

Chapter 5
FLAME HEIGHT MECHANISMS – FUEL BED RELATED

Single layer flame height mechanisms

5.1A Litter bed flame height mechanism

Documented description: Burrows (1999) Rothermel and Anderson (1966)

Identifying features of litter bed flame: Flame height can be up to two orders of magnitude (eg, 100X) times fuel bed depth. Fuel bed is high bulk density at ground level; fuel bed in a bushfire is ignited on top surface; tall flash flame rises above fuel bed at the same time as flame front burns downward through litter bed depth.

Mechanism of tall flash flame: When preheated surface fuel pyrolyses (either by radiation or convection) it creates a high density of volatile gas at the surface. The warm vapour rises and dilutes to flammability level. Mixture then ignites, expands and flame rises to peak height, entraining oxygen into the flame body from air above fuel bed. At the same time as tall flash flame rises above fuel bed, the flame front burns downward through litter bed depth (Burrows, 1999).
- In a zero wind fire, the entire fuel bed depth burns simultaneously to produce the tall flash flame, which explains why flame height increases as fuel bed depth (= fuel loading) increases (Burrows, 1999).
- In a wind driven fire front, ignition occurs across a larger area of fuel bed surface and the flash flame has a larger depth and typically a smaller height than the zero wind fire. A smaller flame height at a given point suggests MLR is lower at that point, and indeed studies have shown that the faster the wind, the less the burn-down depth of the flame phase. Typically, only the top 15 – 20mm of the litter bed burns in wind to produce the tall flash flame (Burrows, 1999, Project Vesta, 2007). This is an approx fuel loading of 10 t / ha (1 kg / sq m)). Therefore greater fuel bed depth does not add to flame height or length during wind.

Figure 14 Litter bed flame in mature pine forest in Sydney bushfires 2002 / 2003. Extreme Fire Danger Index, very strong winds. Flame height less than 1m. Flame can be seen on lee side of some trees.

Flame height algorithm: Tall flash flame height in litter fuel bed is typically correlated with peak MLR per sq m to the power 0.4 (eg, Sun et al, 2006)

Influences on flame height: Increasing litter bed depth or fine fuel loading generates a taller flame in a zero wind but has little effect in a wind driven fire. For a given fuel bed, flame height increases as fuel bed flammability increases, eg, lower FMC, thinner fuel particles, greater aeration. Flame height in a litter bed increases within patches of low shrub or grass. Flame height in wind is often shorter than in zero wind, due to tilt and lower peak MLR. Flame length is not significantly influenced by wind because on the one hand, wind increases MLR which tends to increase flame length, but it also speeds up mixing of air with fuel, which reduced flame length (Thomas, 1962). Thus, as a rule of thumb, a free flame at the edge of a pathway will stretch horizontally as far as its height.

5.1B Grass flame height mechanism

Documented description: Overholt et al (2014)

Identifying features of grass flame: Fuel bed is low bulk density at ground level, comprising thin vertical particles; fuel is ignited at mid height or above; flame burns down and up within fuel bed and free flame rises above fuel bed. Free flame is up to 10X grass height.

Mechanism of tall flash flame: Radiation or convection preheats adjacent unburnt vertical fuel particles, which pyrolyse rapidly, creating a flammable density of volatile gas within the well aerated fuel bed. Mixture ignites within the fuel bed, expands, preheats nearby fuel particles, and air entrains into the flame from within fuel bed; flame then rises to peak height, entraining air into flame body from above fuel bed.

Flame height algorithm: Tall flash flame height in fuel bed is correlated with peak MLR per sq m and pyrolysis height (Overholt et al, 2014)

Influences on flame height: Taller grass generates taller flames because grass height is the pyrolysis height. Flame height is responsive to wind speed increase at low wind speeds, but unresponsive at high wind speed. Influences on flame height and length are similar to litter bed above.

Figure 15 Top picture - kangaroo flees head fire of grass fire, approx 50 – 100m wide, flame height 1 = 2m, Extreme Fire Danger Index, strong winds. Bottom picture - fire fighters attack head as it reaches road and mown grass verge, receiving full blast of hot convection gases and smoke. Green arrow is mown grass verge, now smouldering, dashed line is property boundary, white circle is fencepost. Technically, low flame height on grass verge ensured the flame could not cross the road, meaning it would have stopped without intervention. Key fire fighter role in this case was to be prepared to stop spotovers. Stills from U Tube video – Little River Grass Fire Jan 14, 3013

5.2 Multi layer or vertical layer flame height mechanism

Elevated layers in a forest are either live foliage (typically layers of shrub foliage with low bulk density) or vertically arranged dead fuel particles (eg, flammable trunks or dead debris in branch crotches) or both.

Documented description: Byram (1959) and van Wagner (1977)

Identifying features: Surface flame ignites one or more elevated fuel bed layers from below, each fuel bed layer then generates its own flame; flame height rises up through fuel bed and can rise as free flame above a fuel bed layer, which can ignite also the layer above. Free flame is up 5 - 9X of shrub layer height if contiguous to ground and 3X of elevated fuel bed layer depth (O'Bryan, 2005).

Mechanism of tall flash flame: Prerequisite is flame from below, which preheats fuel bed by radiation and convection power. Flame from below rapidly desiccates, preheats and ignites the base of fuel bed layer, creating an instant supply of volatile gas at flammability level within the fuel bed; volatiles ignite, flame expands, which preheats and ignites nearby fuel particles; air entrains from within fuel bed; if flame body rises higher to peak height, it entrains air from above fuel bed. If flame body rises higher, it can preheat and ignite next layer above.

