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A handbook of wildfire engineering: Guidance for wildfire suppression and resilient urban design

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A HANDBOOK OF WILDFIRE ENGINEERING

Guidance for wildfire suppression and resilient urban design

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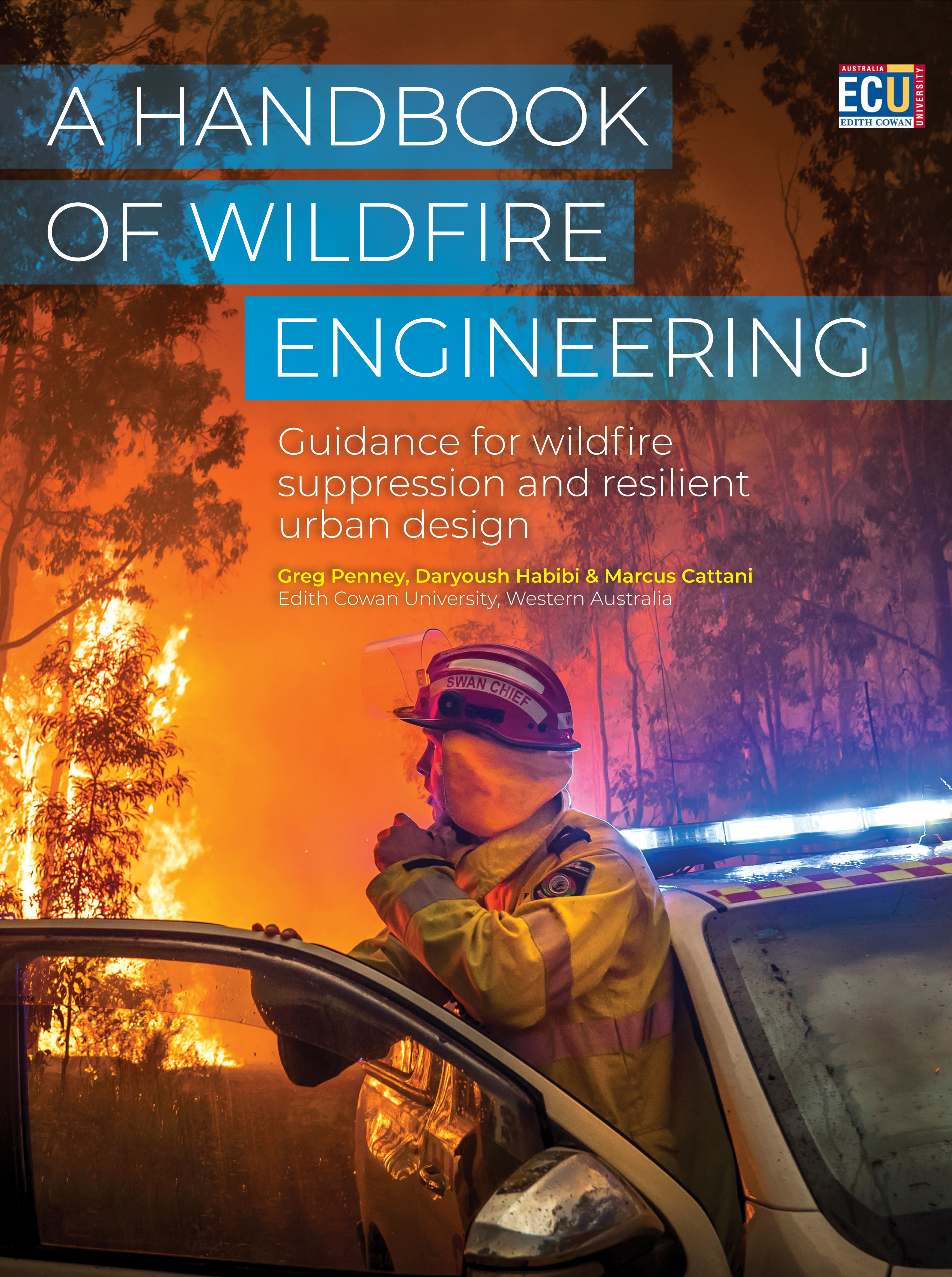

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Greg Penney is the primary author. With over 14 years' experience as a career urban and wildland firefighter / officer in Western Australia (in both metropolitan and country commands), amongst other qualifications he holds a MEng (Building Fire Safety & Risk), MParamedScRes (Risk), GDip Bushfire Protection and Bachelor of Science. During the devastating Waroona/Yarloop wildfires of 2016, Greg received a commendation for distinguished service and outstanding actions in leading the defence of Preston Beach facing catastrophic wildfire conditions. *A Handbook of Wildfire Engineering* builds upon his two existing Masters dissertations and serves as part of his current PhD by publication "*Wildfire suppression – an international analysis of operations, strategy and firefighter safety*". As a subject matter expert, Greg developed the inaugural Fire Protection Association of Australia (FPAA's) Bushfire Protection and Design Accreditation (BPAD) Level 1 course and has previously consulted in the field to the Department of Defence, NBN Co, Western Australian branches of Master Builders Australia, Australian Institute of Building Surveyors, Australian Institute of Architects, Local Governments and private industry. In his current fire service role Greg leads the development and delivery of Incident Management training, including strategic and tactical fire and rescue response across a large range of hazards including wildfire, urban fire, rescue and Hazardous Materials. Greg is not only a highly qualified researcher in the field of wildfire engineering and suppression, he is also a decorated firefighter with extensive experience in both planning and engineering in areas prone to wildfire impacts. As a researcher and lecturer at Edith Cowan University, Greg specialises in risk engineering, occupational safety and business continuity planning.

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Dr Marcus Cattani is a Senior Lecturer in Occupational Health and Safety at Edith Cowan University. Dr. Marcus Cattani has worked as an academic, occupational hygienist, HSE Manager and consultant in the chemical, manufacturing, engineering and resources industries since 1988. Marcus is passionate about improving the management of injury risk to an acceptable level, and assisting organisations develop the risk management partnerships required to achieve this. Dr. Cattani's research focusses on the development of educational materials to assist organisations understand and manage risk, and, the development of processes to measure risk. Marcus is the Chair of the WA Branch of the Safety Institute of Australia, a member of the ECU Sustainability in Education Committee, attends the Chamber of Minerals and Energy OSH Committee, sits on the ECU Vice Chancellors HSE Awards Committee, and the School OHS Committee. Dr Cattani is one of Greg's PhD supervisors and is credited for his review and contribution to this Handbook.

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Dr Steven Richardson is acknowledged for his contributed to Chapter 3 – Modelling wildfire radiant heat flux, and is credited with the alternate view factor equations to AS3959. Steven Richardson is a Senior Lecturer at Edith Cowan University. He completed a PhD in Applied Mathematics in 2007 at The University of Western Australia. His research interests are broadly in mathematical modelling, having been involved in projects related to optimal control, asset management, bush fires, traffic, aviation and optics.

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Contents

Introduction

Each year firefighters from career and volunteer agencies across Australia respond to wildfires that impact the urban interface. When such an event occurs during a period of intense fire behavior, the conditions are often incompatible with life for persons either caught in the open or those seeking refuge in a vehicle. In order to improve firefighter safety and operational effectiveness during landscape scale wildfires, as well as providing sound engineering guidance to improve community resilience to wildfire impacts, this textbook forms part of the lead author's PhD and examines critical components of wildfire response. These components are the wildfire fighting strategies and tactics applied during a landscape scale wildfire event; the procedures and protective systems utilised in the event of burnover; operational risk management; and wildfire resilient urban design. *A Handbook of Wildfire Engineering* (the Handbook) provides firefighters, engineers and town planners with detailed technical approaches and analysis to enhance the resilience of communities in areas prone to wildfire impacts, and enhance the safety and effectiveness of wildfire suppression at the urban interface during catastrophic wildfire conditions.

Each chapter of the Handbook is designed to build upon the previous, providing a holistic approach to understanding vegetation and wildfire basics before exploring evidence based wildfire suppression. The critical linkage between wildfire suppression, firefighter safety and urban design is also explored. Whilst the primary focus of this Handbook is wildfire suppression, there are many aspects applicable to urban designers and policy makers. These are summarised at the conclusion of each chapter.

During the preparation of this book, Australia was suffering from catastrophic wildfires on both the west and east coasts and, tragically, civilians and firefighters alike were injured or killed. The lead author was deployed as a Strike Team Leader from Western Australia and was tasked with wildfire suppression and property defense near Walcha, New South Wales. In addition to his own local experiences in Margaret River in 2011 and Yarloop 2016, during the 2019 NSW deployment he witnessed first-hand the devastating effects of wildfire on firefighters and the communities, survived near miss entrapments and nights spent on the fireground cut off by fire behaviour and falling trees. This book is dedicated to all those affected by wildfires, particularly for the firefighters of all backgrounds and jurisdictions who put themselves in harm's way to protect life, property and the environment. May the guidance provided in this book help firefighters return safely to their loved ones and provide enhanced protection of communities in wildfire prone areas.