Figure 16 Multi layer flame height mechanism ignites tall shrubs (2 – 3m) and free flame extends a further 4m or so.
Photo from cover of book "Game for Anything by Gideon Haigh, Black Inc", and published in Sydney Morning Herald, January 1, 2005 – "A bushfire fails to stop cricketers at Abernethy (near Newcastle) in 2003, Photo: Darren Pateman"

Flame height algorithm Total flame height = pyrolysis height + free flame
Peak flame height in a given fuel bed layer is correlated with peak MLR that layer (Dupuy et al, 2003)

Total flame height of a vertically arranged fuel bed is correlated with total height of fuel bed layers and total peak MLR. (Karlison and Quintere, 1999) and Ingason (2003)

Influences on flame height: the taller that fuel bed layers rise (assumes vertical continuity or small gaps between layers), the taller the flame rises (building block effect). Karlison and Quintere (1999) found that if identical wood pallets are stacked, peak MLR increases linearly with stack height, and flame height follows proportionately). If the gap between layers exceeds free flame height, further flame height rise may not occur.

Figure 17
Multi layer flame height mechanism ignites garden shrubs (1-2m) and free flame extends a further 5m or more.
Fire outbreak in Canberra residential area
29 December 2005.
Photo published in "The Age"

Chapter 6
FLAME HEIGHT MECHANISMS – NON FUEL BED RELATED

6.1 Merged flame height mechanism

Documented description: Baldwin et al (1964), identified by McArthur (1962)

Identifying features: When stationary flames are close (eg, less than a third of flame height) flames merge into one larger flame. Merging of close moving flames causes short lived flame height surges to 2 – 3 X original flame height at junction zones before rapidly subsiding. Separation distances are not well known - Wandilo fire storm was caused by flame merging when adjacent flanks were at least 200m apart (McArthur et al, 1966).

Mechanism When the high speed updraft of one flame is close to another, pressure deficit between plumes causes plumes to deflect together and merge into one flame; flame height increases because air supply to flame body is restricted, in the same way as four identical burners develop greater height when boxed together.

Tentative algorithm If flame height before merge = H, flame height during merge = 2 – 3 x H.
Variations: The merging mechanism can express itself in a number of ways. Eg, merging that occurs between tongues of flame that form along a wide flame front can range from a rapid lateral flame in-fill event to a triple height surge or a flame filled vortex that can remain in place or detach from the fire and run ahead of it as a normal mini tornado.

6.2 Trench effect flame height mechanism

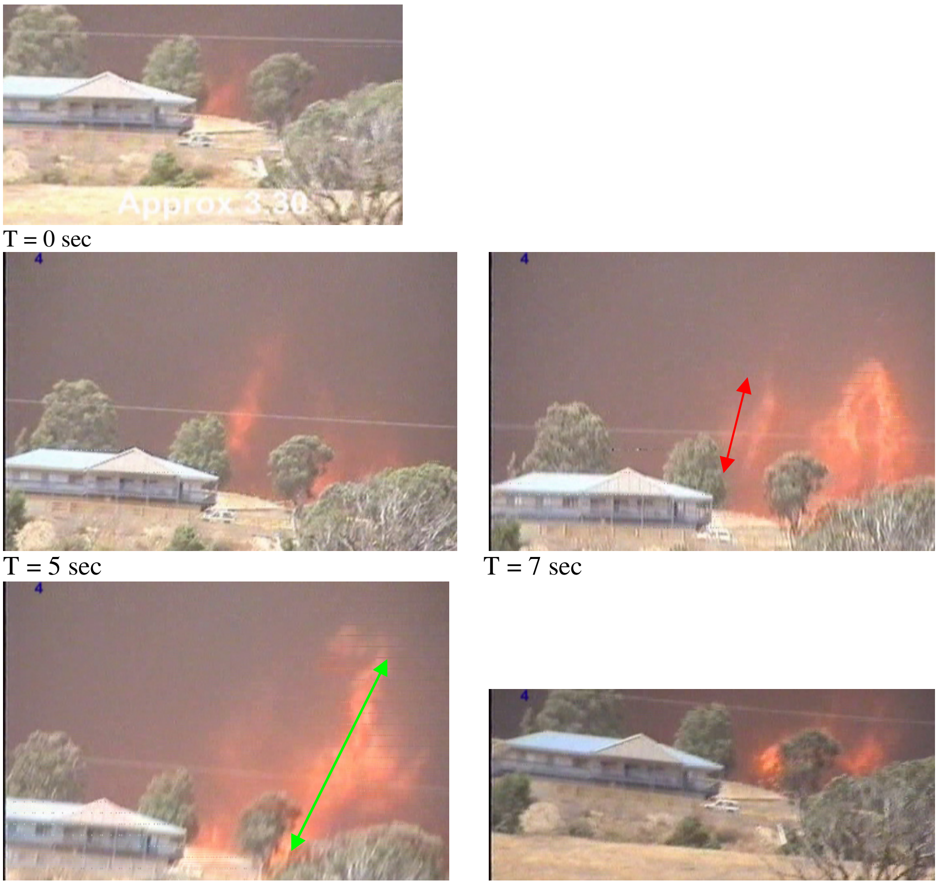
Documented description: Sharples et al (2014), Sharples et al (2010) Dupuy et al (2011)

Identifying features: low flame on very steep uphill slope; tall fleeting flame flash at top of slope; there are two phases – attachment and detachment

(1) Flame attachment mechanism: When a fire burns up a very steep slope (> 25^0), it draws air from one direction, ie, downslope, and air flow rate across fire is high. High air flow generates lower pressure along the slope due to a combination of Bernoulli's equation and Coandă effect, and this pressure differential causes airflow and flame to attach to the slope. The flames lay low to the surface and preheat the fuel ahead, and the flame progresses along the slope, igniting fuel by convection (ie, flame contact).

(2) Flame detachment mechanism: At the top of a slope, air flow and flame detach as air can now entrain from lee side of fire and a mass of flame rises within a hilltop-caused low pressure parcel. Visual appearance of floating flame indicates no turbulence, ie, suggesting a slower mixing rate of fuel air as low pressure mass rises.

Tentative quantification: flame attachment height < 5m; flame detachment height > 50m



T = 0 sec
T = 5 sec T = 7 sec
T = 8 sec T = 12 sec

Figure 18 Video stills of a flame detachment in a trench effect spot fire on Black Saturday, Victoria 2009. The flames are approx 3 km from the video location and house is 0.6 km closer. The flame flash marked red rises to approx 75m and lasts for 7 sec, and the flame flash marked green rises to approx 135m in 2 - 3sec and persists for about 5 sec. Copy of Fig 9 from O'Bryan (2016 a).

6.3 Vortex flame height mechanism

Documented description: Described as fire whirls by Countryman (1971) and Luke and McArthur (1978)

Identifying features Flame filled spike or whirl with tall but narrow rotating body.

Mechanism of ground level vortex: When a local air pressure variation or environmental factor triggers an angular air flow entry into a flame, the flame base spins and fresh air is also drawn into the spiralling streams of flame. Parallel flow within the whirling mass slows air-fuel intermixing and forces more air to be entrained, causing height of flame spike to increase instantly.

Quantification (deduced): Height of flame spike may be related to air rotation rate.

Variations: Fire whirls or tornadoes are frequently seen along fire fronts and flanks of both bushfires and sometimes in lab trials. Extreme example: Keeves and Douglas

(1983) reported a flame filled tornado 250 – 300m high and 35 – 70m diameter between two large parallel rapidly moving fires on flat terrain in mixed grass, woodland, plantation landscape. The tornado area was 1 km behind the fire front which was 4 - 5 km wide and a few km from the adjacent fire that was 8km wide and whose front was 10 - 15 km downwind.

T = 26 seconds

T = 36 seconds

T = 45 seconds

T = 48 seconds

Figure 19 Video stills of a vortex flame in spot fire on Black Saturday, Victoria 2009. The spike of flame is approx 100m long and 20 m diameter, tilted 60^0 from vertical. This vortex lasted no longer than 4 or 5 seconds before collapsing abruptly. Immediately, the leeward slope was covered with rising clouds of dense white smoke. Copy of Fig 25 from O'Bryan (2016 a).

Convection column influences

6.4 Convection column updraft mechanism

Documented description: Chandler et al (1983), Treloar (1999)

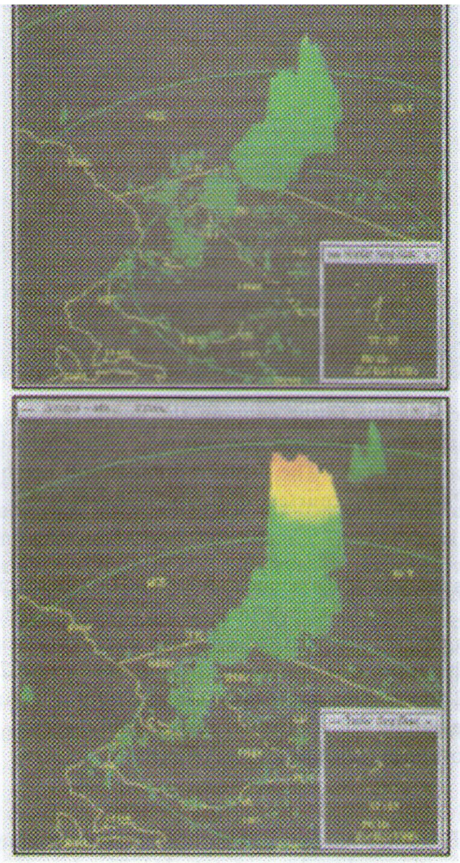
Identifying features: Moist air mass in upper atmosphere crosses a large fire and causes the plume to rise with renewed vigour; stimulates higher fire intensity, with longer flames and greater spotting activity and higher ROS. Winds are low to moderate.
Cloud identifiers – rapid convection, cloud rises, sustained uplift speeds of 10 m/sec, and heights of 10,000m.

Mechanism
Atmospheric mechanism: If a moist air mass crosses a fire it can generate a massive convection cell as it rises; when it reaches condensation point, it releases another mass of energy and warmth that increases the convection uplift again (Treloar, 1999)

If atmosphere is unstable, the uplift of air is unlimited and the updraft becomes more powerful. It generates higher fire intensity, with longer flames and higher ROS and greater spotting activity.
If the atmosphere is stable, its rise is checked at the height of the inversion, and fire behaviour is "normal". If the convection column breaks through the inversion, it can cause the fire to suddenly intensify as the updraft strengthens. It can also cause upper level winds to come to ground and further intensify the fire (Chandler et al, 1983).

Fire height mechanism: Increased convection aloft reaches down to ground level, increasing air inflow at the fire ground. Flame height grows larger, either due to lower air pressure or increased entrainment into the plume.
Example: The Berringa fire reportedly grew in flame height and ROS at the same time as the moist air mass crossed the fire, causing the convective cloud height to grow vigorously from 4,000m to over 10,000m in 10 minutes, an uplift rate of 10.5 m / sec. Yet winds were light (Treloar, 1999). This Manual suspects the most likely spread mechanism in these conditions was ***tall flame / piloted ignition***. The forest type of flammable messmate trunks was conducive to tall flames.

Also refer to ***3.3 Atmospheric downburst spread mechanism***



Three-dimensional weather radar imagery showing spectacular growth in radar echo between 1832 hours (0732Z) and 1852 hours (0752Z). Radar top height increased from 3,300 m to 11,500 m during this period. Colours represent echo height increasing from green to yellow and then brown. The view is looking towards the west-northwest.