1. Wildfire Fuels

1.1 Introduction

For frontline firefighters, fire behaviour specialists and Incident Management Teams alike, understanding how vegetation type and structure affects wildfire behaviour is critical to the planning and execution of safe and successful suppression strategies. Just as important is the understanding of how vegetation is represented in the empirical and physics based models used to predict wildfire spread. During mega-wildfires that occur in catastrophic fire weather conditions, wildfire behaviour through vegetation of even moderate density may be near impossible to suppress. Conversely, over or under representing fuel structure and density when completing wildfire behaviour predictions may result in fire behaviour being incorrectly quantified and inappropriate suppression strategies being recommended.

For urban planners and decision makers reviewing planning applications at the Rural Urban Interface, including those using *AS3959 Construction of buildings in bushfire prone areas* (SAI Global, 2018) and the relevant bushfire planning guidelines in each jurisdiction, it is equally as important to understand how vegetation contributes to wildfire behaviour. When considering the benefits and costs of development in Bushfire Prone Areas, misunderstanding the vegetation related limitations and inherent assumptions of Deemed To Satisfy (DTS) or simplified planning / construction standards and guidelines can have significant and costly impacts. Whilst under calculating wildfire behaviour and impacts may result in avoidable loss of life (of both the public and the firefighters who defend them) and property, inappropriate identification of fuel structures and resultant calculation of potential wildfire behaviour can stifle safe and appropriate development and lead to unnecessary expenditure of potentially hundreds of thousands of dollars in over engineering and redundant infrastructure.

This chapter explores how vegetation structure not only contributes to wildfire behaviour, but also how it is represented in the models used to predict it on both the fireground and in the urban planning context. It should be considered the introductory preparation for firefighters as it represents the first step in “knowing the enemy”.

1.2 Vegetation structure

Wildfire fuel is the vegetation consumed by a fire burning in vegetation regardless of the size of the fire itself. The term wildfire fuel applies to vegetation involved in a 10m^2 fire in the same manner as the vegetation involved in a 100,000m^2 wildfire. Often referred to as fuel load, wildfire fuel is defined by its physical structure and density. The extent to which fuel load needs to be defined is dependent on the model used to predict wildfire behaviour. In order to demystify the concept of wildfire fuels this chapter first discusses the concept of fuel load and subsequently discusses how this is considered within common empirical and physics based wildfire models. Understanding the classification of wildfire fuels and how they are represented in wildfire modelling is the first stage of interpreting modelling outputs and their application in assessing the suitability of wildfire suppression strategies, construction requirements and land use planning decisions.

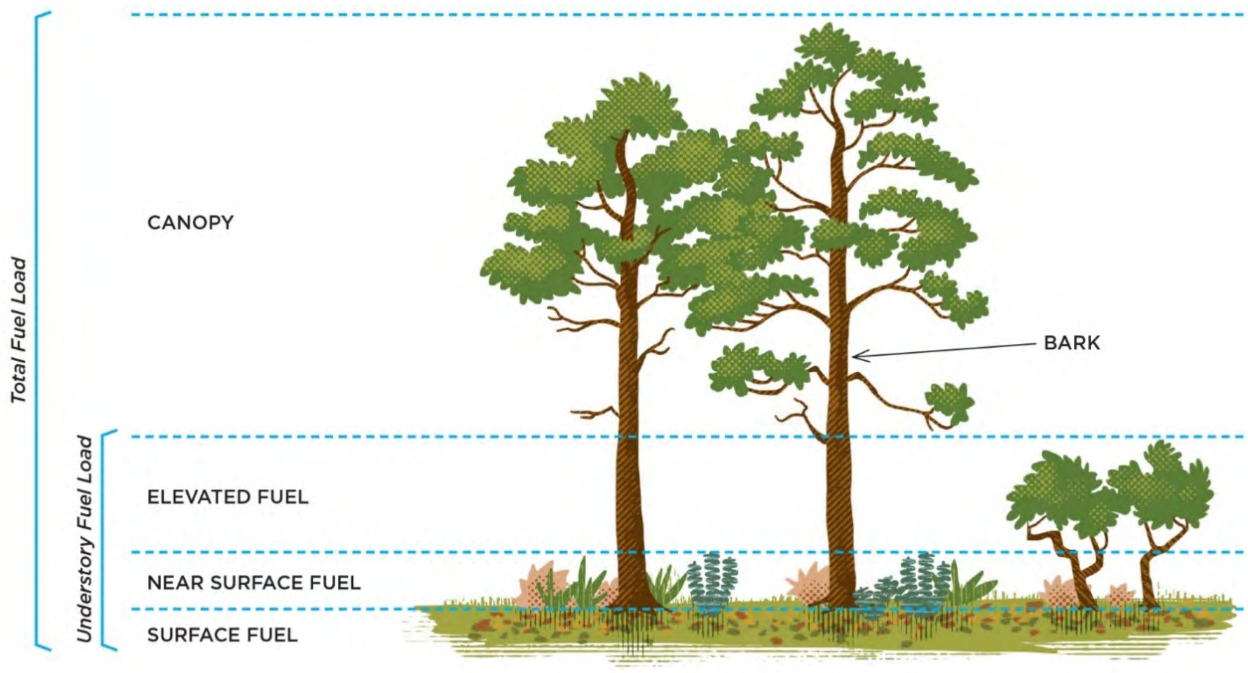


Figure 1.1: Fuel load by strata

As detailed in Figure 1.1, four main fuel strata layers and the bark layer are considered (Hines et al., 2010; Gould et al., 2007) when describing wildfire fuels. These are canopy; elevated; near-surface; and surface fuels as well as the bark. The height of each layer is not considered in the forest, woodland or grass fuel empirical models of Australian Standard 3959 – Construction of buildings in bushfire-prone areas (subsequently referred to as AS3959)[1] but is relevant for heath or scrub fuels and the empirical model of (Gould et al., 2007). Each layer and description are provided in the list below:

- Canopy fuel is contained in the forest crown. The crown encompasses the leaves and fine twigs of the tallest layer of trees in a forest or woodland. Crown involvement may lead to erratic and extreme fire behaviour and contributes to spotting distances.
- Elevated fuel includes shrubs, scrub, and juvenile understory plants up to 2–3m in height, however, canopy of heights less than 4m can be included when there is no identifiable separation between the canopy and lower shrubs. The individual fuel components generally have an upright orientation and may be highly variable in ground coverage. Elevated fuels influence the flame height and rate of spread of a fire whilst also contributing to crown involvement by providing vertical fuel structure.
- Near-surface fuels include grasses, low shrubs, and heath, sometimes containing suspended components of leaves, bark, and twigs. This layer can vary from a few centimetres to up to 0.6m in height. Near-surface fuel components include a mixture of orientations from horizontal to vertical. This layer may be continuous or have large gaps in ground coverage and influences both the rate of spread of a fire and flame height.

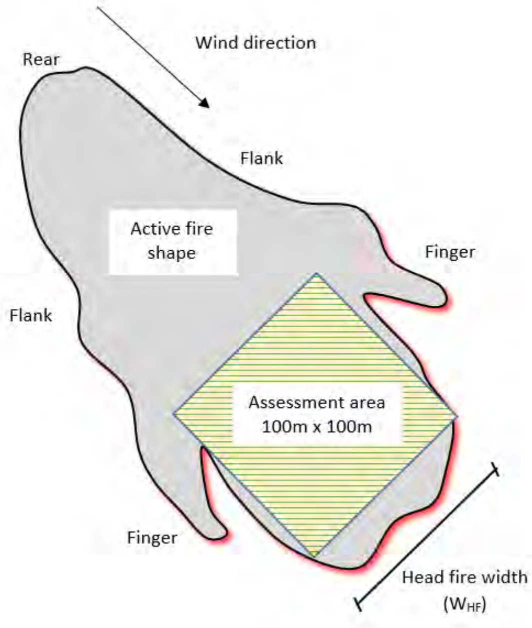
[1] *Introduced after the devastating 2009 Victorian Bushfires, AS3959 not only details the construction enhancements to the Buliding Code of Australia in order to enhance a dwelling's resilience to wildfire impacts, it also details the methodology and equations for calculating wildfire radiant heat flux across all Australian vegetation structures. Bushfire is the Australian colloquial equivalent of the term 'wildfire'.*

- Surface fuel includes leaves, twigs, and bark on the forest floor. Surface fuel (or litter) components are generally horizontally layered. Surface fuel usually contributes the greatest to fuel quantity and includes the partly decomposed fuel (duff) on the soil surface. This fuel layer influences the rate of spread of a fire and flame depth as well as contributing to the establishment of a fire post initial ignition.
- Bark fuel is the flammable bark on tree trunks and upper branches that contributes to transference of surface fires into the canopy, embers and firebrands, and subsequent spot fires.

The consideration of Vegetation Height is only considered in the empirical models of shrubland, scrub and heath fuel structures and the dry eucalypt forest fire model (DEFFM) of Gould et al. (2007). The effects of vegetation height on fire line intensity and flame length are discussed in the following section of this report. For treed structures, whilst vegetation height has some bearing on the deemed fuel loads assigned within AS3959, it is not considered in the empirical model itself. For grasslands structure, the effect of vegetation height is not considered in any form in AS3959.

The "*Framework for an Australian fuel classification to support wildfire management*" (Hollis et al., 2015) provides enhanced taxonomy for fuel classification with greater emphasis on fuel attributes (composition, geometry, density and physical aspects) within each stratum. Unfortunately the corresponding fuel load data sets and attributes for each stratum remain the subject of potential future research. The full potential of the framework may also be limited by empirical wildfire models which consider binominal fuel structure (understory and total) as opposed to incorporating the detailed fuel load data presented by (Hollis et al., 2015).

Appropriate definition and consideration of wildfire fuel is essential as it directly affects calculated wildfire outputs including head fire rate of spread, fire line intensity, flame height and radiant heat outputs. The manner and detail with which wildfire fuel is considered is largely dependent on the model applied. The forward Rate of Spread (RoS) and intensity of an active front of a fire, known as the head fire, is dependent on the fuel available for consumption in the active flaming front (Alexander, 1982; Alexander & Cruz, 2016). This is incorporated into existing empirical wildfire models of AS3959 through the consideration of available fuels within a 1ha assessment area, representative of the active fire area directly behind the head fire. Typically driven by wind direction, the head fire is the main component of a wildfire contributing to the RoS and fire behaviour intensity. Subsequently, it is the focus when calculating radiant heat flux for the purposes of determining the appropriate standard of bushfire resilient residential construction in AS3959. In landscape scale wildfire scenarios, being those greater than 1ha, the 1ha area of assessment falls within the greater active fire area, whilst in sub-landscape scale wildfire scenarios the active fire area instead falls within the 1ha assessment area. This is illustrated in Figure 1.2.



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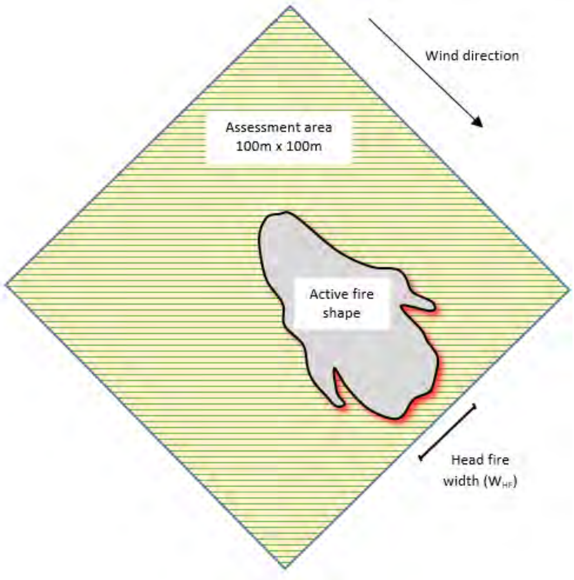


(**b**)

Figure 1.2. (**a**) Landscape scale wildfire scenario; and (**b**) sub-landscape scale wildfire scenario.

1.3 Consideration of wildfire fuel in empirical models

Wildfire fuels are represented in empirical models through numerical inputs in wildfire behaviour equations including Rate of Spread (*RoS*), fire line intensity (*I*) and flame length (L_f). AS3959 (cB3) states the appropriate surface (understory) fuel load (*w*) and overall fuel load (*W*) must be determined and that "both the understory and the canopy should be considered in the assessment. The rate of spread for forest fires should be determined using the understory fuel loads. Flame heights should be determined on the basis of both the combined understory and canopy fuels (overall fuel loads) for forest fires." Further, AS3959 (c1.5.27) defines the understory as "the vegetation beneath the overstory" whilst AS3959 (c1.5.20) defines the overstory as "the canopy, being the tallest stratum of the vegetation profile." This two layered classification of fuel load requires the surface fuel load to also incorporate all fuel layers below the canopy as illustrated in Figure 1.1.

Mathematically this broadly assumes that despite the complex structure and geometry of fuel below the canopy, all fuel below the canopy will contribute to fire behaviour as a single fuel unit, resulting in the assumption of cell dimensions for treed fuel structures illustrated in Figure 1.33. Cell dimensions for all other fuel structures are identified in Figure 1.4 and consider understory and total fuel load as the same value.

This two layered mathematical simplification does not necessarily provide true consideration of the influence of the fuel layers and their contribution to wildfire behaviour, especially where fires occur in small pockets of vegetation that do not support the development of a 100m head fire (detailed in section 2.2.3 of this report). Greater consideration of the impact of wildfire fuels by strata on wildfire behaviour is considered in Hines et al. (2010) and Gould et al. (2007), however when applied to the models identified in AS3959, the two layered fuel load classification requires fuel loads to be simplified back to understory and total fuel density only. The alternative lies in developing new empirical models that have greater consideration of fuel strata or using physics based models discussed later in this report.

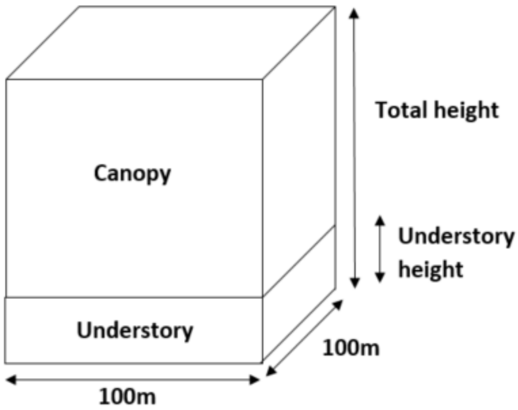


Figure 1.3: Cell dimensions treed fuel structures

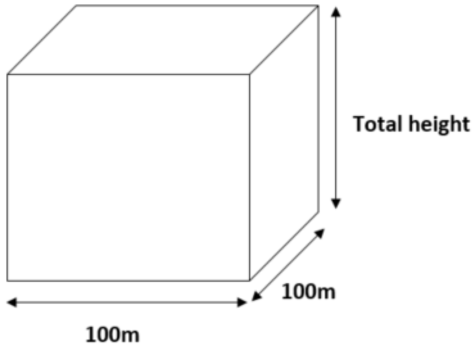


Figure 1.4: Cell dimensions non-treed fuel structures – scrub, shrub and grassland

Case Study 1 – Models used in Australian Standard 3959

Despite significant variance in fuel structure between vegetation species throughout Australia, only four empirical models are suggested in AS3959 to quantify wildfire behaviour. These empirical approaches consist of a wildfire behaviour model enabling calculation of the physical parameters of wildfire behaviour (each model unique to the classification of vegetation structure); and separate view factor model, otherwise known as configuration factor, which details the calculation of the receiving body's resultant radiant heat flux (the same view factor model is used regardless of vegetation structure and resultant fire behaviour). Each of these models assume that all wildfire has attained a quasi-steady rate of spread (RoS) and are of landscape proportions.

The six wildfire behaviour models detailed in AS3959 are:

- Noble *et al* (1980) used for all treed fuel structures subsequently classified as Group A Forest, Group B Woodland and Group F Rainforest;
- Cruz *et al* (2013) shrub, scrub and heath vegetation structures subsequently classified as Group C Shrub, D Scrub and E Mallee/Mulga;
- Purton, (1982) for grassland fuel structures subsequently classified as Group G Grassland;
- Marsden-Smedley et al (1995) for Tussock Moorland subsequently classified as Group H Grassland specific to Tasmania.

Alternate models that may be also be suitable are:

- Forest & Woodlands - Dry Eucalypt Forest Fire Model or DEFFM (Gould et al, 2007);
- Anderson *et al* (2015) for scrub and heath vegetation structures; and
- Cheney et al (1998) for various vegetation within the identified Rangelands geographical areas

The empirical models are reliant on prescribed fuel load densities measured in tonnes per hectare which equates to large cell sizes of a minimum 1ha land area (fuel height may vary). Further, AS3959 prescribes set fuel load densities for each vegetation structure regardless of the actual geometry of the vegetation involved in the wildfire or the amount of vegetation consumed during the fire scenario. This results in fires burning through small areas of vegetation being modelled as landscape scale fires as opposed to scenario specific heat release rates that consider the geometry and volume of the fuel consumed. Subsequently the use of landscape scale models detailed in AS3959 for predicting sub-landscape scale fires (road reserves, verges, landscaped gardens, vegetation adjacent to rivers etc.) or where there is restricted fire run potential, limited fuel loads are consumed or substantial boundary walls are present, may not be appropriate as currently applied and may significantly over estimate radiant heat flux.

Defining fuel load and structure is perhaps the most critical input of existing empirical models. It not only determines which mathematical model is applied, each model being specific to a broad vegetation type (AS3959; Noble, Bary & Gill, 1980; Catchpole et al, 1998; Marsden-Smedley & Catchpole, 1995), but when used for determining construction standards for buildings in wildfire prone areas, it also determines which prescribed fuel load is assigned. The vegetation descriptors with fuel load and fire behaviour model are detailed in Table 1.1.

Table 1.1. Vegetation descriptors with fuel load and fire behaviour model (adapted from AS3959, Table 2.3).