Figure 20 Copy of Fig 7 from Treloar (1999)

Summary of flame height mechanisms
Table assumes severe weather conditions

Category – flame height mechanisms influenced by fuel bed factors

Flame height growth mechanism	Surface fuel bed layer	Elevated fuel bed layer	Fuel bed Factors	Flame behaviour
5.1A Single layer mechanism Litter bed ***Heat transfer mechanism***: Any ***Ignition mechanism***: Any	Fuel bed ignites on upper surface. Surface volatiles too rich Flame height rises for dilution and combustion	NA	Fuel bed has high bulk density, Flammability determines peak MLR Flame height is correlated with peak MLR of layer	Flash flame is above fuel bed Flame height is two orders of magnitude times (100X) fuel bed depth
5.1B Single layer mechanism Grass ***Heat transfer mechanism***: Any ***Ignition mechanism***: Any	Fuel bed ignites mid height, Volatiles are at flammability level. Flame height rises as lower and taller fuel particles pyrolyse	NA	Fuel bed is low bulk density, Flame height is correlated with peak MLR of layer and pyrolysis height	Flash flame is within and above fuel bed Free flame is up to 10X grass height
5.2 Multi layer / Vertical layer mechanism ***Heat transfer mechanism***: Radiation and Convection ***Ignition mechanism***: Flame contact	Prerequisite: flame exists in surface layer, ignition of upper layer from below by direct flame contact	Ignites at base. Pyrolised volatiles are at flammability level within low density of layers. Flame rises through rapidly preheated fuel particles	Flame height of a layer is correlated with peak MLR of layer and depth of layer. Total flame height is correlated to pyrolysis height	Flash flame is within and above fuel bed Free flame is up to 3X fuel bed layer depth

Category – flame height mechanisms influenced by non fuel bed factors

Flame height growth mechanism	Surface fuel bed layer	Non fuel bed factors	Flame behaviour
6.1 Flame merge mechanism	Prerequisite: flame exists in surface layer of adjacent fires	Pressure deficit between fires causes plumes to deflect and merge into one flame, Flame height increases because air supply to	The merger can express itself as rapid lateral flame in-fill or 2X – 3X flame height expansion or flame

		flame body is restricted.	filled vortex
6.2 (1) Trench effect flame - attachment	Prerequisite: flame exists in surface layer Flame spreads by ***Heat transfer mechanism***: Convection ***Ignition mechanism:*** Flame contact	Steepness of hill causes one sided entrainment and rapid air flow uphill across fire area consequent air pressure deficit along hillside	Flame height is low because it is attached to slope due to high speed air flow from down hill and consequent air pressure deficit along slope
6.2 (2) Trench effect flame - detachment	Prerequisite: flame exists in surface layer	Flame lifts up within low pressure parcel at top of slope.	Flame height is independent of fuel or surface flame at break of slope.
6.3 Vortex flame height mechanism	Prerequisite: flame exists in surface layer	A trigger factor causes angular air flow entry into flame, which then spins. Parallel flow within the whirl slows air-fuel intermixing, causing flame height to increases.	Flame height is independent of fuel Flame spike can be many times original flame height. Flame vortex height growth stops when all volatiles combust

APPLICATION OF BUSHFIRE BEHAVIOUR MECHANISMS

This section explores how to apply the Manual's mechanisms with some practical examples. The first is a preliminary review of fire behaviour models.
Models were built without the benefit of the discipline of this Manual of mechanisms, even though researchers are fully familiar with each component process. The Manual presents one model as an example of partially successful application, meaning essentially that research focused on a single mechanism (wind spread) and a clearly defined theory, and extrapolation limited itself to the same mechanism and theory. This is the CSIRO Grassfire Meter. It has been only partially successful because the influence of FMC incompletely analysed as was the prediction of flame height.

Several other well known models are examined with the same criteria, and all are found to have diverged from clear focus on one mechanism and clearly defined theory in both research trials and particularly in extrapolation. The Byram fireline intensity equations were more likely a by-product of research in another area rather than a result of specific research. However, it is examined at its roots using the same criteria because it has become mainstream among researchers and managers to apply it well beyond its design capability. It may well have a useful role if it can be re-rooted in scientific foundations, along the lines of the Thomas et al (1964) analysis.

The Manual also identifies the Australian bushfire building standards regulations as a cause of concern because it is built on application of the wrong research findings and not only on application of the wrong fire behaviour equations but also extrapolating them well beyond their design criteria. The standards were originally designed to increase fire resistance in new buildings, for example by classifying a house with a specific Bushfire Attack Level. But now fire agencies are extrapolating these standards well beyond their design criteria by applying them as defacto fire protection measures - classifying whole areas at specific Bushfire Attack Levels. While the concept of classifying an area according to level of bushfire threat is useful as a first step in a threat management strategy, its success depends on identifying the correct threats. The quantified threat in the Bushfire Attack Level standards is radiation from a flame face of the fire front whereas the overwhelming cause of house loss is ember attack from a distant fire front. Until the authorities identify the correct threat, new house industry in bushfire prone areas will continue to be beset with unnecessary additional costs and bureaucratic torpor.

This Manual may be useful in refocusing the attention of bushfire managers and researchers and authorities in the value of rooting research and laws in scientific foundations. For this reason, the Manual includes a section on how to identify and manage bushfire threat from a first principles approach, commencing with the smallest units - the property and the neighbourhood. As always, the best community outcome occurs when the correct approach is applied appropriately and when people are armed with knowledge and skill and coordination is effective. However, there appear to be a number of hurdles in the way, so until then, people can take individual action to protect their own properties or their neighbourhoods very effectively from the bushfire threat.

Chapter 7

CASE STUDIES

Fire behaviour models are now systematically analysed against the two of the critical criteria of the first principles approach, namely, what spread mechanism is the model describing, and what theory is it based on? These criteria gauge how well the model relates back to fire principles of science, and in particular, bushfire behaviour science.

1 Example of partially successful application of first principles criteria

CSIRO Grassfire Meter (Australia, 1997)

ROS

The two key questions can be answered by deduction as follows. The ROS predictions in the CSIRO Grassfire Meter derived from a range of experiments designed around the wind driven mechanism and the theory that ROS was causally correlated to wind speed and inversely correlated to FMC.

Their trials (eg, Cheney et al, 1993) were conducted in wind up to 8m/sec wind and they recorded ROS up to 2m/sec. Grass was mostly fully cured and average FMC was 7% (range 6 – 8%). There were two species of grass and two heights, 10cm and 30cm, approx. They found an approximate linear correlation with wind speed for both grass heights, noting that ROS of short grass averaged 80% of the tall grass ROS.

They assumed an inverse correlation between FMC and ROS, but their range of FMC in the trial was too narrow to confirm it. Furthermore, they said they were unable to physically measure FMC, so they estimated equilibrium moisture content (EMC) from Temperature and RH scales and confirmed an inverse correlation between EMC and with ROS. It can be deduced that they eventually found that this FMC function - (***exp (-0.108 x FMC***)) - could comfortably incorporate bushfire data up to 3% FMC.

The extrapolation process integrated trial fire data with bushfire data in very dry fuel (2 – 3% FMC) up to wind speeds of 11m/sec (50 kph at 10m height) and ROS of 6 m / sec (22 kph). The algorithm splits the data spread, but the range of predicted ROS for a given wind speed is within ± 30%.

Comments:
(1) Whilst there was no direct reference to the wind driven mechanism and its causal influences, the trials and findings imply it was well understood.
(2) It may have been an oversight that they did not derive the exponential FMC function empirically because FMC is such a critical input variable. Their log function approximates to FMC to the power - 0.6. An earlier systematic study by Byram et al (1966) found that in 12 mm square sticks, found ROS was correlated with FMC to the power – 0.38. They found one other input variable, fuel density also influenced ROS, but they did not examine the influence of FMC and fuel thickness. The Vesta algorithm seems to have been close to actual. Recent grass studies (eg, Overholt et al, 2014) found a slightly lower index, approx 0.3 – 0.4, perhaps confirming that FMC

changes in low density particles like dry grass (below FMC 10%) have minor influence on ROS.

Flame height
Answers to the two key questions cannot be deduced. Flame height was measured, but no causal mechanism or theory was referred to. Clearly, they obtained flame height measurements for their trial fires, but the source of flame height data for severe weather was not referenced. Instead, the Grass Meter presents a table that implies flame height is correlated with fuel height and ROS. Fuel height is linked to pyrolysis height, but ROS is inappropriate to use as an input variable because it is a dependent variable, but is probably their proxy for wind speed.

The single layer flame height mechanism shows that flame height is a function of peak MLR and pyrolysis height. Peak MLR is not mentioned in their reports and although they did not examine the link between wind speed and either peak MLR or flame height. For example, wind speed is known to increase MLR, which increases flame length, but it also increases mixing in the flame which reduces flame length. The net effect on flame length is negligible change (Thomas, 1962). They found that fuel height influenced flame height, they did not reveal their data or analyses.

Comments:
(1) Because there is no reference to flame height mechanism, the flame height prediction is weakened because it lacks lineage to core foundations and the correlation with ROS is invalid.
(2) The Cheney and Sullivan (1997) chart of flame height vs ROS is confusing because the X-axis by convention should be an independent variable, and ROS is a dependent variable. They have delivered the perception to the reader that flame height and ROS are causally correlated, when at best, the correlation is coincidental.

2 Examples of divergence from the first principles criteria

Byram's fire line intensity (BFI) equations (USA, 1959)
The two key questions can be answered by deduction. Based on his one and only data chart of ROS vs wind speed, the Byram equation is presumably related to the wind spread mechanism, ie, the theory is that ROS is directly correlated with wind speed. The flame length equation implies a causal link between total energy released times ROS and flame length, which is very different to the contemporary understanding that the link occurred between flame length and rate of mass loss, which is a direct measure of fuel supply rate.

Byram's fire intensity BFI = Hc x W x ROS (where W = weight of fine fuel consumed in the flash flame phase [usually abbreviated to BFI = H W R]
Meaning - the product of total flame energy and ROS determines fire intensity. Byram (1959) envisaged a bushfire as an energy wave times speed concept - a line of flame energy per unit length of fire line (HW = kJ / kg x kg / sq m = kJ / sq m) spreading across the landscape at a measurable ROS. This was out of sink with contemporary understanding that mass loss rate (not initial mass) was the fuel supply that powered the flame. Eg, the first thing Thomas et al (1964) did in their analysis was to convert Byram's equation from **H W R** to **Hc x MLR x depth** and insist that

the power function derived from first principles was 0.66 not 0.46. Although the Thomas et al approach was scientifically correct, the Byram equation retained its format as HxWxR. Although both equations delivered the same units (kW / m), the subsequent incorrect usage of initial fuel load by bushfire researchers and managers alike has had led to entrenched misunderstanding of core principles of bushfire behaviour science, which specifies that flame size is a function of mass loss rate and has no causal connection with initial mass (W), or total energy release (HxW) or its rate of spread. Thus there can be no quantitative or causal connection between the HWR version of Byram's fire intensity and any aspect of fire behaviour or physical danger to house or person, eg, radiation level.