Fire Behaviour Model	Vegetation Classification	Vegetation Type	Description	Assigned fuel load (t/ha)
Noble et al/ Note: DEFFM is also suitable as an alternative	A Forest	Tall open forest Tall woodland	• Trees over 30m high; • 30-70% foliage cover (may include understory ranging from rainforest and tree ferns to low trees and tall shrubs); • Found in areas of high reliable rainfall. Typically dominated by eucalypts.	*w* = 25 *W* = 35
		Open forest Low open forest	• Trees 10-30m high; • 30-70% foliage cover (may include understory of sclerophyllous low trees and tall scrubs or grass). • Typically dominated by eucalypts.	
		Pine plantation	• Trees 10-30m in height at maturity; • Generally comprising Pinus species or other softwood species, planted as a single species for the production of timber.	
Noble et al / Note: DEFFM is also suitable as an alternative	B Woodland	Woodland Open woodland	• Trees 10-30m high; • 30-70% foliage cover (may include understory of sclerophyllous low trees and tall scrubs or grass). • Typically dominated by eucalypts.	*w* = 15 *W* = 25
		Low woodland Low open woodland Open shrubland	• Low trees and shrubs 2-10m high; • Foliage cover less than 10%.	

			• Dominated by eucalypts and Acacia. Often have a grassy understory or low shrubs. Acacias and Casuarina woodlands grade to Atriplex shrublands in the arid and semi-arid zones; • Low open woodland is classified on the basis of the understory present.	
Catchpole et al	C Shrubland	Closed heath Open heath	• Found in wet areas and/or areas affected by poor soil fertility or shallow soils. • Shrubs 1-2m high often comprising Banksia, Acacia, Hakea and Grevilea. • Wet heaths occur in sands adjoining dunes of the littoral (shore) zone. Montane heaths occur on shallow or water logged soils.	*w* = 15 *W* = 25
		Low shrubland	• Shrubs <2m high; • greater than 30% foliage cover. • Understory may contain grasses. Acacia and Casuarina often dominant in the arid and semi-arid zones.	
Catchpole et al	D Scrub	Closed scrub	• Found in wet areas and/or areas affected by poor soil fertility or shallow soils; • >30% foliage cover. • Dry heaths occur in rocky areas. • Shrubs >2m high. • Typical of coastal wetlands and tall heaths	*w* = 25 *W* = 25
		Open scrub	• Shrubs greater than 2m high; • 10-30% foliage cover with a mixed species combination	
Catchpole et al	E Mallee / Malga	Tall shrubland	• Vegetation dominated by shrubs (especially eucalypts and acacias) with a multi-stemmed habit; • usually greater than 2m in height; • <30% foliage cover. • Understory of widespread to dense low shrubs (acacias) or sparse grasses.	*w* = 8 *W* = 8
Noble et al	F Rainforest	Tall closed forest Closed forest Low closed forest	• >90% foliage cover; • understory may contain a large number of species with a variety of heights; • Not dominated by eucalypts	*w* = 10 *W* = 12
Purton	G Grassland	All forms, including situations with shrubs and trees, if the overstory foliage cover is less than 10%		*w* = 4.5 *W* = 4.5
Marsden-Smedley et al	H Grassland	Tussock Moorland	• All forms of vegetation where the overstory is dominated by the species Buttongrass. Only occurs as a significant vegetation type in Tasmania.	*w* = 17 *W* = 17

Some of the confusion regarding wildfire fuel can be attributed to the multiple inconsistencies between the qualitative and pictorial descriptions of the classifications of vegetation in AS3959 and the quantified inputs such as vegetation height and foliage cover used in the calculations (AS3959; DOP, 2016; FPA, 2016). Several of the more significant inconsistencies that cause confusion regarding wildfire fuels are summarised in Table 1.2.

Table 1.2: Discrepancies of fuel classification in AS3959

Discrepancy in Fuel Classification in AS3959	Effect on Empirical Modelling
Table 2.3, Figures 2.3 and 2.4 requires classification of treed vegetation structures on the basis of foliage cover (defined as the proportion of the ground that would be shaded by foliage when the sun is shining directly overhead, expressed as a percentage for each stratum or identifiable layer of vegetation [AS3959, c1.5.17]): • 30-70% for Group A Forest • 10-30% for Group B Woodland • 10-30% for Group B Open Woodland (subsequently classified on the basis of the understory vegetation) Table B2 identifies the same amount of wildfire fuel above the surface strata (being 10t/ha) for both Forest and Woodland vegetation structures regardless of foliage cover. Figure 2.4(B) illustrates Open Woodland as being a single tree in a field, however the suggested foliage cover may be interpreted as 30%, the same as that required for Group A Forest. Figures 2.4(A) and 2.4(B) illustrate significant overlap between understory fuel structures as densities with an almost total absence of understory fuel for the Low Open Forest classification. Table 2.3 Note 2 states "*Overstorys of open woodland, low open woodland, tall open shrubland and low open shrubland should be classified to the vegetation type on the basis of their understorys; others to be classified on the basis of their overstorys*."	This discrepancy can result in incorrect surface fuel load inputs being utilised between Group A (25t/ha), Group B (15t/ha) and Group F (10t/ha) vegetation structures. In the case of confusion between Group B Woodlands and Group B Open Woodlands, the incorrect empirical model being applied for Group C Shrubland, Group D Scrub or Group G Grassland understories. These discrepancies can ultimately result in significantly different fire engineering outputs including flame angle, view factor and radiant heat flux as shown in figures 1.4 to 1.6.
Table 2.3 "Tall woodland" has the same qualitative description and classification as Group A Forest resulting in wildfire modelling reflective of Group A Forest fire behaviour as opposed to reflecting the reduced understory fuel structure that defines 'woodland' wildfire fuels.	This discrepancy can result in incorrect surface fuel load for Group B Woodland (15t/ha) as opposed to the greater Group A Forest (25t/ha) being applied. These discrepancies can ultimately result in significantly different fire engineering outputs as shown in figures 1.4 to 1.6.
Table 2.3, Figures 2.3 and 2.4 requires classification of all treed vegetation greater than 10m in height and a foliage cover in excess of 90% to be classified as Group F Rainforest regardless of climate or species.	This discrepancy can result in incorrect surface fuel load inputs being utilised between Group A (25t/ha), Group B (15t/ha) and Group F (10t/ha) vegetation structures. Wildfire behaviour through dense Eucalypt forest matching the descriptions in AS3959 Table 2.3 and

	AS3959 Figures 2.3 and 2.4 will consume significant fuels and result in the highest magnitude of wildfire intensity. Empirical modelling using the Group F Rainforest fuel loads will significantly underestimate radiant heat flux where treed fuel structures are dense and significant. For modelling the effect is variable fuel load inputs which result in significantly different engineering outputs as shown in figures 1.4 to 1.6.
Table 2.3 describes Group C Shrubland as shrub vegetation less than 2m in height potentially with foliage cover greater than 30% whilst Group D Scrub is identified as shrub vegetation greater than 2m in height, potentially with foliage cover greater than 30% Table B2 defines the vegetation height for Group C Shrubland as 1.5m and the vegetation height for Group D Scrub and Group E Mallee Mulga as 3m. B2 identifies the 'fuel type' for all three classifications as "Shrub and Heath."	The variance in qualitative descriptions of vegetation height from that of the empirical inputs result in potential discrepancy between vegetation classification and calculated wildfire behaviour. The discrepancy in fuel type description between "shrub and "heath" may introduce further confusion. This inconsistency can result in incorrect surface fuel load inputs being utilised between Group C (15t/ha), Group D (25t/ha) vegetation structures. It can also result in the incorrect vegetation height input being used. These inconsistencies can ultimately result in significantly different fire engineering outputs as shown in figures 1.7 to 1.10.

Using Figures 1.5a-1.5b as a case scenario, the ambiguity surrounding fuel classification using the qualitative descriptions in AS3959 become apparent. The vegetation structure in the case scenario could arguably be considered Group A - Low Open Forest or Group B – Open Woodland as the foliage cover, defined as the "*proportion of the ground that would be shaded by foliage when the sun is directly overhead, expressed as a percentage of each stratum or identifiable layer of vegetation*" (AS3959, c1.5.17), exceeds 30%. Further, the surface and near surface fuel layer do not clearly fit the description for either category and arguably does not satisfy the definition of minimal fuel condition, defined as "insufficient fuel to significantly increase the severity of wildfire attack (*recognizable as short-cropped grass for example, to a nominal height of 100mm)*" (AS3959, c2.2.3.2(f)) required to be considered low threat vegetation and excluded from consideration for calculation of wildfire impacts in accordance with AS3959.

The effect of these variable fuel load inputs for the scenario examined results in significantly different wildfire outputs as shown in Figures 4 to 10. The outputs detailed were calculated using the detailed methodology detailed in AS3959; assuming flat site and effective slopes; and standard inputs of AS3959 appropriate to each fuel classification.

Figure 1.5. (**a**) Case study; and (**b**) Case study surface fuel.