Byram said most bushfires were between 3,500 and 35,000 kW / m, but his description mentioned fast moving fires with intensities greater than 100,000 kW / m. His 35,000 kW / m fire would be burning available fuel loads of 13 t / ha (1.3 kg / sq m) and spreading at ROS 0.6 kph with a flame height of 3m that was consuming the litter bed and undergrowth and licking up into the canopy. His accompanying chart showed that this ROS was caused by a sub canopy wind of 7 kph at fuel bed. He also said a fire spreading at 1.8 kph and consuming 3 t / ha would have the same intensity, but could not physically occur in this forest.

His examples indicated that a low BFI was clearly low fuel load - low ROS and very high BFI was high fuel load - high ROS, but moderate BFI could be either high fuel load - low ROS or low fuel load - high ROS. The correlation between these BFI levels and fire danger is vague.

He did not explain how to deal with fire intensity for stationary fires, which by definition must be zero because ROS is zero, yet they are a substantial cause of house loss.

Intensity and flame length
Byram's original equation:
Flame height (ft) = 0.45 x (fire intensity in BTU / foot / sec) ^0.46
It was developed in a grassy pine litter bed beneath a pine forest in USA, He clearly intended his flame length equation to be a causal correlation for litter and undergrowth in this fuel type, but he noted it was unsuitable for tall forests because "much of the fuel is a considerable distance above the ground". He proposed an adjustment to deal with the equation's systemic underestimation for tall forests. Eg, fire intensity increased as flame height rose upward, making more fuel available His examples reinforced its applicability to sub canopy fires in a pine forest, with no reference to other fuel types. Byram did not explain the mechanism that linked total energy or its combination with ROS with flame length. In absence of a theoretical justification, the linkage appears to be coincidental, not causal, and is therefore inappropriate for prediction purposes.

McArthur Meter model (Australia, 1967)
ROS
The two key questions can be answered by deduction as follows. Research and data were sourced from several mechanisms (radiation, wind spread and spotting) and the model appeared to be based on the theories that ROS was causally correlated with

wind speed, fuel load and intensity of short distance spotting, and inversely correlated to FMC.

McArthur conducted low intensity fire trials in zero wind and in windy conditions in the "McArthur forest", defined as a tall eucalypt forest with predominantly litter bed underneath. He explained qualitatively how the Meter's predictions could be adjusted and applied as estimates to all eucalypt forests.

It can be deduced that his model amalgamated data for three mechanisms, and accounted for the boost due to short distance spotting by giving wind speed and FMC a higher power function than his original data may have found. His model was extrapolated to account for severe bushfires. It appears that his data amalgamations did not include the very fast ROS of leap frog spot fires. In this sense, his model was more or less loyal to the wind driven mechanism.

Flame height

Answers to the two key questions cannot be deduced. His trials and bushfire reports probably measured flame heights, but data is scarce. No causal mechanism or theory was referred to. The Meter presents a table that implies flame height is correlated with fuel load, ROS and Fire Danger Index.

Comments

Whilst the McArthur Meter initially appeared to be effective, it actually concealed the true influence of each mechanism, which effectively prevented user feedback, verification and advancement of bushfire behaviour knowledge. Users also lost sight of its original design criteria, and began stretching them to meet the demand for an all purpose predictive model. Eg, they discovered that manipulating fuel loads allowed any ROS to be predicted or explained. His recent critics (eg, Project Vesta, 2007) pointed out how disappointing it was that the McArthur Meter model failed to accurately predict the 10 kph ROS of the Deans Marsh leap frog fire. But they were unfairly comparing corgis with greyhounds.

Rothermel's model (USA, 1972)

ROS

The two key questions can be answered by deduction as follows. Rothermel's (1972) data and analyses were based on the radiation and conduction mechanisms. His spread theory was based on ROS being directly proportional to fuel bed aeration and inversely proportional to particle size. He theorised that ROS due to aeration and particle size was transferrable to all fuel beds at given FMC. In hindsight, the assumed ignition mechanism was auto-ignition.

Rothermel developed a complex ROS model of energy transfer into and out of a fuel bed, complete with conservation of energy and mass for zero wind and zero slope. To account for wind driven spread, he then multiplied this zero wind model by a wind coefficient derived from wind driven fires. He clearly assumed that the ROS mechanisms of zero wind continued unchanged with wind. When seen in the context of mechanisms, he amalgamated two mechanisms (radiation and conduction) with a different one (wind driven) into one and extrapolated from a single layer into multiple layers.

Comments
Amalgamation of different mechanisms is not a comfortable fit. It assumes that the radiation / conduction spread-determined mechanisms in zero wind have the same influence on ROS as the very different wind spread mechanism, whose heat transfer mechanism is primarily convection and whose ignition mechanism is flame contact by flame tilting and slapping onto and into the unburnt fuel bed.

Project Vesta model (Australia, 2007)
ROS
The two key questions can be answered by deduction as follows. Data and analysis were based on the wind spread mechanism, ie, that ROS was causally correlated with wind speed and inversely correlated to FMC. They also theorised that ROS was also dependent on an unidentified aspect of fuel bed, probably fuel age, and this aspect appeared to be the focus of their matrix of data and analyses.

Their results featured a wide range of ROS data, including many fast spreading fires at low wind speeds. They amalgamated the data and sorted on an unverified FMC algorithm, yet the data scatter remained large. They excluded some data that featured very high ROS on days of low wind speed on the grounds that they could not explain it. A separate study by the author (O'Bryan, 2016 b) found these fires were due to a second spread mechanism, the tall flame / piloted ignition spread mechanism, one that was more or less independent of wind speed. Nevertheless, their final algorithms included all data together. They then verified their wind spread algorithm with high ROS data caused by another mechanism – leap frog spot fires, and then claimed that their algorithms were now suitable for use across Australia.