In accordance with the vegetation descriptions provided in AS3959 the vegetative fuel in the case study could be qualitatively classified as being Group A Forest, Group B Woodland or Group F Rainforest (being low closed forest) depending on the individual assessor. Whilst the same empirical model (McArthur) is applied to each of these vegetation structures, the associated assigned fuel loads vary significantly. A result is the fire behaviour outputs and subsequent radiation modelling outputs are vastly different as illustrated in Figures 6-12. Subsequently, the associated construction responses required under the Building Code of Australia (ABCB, 2015) for a typical residence could vary by over a hundred thousand dollars (FPA, 2016) and result in significant over engineering in situations where landscape scale fire behaviour is not possible. These inconsistencies also facilitate the opportunity for consultants and home owners alike to underestimate potential wildfire impact in order to reduce construction costs, leaving houses potentially vulnerable where landscape scale wildfire impacts occur. This subsequently highlights the need for comprehensive understanding of wildfire engineering with greater analysis of fuel loads where landscape scale fire behaviour is not possible, typically within the urban and peri-urban area, as opposed to blind reliance on the broad qualitative descriptions and simplified radiant heat flux tables detailed in AS3959.

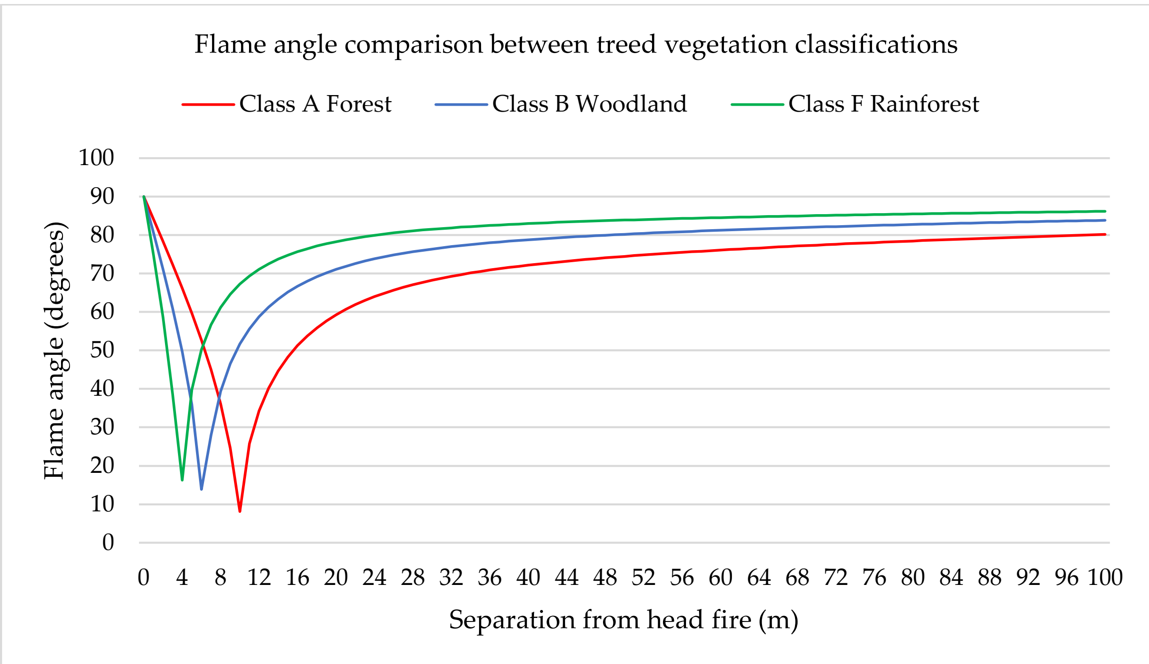


Figure 1.6. Flame angle as a function of separation from head fire comparison – treed fuel structures

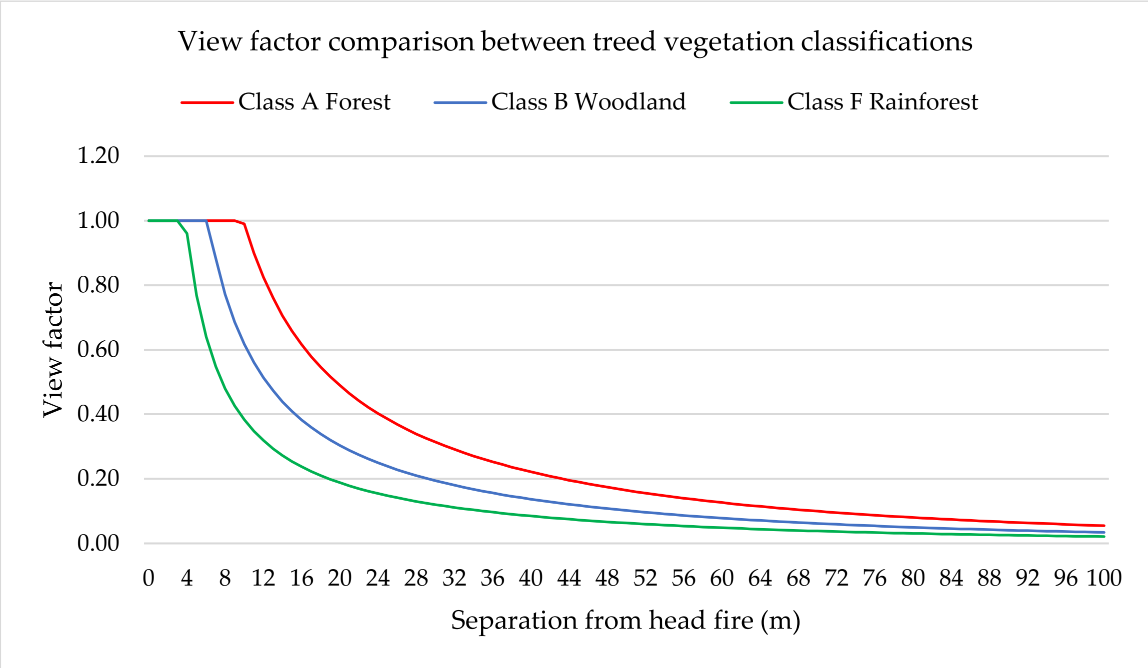


Figure 1.7. View factor as a function of separation from head fire comparison – treed fuel structures

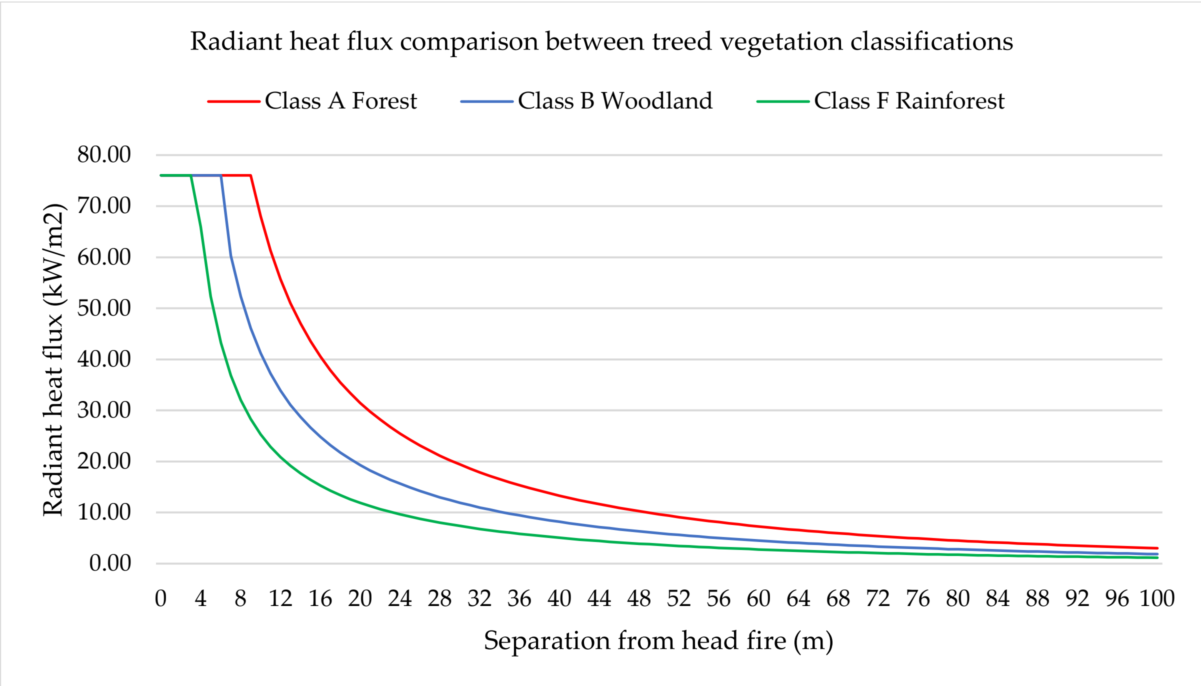


Figure 1.8. Radiant heat flux as a function of separation from head fire comparison – treed fuel structures

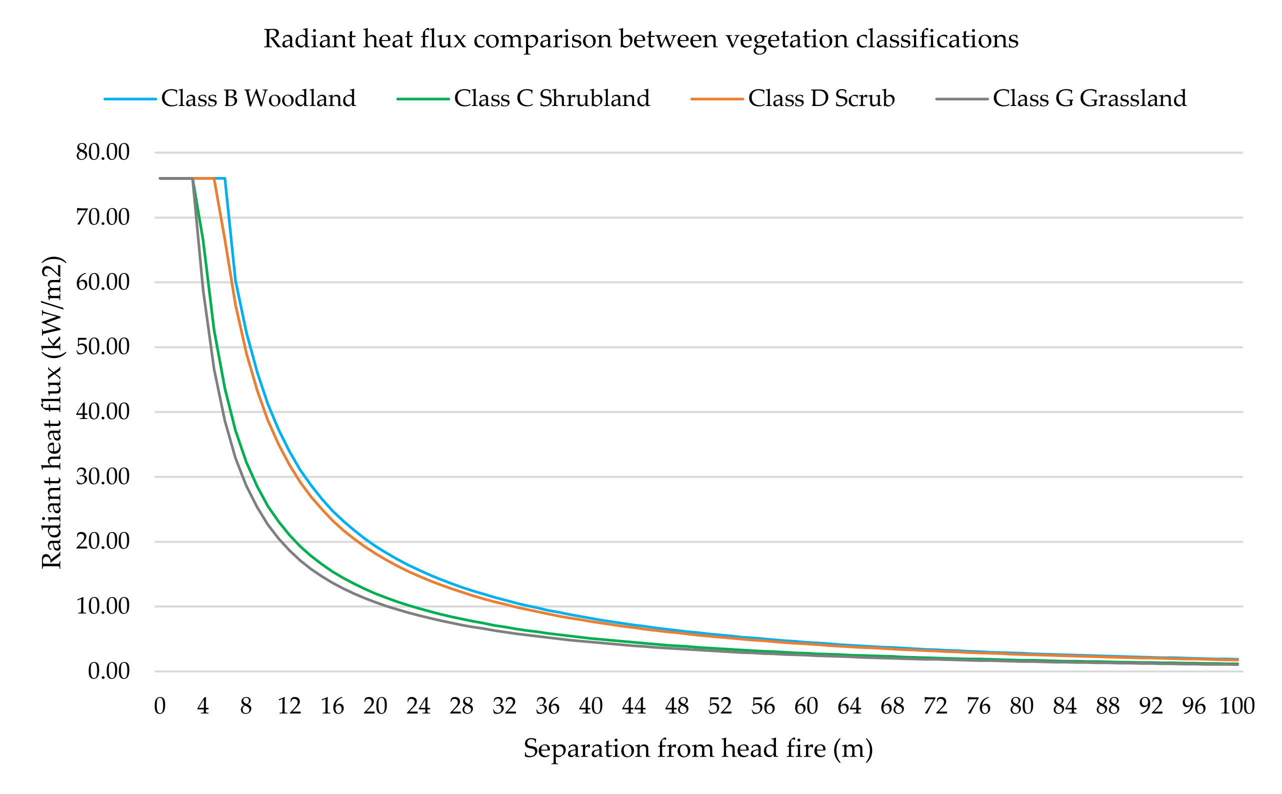


Figure 1.9. Radiant heat flux as a function of separation from head fire comparison – Woodland and open woodland structures (open woodland modelling based on the understory structure)

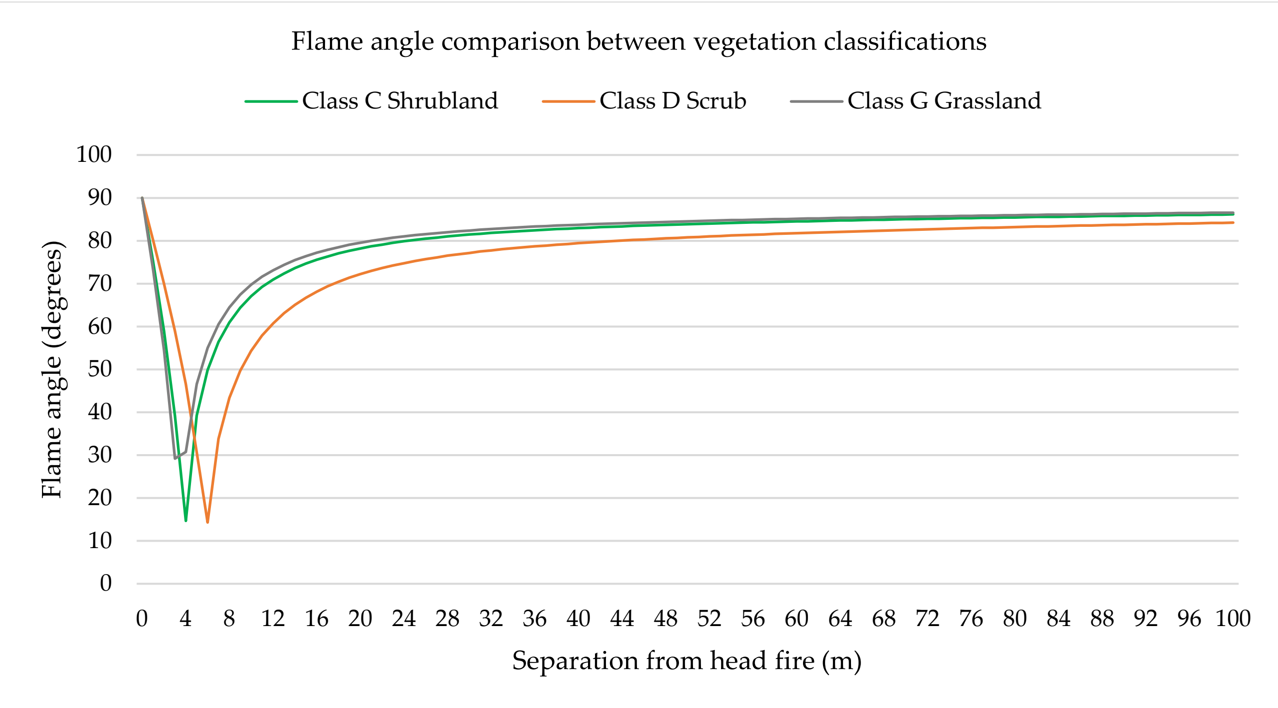


Figure 1.10. Flame angle as a function of separation from head fire comparison – shrub, scrub and grassland

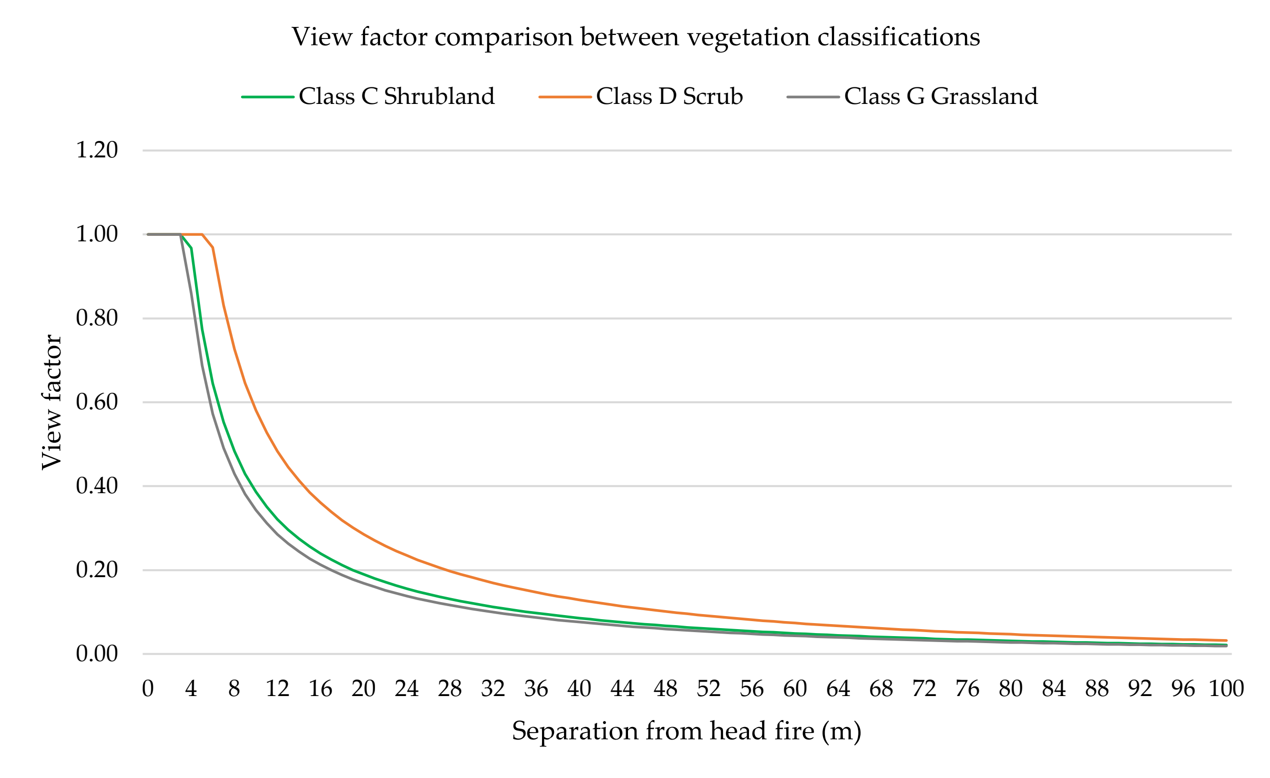


Figure 1.11. View factor as a function of separation from head fire comparison – shrub, scrub and grassland