In the context of mechanisms, they assumed their data applied to the wind spread mechanism and unknowingly amalgamated trial data from two spread mechanisms, thereby unknowingly diminishing the predictive value of their data. Their verification process used data from a very high speed leap frog bushfires, further unknowingly devaluing the predictive value of their model.

Flame height
Answers to the two key questions cannot be deduced. Vesta trials measured flame heights, but no causal mechanism or theory was referred to. Their model Meter presents a table that implies flame height is correlated with ROS.

Comments
Project Vesta model is based on amalgamated data from three very different spread mechanisms (wind spread, tall flame / piloted ignition spread, leap frog spotting spread). Because there is no defined spread mechanism, the user will be unable to explain why it predicts or mis-predicts a given fire, and will therefore be unable to grow in bushfire behaviour knowledge.

Chapter 8
HOW MANUAL CAN HELP SOLVE THE BUSHFIRE PROBLEM

1 Example of mis-application of models, theories and fire behaviour mechanisms

Australian bushfire building standards

The bushfire building regulations model uses a combination of risk management and fire behaviour modelling to assess bushfire risk of new houses in bushfire prone areas, and then applies construction standards that purport to counteract that risk.

In practice, the assessed risk is incident radiation level from a deemed tall flame in the nearest forest which is deemed to be at highest fuel load and the construction standards are deemed to protect against piloted ignition at that radiation level. They also include features that aim to prevent ember ignition. This model is packaged into Australian Standard AS3959.

AS3959 identifies that the threats to the house are radiation and embers from the flame in the nearest vegetation, which it deems to be the fire front that is deemed to pass over the house. The AS3959 model does not contemplate how the fire front will pass from the nearest vegetation (sometimes this vegetation is downwind of the house), nor does it contemplate any other source of threat. In fact, it clearly states that vegetation beyond 100m is not a threat (yet most spotting comes from forests > 100m away. Its theory is that if they equip the new house against perceived threats from the nearest vegetation, the house will be protected against bushfires.

Threat identification - nearest vegetation

The source of the belief that risk level is inversely related to distance from the nearest vegetation is a low quality but often quoted report by Ahern and Chaldl (1999). The belief mysteriously endures even though they did not investigate whether house loss was caused by the nearest vegetation nor did they investigate the coincidence hypothesis that house loss was higher near vegetation because most houses occurred near vegetation. A report to the VBRC indicates how entrenched this belief has become. It produced evidence that supported this hypothesis (Leonard, 2010), but overlooked data that showed that house loss was higher near vegetation because most houses occurred near vegetation:
"The influence of trees close to the house is strongly expressed in Table 33, with a strong correlation between houses with overhanging or adjacent trees and house loss.
Their leading evidence said:
Of 756 surveyed houses, 63% were destroyed.
Of 540 houses with bushes or trees adjacent to house, 67% (363) were destroyed
The survey asked two independent questions per house – what are the adjacent vegetation types and what is the level of house damage. Thus there was no requirement for evidence that adjacent vegetation was the cause of house loss. This lack of causal damage can be demonstrated with data from their Table 33.
Of all 756 surveyed houses, 71% have trees and bushes close to the house.
Of 476 destroyed houses, 76% have trees and bushes close to the house.

Thus, in round figures, they discovered that approx 2/3 of destroyed houses had bushes or trees close to the house and that approx 2/3 of all houses had bushes or trees close to the house.

Threat identification Ignition mechanism

AS3959 identifies two of the four heat transfer mechanisms as threats, radiation and spotting. It calculates flame height for forests using a tortuous route with equations that have been extrapolated beyond their design criteria.
Firstly, it uses the McArthur Meter model and loads it up with the maximum fuel load so that it predicts the highest ROS. It is applying this model well beyond its design criteria.
It then uses Byram's equation to calculate fire intensity using maximum fuel load and maximum ROS.
It then uses Byram's flame length equation designed for a sub canopy pine forest fire in USA to calculate flame height of a crown fire in a eucalypt forest. Again, this equation is well beyond its design criteria. It then calculates incident radiation using this flame height and deems its width to be 100m.

Threat mitigation

It calculates radiation levels and specifies fire resistant construction materials based on exposure tests done in the lab under 25 kW / sq m radiation for 10 minutes.

Comments

AS3959 is primarily designed to protect houses from radiation despite radiation being a very minor cause of house loss (eg, Blanchi et al 2006). It also claims to protect against embers from the flame in the nearest vegetation. As such, it misses the mark. The proven primary cause of almost all house loss is direct ember attack onto the house from a distant upwind fire front (This is the mass transport heat transfer mechanism and the cold ember ignition mechanism), and the secondary cause is the same embers igniting flammable fuel near and around the house, generating "urban flame" very close to the house (This is the convection and radiation heat transfer mechanisms and the ignition mechanisms are piloted ignition and direct flame contact). A rather uncommon cause of house attack is the mother fire front reaching the house. It rarely happens, and in fact people tend to mistakenly believe that the urban flame is the main fire front.

In conclusion, the building standard aims to protect the house against radiation from the nearby flame face, ie, technically up to 25 kW / sq m. But it is a futile protection exercise. Apart from the fact that it almost never happens in a bushfire, it is benign compared to the overlooked furnace – the convective power searing out of the flame tip at 1000 kW / sq m and more (refer p 8 above).

2. Summary of prediction tools and quantitative guidelines for fire behaviour mechanisms

Flame spread mechanisms

Model for specific spread mechanism in specific fuel type

Flame spread mechanism	**Indicative spread rate and correlation with wind speed ****	Grass	Forest without shrubs	Forest with shrubs	Heathland
2.1 Radiation Occurs in low to moderate wind	Slow < 0.1 kph				
2.2 Tall flame / piloted ignition Occurs in low to moderate wind	Moderate to fast, eg, up to 3 kph ROS can be 20 to 100% of wind at fuel bed	N A*	N A*	Vesta Model (when reanalysed)	N A*
2.3 Wind driven continuous spread	Slow to fast Grass ROS = 40% Heath ROS= 25% Litter bed ROS = 10% of wind at fuel bed **	CSIRO grass fire Meter	McArthur Meter Model	Vesta model (when reanalysed)	Marsden Smedley model format is suitable for heathland
2.4 Backing fire Flame backs slowly into prevailing wind	Slow < 0.1 kph				
2.5 Upslope, Low to moderate slope	McArthur's ROS doubles for each 10 deg increase				
2.7 Down slope	McArthur's ROS halves for each 10 deg decrease				
3.1 Trench effect: (Very steep upslope)	Theoretically exceeds # 2.5 spread rate				
3.2 Merging flame					
3.3 Atmospheric downburst 3.4 Below canopy convection	Use wind spread guidelines / models Intermittent slow and fast ROS				

* Mechanism not applicable in this fuel type
** Indicative spread rates for common fuel types as a percentage of wind speed at fuel bed for bone dry dead fuel particles

Firebrand spread mechanisms

Model for specific spread mechanism in specific fuel type

Spot fire spread mechanism	**Indicative spread rate of leading spot fires**	Grass	Forest without shrubs	Forest with shrubs	Heathland
4.1 Short distance spotting (Wind assisted)					
4.2 Medium to long distance spotting (Wind and plume assisted)					
4.3 Leap frog spotting (Wind and plume assisted)	ROS of 5 – 15 kph is common, but up to 24 kph has occurred	N A*	N A*	Red Eagle model	N A*
4.4 Wandilo effect (wind and plume assisted)					

Flame height mechanisms influenced by fuel bed factors

Model for specific flame height mechanism in specific fuel type

Flame height growth mechanism	**Indicative flame height**	Grass	Forest without shrubs	Forest with shrubs	Heathland
5.1A Single layer mechanism Litter bed			Burrows		
5.1B Single layer mechanism Grass		CSIRO Grass fire Meter			
5.2 Multi layer / Vertical layer mechanism			N A*	Vesta Model (when reanalysed)	Marsden Smedley model format is suitable for heathland

Flame height mechanisms influenced by non fuel bed factors

Flame height growth mechanism	**Indicative flame height**
6.1 Flame merge mechanism	2X – 3X flame height expansion
6.2 (1) Trench effect flame - attachment	Flame attachment height < 5m
6.2 (2) Trench effect flame - detachment	Flame detachment height > 50m
6.3 Vortex flame height mechanism	Grass vortex flame height < 5m Forest vortex flame height > 50m Heath vortex flame height < 20m

3 How to use this Manual to identify and manage the bushfire threat on a property or neighbourhood

A good starting point is to begin with the standard threat analysis method:

- Identify threat eg. stationary flame, moving flame, fire brands
- Assess potential damage of each threat
- Take action Counter measures include - tolerate, mitigate or eliminate threat

The Manual can then be used to help identify the threat to your property and whether your property is a threat to the neighbourhood. [This approach can be extended regionally.]

A Is your property at threat from bushfire attack?
Answer these questions:
Is your property at threat from bushfire attack?
If so how and what can be done to prevent / mitigate?

Assess type of bushfire attack expected in worst case weather:
Identify flame height mechanisms on neighbouring properties
Assess flame heights in severe bushfire weather
Identify potential flame spread mechanisms between nearby properties and your property
Assess fuel continuity between nearby properties and your property
Identify potential firebrand spread mechanisms on neighbouring properties

Identify threat on your property
Identify flame height mechanism on your property
Identify spread mechanism on your property
Identify vulnerability of people or assets to firebrand exposure

Assess potential damage to people or assets on your property caused by:
Proximity and exposure of people or assets to radiation and convection heat from nearby flame
Exposure of flammables to firebrands that will ignite and develop into flame
Exposure of people or assets to firebrands that can cause damage
Exposure of people or assets to falling trees and branches or loose debris that can damage house and allow entry of firebrands

Take action

- Prevent threat from stationary flame, eg, change flame height mechanism by changing vertical fuel bed structure
- Prevent threat from moving flame, eg, change flame spread mechanism by managing fuel bed continuity on ground
- Reduce or eliminate flame height in nominated areas, eg, change flame height mechanism by changing vertical fuel bed structure
- Prevent ignition threat from firebrands
- Prevent damage threat from firebrands
- Prevent threat from physical damage

B Is your property a threat to the neighbourhood?
Answer these questions:
Is your property a source of threat to the neighbourhood?

If so, what can be done to prevent your property being a source of threat?

Identify threat of your property to neighbourhood
Threat of flame escape: Identify flame spread mechanisms on property
Threat of firebrand escape: Identify flame height mechanisms, assess firebrand volume and type

Assess potential damage to people or assets on your property
Threat of flame escape: Using flame spread mechanism, identify potential of flame to escape from property
Threat of firebrand escape: Assess maximum flame height on property, and distance of travel

Take action
Threat of flame escape: change flame spread mechanism by managing horizontal (on ground) fuel bed continuity
Threat of firebrand escape: change firebrand spread mechanism by managing vertical fuel bed continuity

Potential threat to your property

Type of threat on your property

Upwind or down hill of property

Flame threat

Firebrand threat

On your Property

Flame height mechanism

Flame spread mechanism

Firebrand impact

Is your property a a potential threat to neighbourhood?

Downwind or uphill from property

Flame spread from property

Firebrand spread from property

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