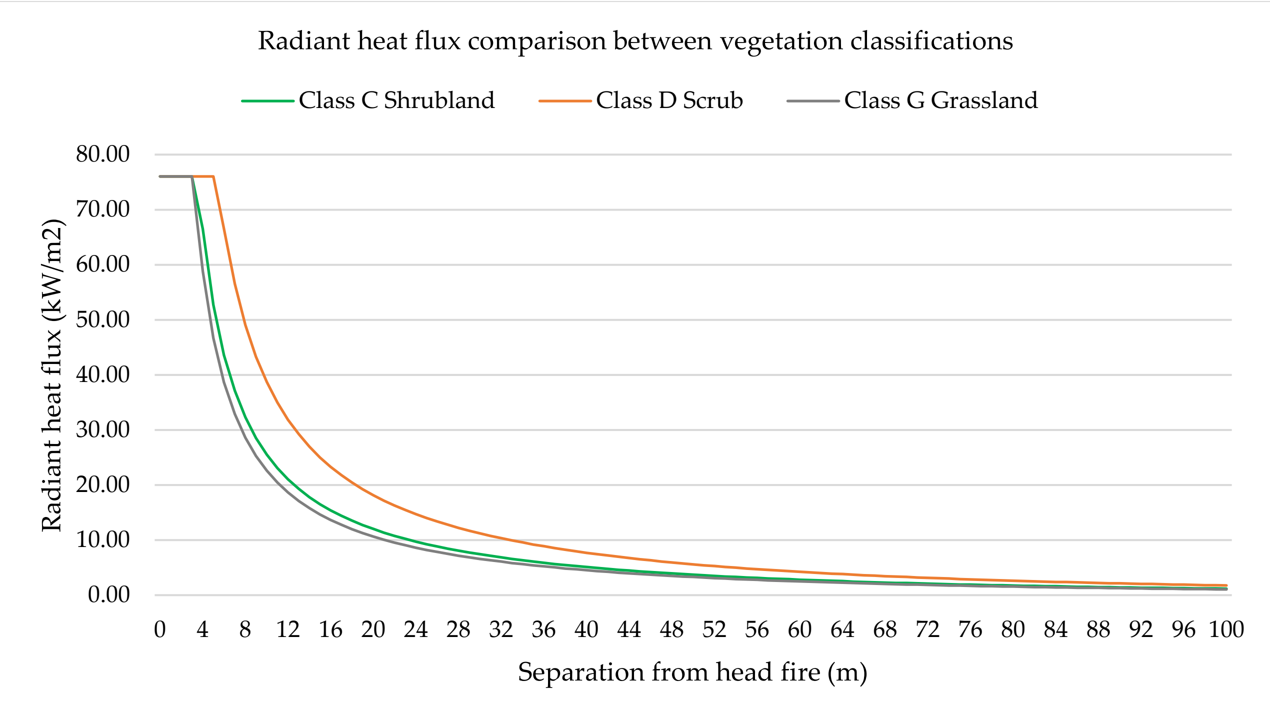


Figure 1.12. Radiant heat flux as a function of separation from head fire comparison – shrub, scrub and grassland

Case Study 2 – Project Vesta and Hazard Ratings

Two of the aims of Project Vesta, perhaps the most significant research project into fire behaviour through dry eucalypt forest of recent times, were to (Gould et al., 2007, piii):

i. develop new algorithms describing the relationship between fire spread and wind speed, and fire spread and fuel characteristics including load, structure and height; and
ii. develop a fuel hazard assessment guide that provides quantitative description of fuel hazard and its effects on fire behaviour.

The published results have subsequently been adapted to other jurisdictions including Victoria (Hines et al., 2007) and South Australia (DENR, 2011).

Unlike the two layered fuel structure incorporated by the models suggested in AS3959, the dry eucalypt model of Gould et al. (2007) considers three fuel layers contributing to head fire rate of spread being surface, near-surface and elevated fuels (illustrated in Figure 1, with bark fuels being used to estimate potential spotting distances. Using the approach of Gould et al. (2007) fuels in each strata are assigned hazard scores based on qualitative descriptions and the assessor's inspection. If the approach of Gould et al. (2007) is used, fuel loads are first assigned hazard ratings which are then converted to the required hazard scores shown in Table 1.3.

Table 1.3. Vesta Fuel Hazard Scores (Gould et al., 2007, Table 9.3, reproduced with permission from L.McCaw on behalf of CSIRO and the Department Environment and Conservation)

Vesta Fuel Hazard Score				
Fuel Hazard Rating	Surface	Near-surface	Elevated	Bark
Low	1	1	1	0
Moderate	2	2	2	1
High	3	3	3	2
Very High	3.5	3.5	3.5	3
Extreme	4	4	4	4

The assigned scores are subsequently utilised in the head fire rate of spread equation (see Chapter 2). The approach of Gould et al. (2007) not only provides greater consideration of wildfire fuel structure than the empirical methods detailed in AS3959, but also provides a guide to potential spotting behaviour resulting from fire brands. Specific to dry eucalypt forest with litter and shrub understory, Gould et al., (2007) does not allow assessment of fuel loads or fire modelling in woodland, shrub, or grassland fuel structures. Perhaps the main benefit of Gould et al. (2007) is the ability to vary fuel loads on the basis of ground truthing and field interrogation, even if this is somewhat subjective and constrained by the assumptions of 100m head fire width and sufficient vegetation geometry to sustain landscape scale wildfire behaviour. The calculated rates of spread and flame heights from the model can theoretically be combined with the view factor model of AS3959 to calculate radiant heat flux, however there is no evidence within the literature to support one approach over the other.

1.4 Consideration of sub-landscape scale vegetation geometry

Within the urban environment, wildfire growth in road reserves, urban parklands, and similar scenarios can be restricted by the geometry of the available fuel beds. Current approaches of AS3959 suggest modification of the head fire width may be appropriate in these instances. However, whilst the width of the head fire is a vital component in determining radiant heat flux, head fire widths greater than 40m resulted in negligible differences between the view factor and radiant heat flux within 30m of the flame front (Penney, 2017). Through analysis of heat release rates, the same study identified that reduction of head fire width alone without further consideration of fuel bed geometry was not suitable in scenarios where the fuel bed geometry restricted fire growth. It was subsequently identified that:

1. Regardless of the actual geometry and coverage of fuel within the assessment area, AS3959 assumes landscape scale wildfire behaviour with a 100% homogenous fuel loading within the assessment area and a head fire width of 100m;
2. When fuel bed geometry prevents a 100m head fire or quasi-steady RoS being obtained, failure to adjust wildfire fuel inputs may result in significant overestimation of wildfire impact, particularly radiant heat flux; and
3. In order to more accurately model wildfires in fuel beds that restrict fire growth, it is necessary to calculate available fuel loads that will contribute to fire behaviour over the area being assessed using the vegetation availability factor equation as described below.

As previously published (Penney & Stevenson, 2019), whilst the head fire flame width should be considered as the width of the continuous fuel contributing to the active fire front, the area covered by potential fuel load available for contribution to the RoS and intensity of the active fire as a fraction of the total assessment area is defined as the vegetation availability factor (V_F), given by

$$V_F = \frac{Fuel\ cell\ area\ (m^2)}{Assessment\ area\ (m^2)} \tag{1.1}$$

where the fuel cell area is the coverage of vegetation present within a 100 m by 100 m assessment area directly in front of the receiving body. The available surface fuel load wA (t/ha), and the available total fuel load WA (t/ha), are then defined as

$$w_A = w \times V_F \tag{1.2}$$

and

$$W_A = W \times V_F \tag{1.3}$$

where w and W are respectively the surface fuel load and total fuel load sourced from relevant jurisdictional data sets.

The calculated fuel loads can then be applied to the relevant fire behaviour equations of RoS , fire line intensity, and flame length for the purposes of determining the suitability of wildfire fighting strategies and tactics or for calculating the radiant heat flux on receiving bodies in the path of the head fire. Where models do not consider the fuel load when calculating RoS , the vegetation availability factor can still be applied for the purposes of calculating radiant heat flux, fire line, and intensity.

Individual Trees and Small Garden Beds

Where individual vegetation or small vegetation beds are present that would result in an isolated fire but would not facilitate the type of fire propagation present during wildfire events, it is appropriate to model those instances accordingly. This is discussed in further in Chapter 2.

1.5 Consideration of wildfire fuel in physics based modelling

As opposed to empirical models derived from statistical data, physics based wildfire modelling involve computational models that considers interaction of atmosphere, fire and vegetative fuel using partial differential equations to solve for filtered fire spread. Physics based models predict the wind flow through and above the fuel strata, incorporates 'chemical kinetics' to describe the drying and pyrolysis and simplified combustion equation to predict combustion of the vegetation in defined time steps.

Significantly more complex than empirical approaches, physics based models such as Firestar require both atmospheric quantities and vegetation inputs (Finney & McAllister, 2011; Pimont et al., 2006) to be defined on a two or three-dimensional spatial grid. Some models including the Wildland Fire Dynamic Simulator (WFDS) allows the resolution of the grid to be altered to suit the specific scenario with fine grid sizes as small as 1.6m x 1.6m x 1.4m (Pimont et al., 2006), allowing vegetation structures and fires of almost all scales to be modelled. This enables enhanced analysis of potential wildfire behaviour compared to traditional empirical models by accounting for each mechanism of heat transfer (conduction, convection and radiation) (Porterie et al., 2005; Finney & McAllister, 2011; Finney et al., 2015) but subsequently requires powerful computers and extended analysis durations (Cruz et al., 2014). Whilst the use of physics based models is widely accepted in traditional fire engineering analysis (ABCB, 2005; SFPE, 2008) its use in the prediction of wildfire behaviour in Australia remains in its relative infancy in part due to the complex computational analysis required (Cruz et al., 2014).

One of the main characteristics of physics based wildfire modelling is the requirement to input spatial and physical characteristics for each fuel type and structure within the cell to be analysed. This permits the modelling and evaluation of heterogeneous fuels in a single simulation (Cruz et al., 2014; Parsons, Sauer & Linn, 2010). The result of the analysis is a fire 'map' with outputs including fire line intensity, temperature and radiant heat flux captured at set timed intervals in a separate spreadsheet.

Physics based models categorise wildfire fuel into two separate layers being surface and raised fuels. Unlike empirical approaches however, the two categories of fuel are not simply modelled as two distinct fuel layers. Fuel structures within each layer are represented as individual fuel units within the confines of the grid resolution (Cruz et al., 2014; Parsons, Sauer & Linn, 2010). A comparison between the two approaches is illustrated in Figure 1.13 and enables individual trees to be considered separately as opposed to the empirical approach of an entire forest being modelled as a single fuel unit.

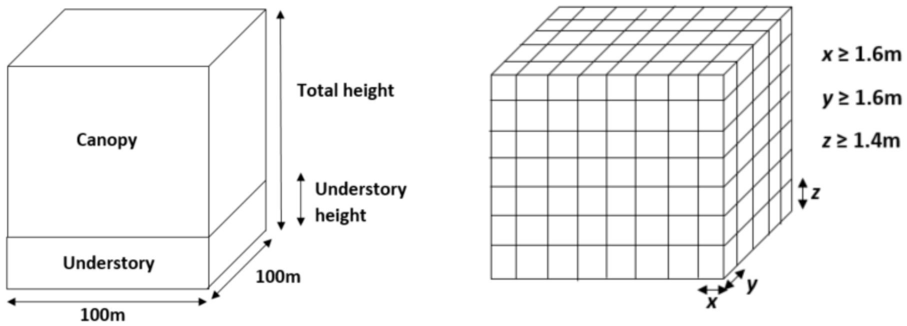


Figure 1.13. Empirical (left) compared to WFDS (right) wildfire fuel cells

Input parameters for surface fuels including grasses and litter are the descriptors of the fine fuels, which are vegetation with a diameter or thickness of approximately 6 mm or less. If the surface vegetation is not uniform in size then the loading in each representative size class (i.e., surface-to-volume ratio) can be inputted. Grasses, for example, are more likely to be sufficiently represented by one value of the surface-to-volume ratio and the fuel loading would be for that size class. However, litter may be better represented using more than one surface-to-volume ratio. Input parameters for raised fuels include trees and shrubs that are large enough to be resolved on the computational grid. For example, if the grid cells are 1 m cubes and the shrubs are 0.5 m tall, then they are not resolved. Where raised fuels are not considered due to grid resolution they are modelled as surface vegetation.

Similar to WFDS, FIRETEC is a three dimensional physics based model for fires through vegetation. It relies on the formulations of physics and chemistry to model the fire behaviour through vegetation in cells of horizontal grid resolution as small as 2m and fine fuel grid resolution as small as 0.05m (Pimont et al., 2006).

WFDS has two distinct ways of modelling vegetative fuels, being the Fuel Element (FE) model for vegetation that occupies a specified volume such as trees (for example, Douglas fir trees are modelled as cones), and the Boundary Fuel (BF) model for surface fuels such as grasslands.

In the FE model thermally thin vegetation is represented on a three-dimensional grid. Porterie et al. (2005, p573) describes the gas phase grid as the pyrolised fuel vapour leaving the fuel material, diffusing with the available oxidizer and forming a combustible mixture ahead of the flaming edge that is subsequently ignited by the flame itself. The gas phase grid requires sufficient resolution so that temperature gradients and conjugate heat transfer between the gas and solid phases in the fuel bed can be calculated to an acceptable level. As a result, it is regarded as providing better predictions than the BF model if adequately resolved, however it is also both computationally intensive and time consuming.

The BF model utilises a vertical grid with sufficiently high spatial resolution to capture vertical radiant heat transfer. A horizontal grid is also utilised similar to the FE model, typically however with larger resolution. The underlying assumptions of the BF model are most consistent with landscape scale fires in which the majority of heat release and radiant emission occurs vertically above the thermally degrading surface fuel bed.

Two models may be utilised for thermal degradation of wildfire fuel, 'Linear' or 'Arrhenius', both derived from empirical studies. The Linear model assumes a two-stage endothermic thermal decomposition (water evaporation and then solid fuel pyrolysis). In contrast, the Arrhenius model considers a three-stage endothermic thermal decomposition being water evaporation, solid fuel pyrolysis and subsequent char oxidisation (Morvan & Dupuy, 2014). Solid fuels are represented as a series of layers that are consumed from the top down until the solid mass reaches a predetermined char fraction at which point the fuel is considered consumed (Cruz et al., 2014). The model then continues the process throughout the fuel structures in predetermined time intervals providing illustrative and tabularised outputs.

1.6 Use of existing data to advance physics based models

The structural framework provided by Hollis et al. (2015) includes several of the fuel characteristic inputs required for physics based modelling. By combining datasets when information becomes available, improvements to both empirical and physics based models may be achieved. Table 1.4 summarises the status of fuel attributes within existing data sets and how they correspond to physics based inputs.

Table 1.4. Fuel attributes

Fuel Attribute from Hollis et al.	Equivalent Attribute for physics based models	Notes
Mass	Mass	Mass is not currently considered in empirical models which rely on density in (t/ha).
Compactness	Density	Compactness is not currently considered in empirical models.
Mineral content	-	Not considered in either form of model.
Heat content	Specific heat	Considered in empirical models through Heat of combustion, being 18600kJ/kg. This would be altered in physics based models to suit the individual fuel. Data sets from physics based models could be applied to empirical scenarios.
Density	Density	Empirical models utilise t/ha, however physics based models would rely on density in 3 dimensions.
Horizontal continuity	Fuel geometry	Existing empirical models do not consider horizontal continuity due to the 1ha grid size. For physics based models the fuel geometry

		can be manually inputted to suit the specific scenario.
Particle shape and size	Fuel geometry	Empirical models do not consider particle size due to the 1ha grid size. Particle size is captured in physics based models through enhanced definition of fuel geometry. The shape of the fuel (cylindrical, conical or cubic for instance) can also be considered.
Surface area	Fuel geometry	Empirical models do not consider surface area. Surface area is captured in physics based models through enhanced definition of fuel geometry.
Height to base of canopy	Fuel geometry	Whilst empirical models use canopy height as a guide to selecting vegetation fuel load inputs, they do not consider height to base of canopy in the calculation of fire behaviour itself. Physics based models can capture this through detailed fuel geometry inputs.
-	Drag coefficient	A coefficient derived from empirical correlation for laminar or turbulent flow around a simplified shape. Individually imputed for each specific scenario and affects physics based modelling of fire behaviour. Not considered in empirical approaches.
-	Char component	Determines the point at which the fuel is considered completely consumed in physics based models and value depends on individual scenario. Not considered in empirical models.
-	Pyrolysis range	When the pyrolysis starts and finishes, assessed in set time steps in physics based modelling. Not considered in empirical models.

Existing data sets are limited, however combining the accepted empirical two layered fuel loads detailed in AS3959 with analysis of fuel strata detailed in (Hines et al., 2010; Gould et al., 2007; Hollis et al., 2015) may provide a suitable starting point for vegetation fuel inputs required for physics based modelling. Tables 1.5 to 1.8 detail suggested bulk densities for initial analysis and comparison against existing empirical models (Penney, 2017).

The suggested fuel loads in Tables 1.5 to 1.8 have been determined by adapting the existing data sets identified for the associated empirical models to the three-dimensional t/m^3 from the existing two-dimensional t/ha that may be suitable in the absence of other data. In the absence of other data they may provide suitable inputs.

Table 1.5. Suggested bulk density Forest

Fuel Strata	**Bulk Density in tonnes per hectare**		**Suggested Bulk Density in kg/m^3 (Overlap will occur between strata if height is less than 1m)**
	AS3959	**(Hines et al., 2010)**	
Surface		2-20	
Near Surface		1-8	25[A]
Elevated		0-8	4
Bark	25	0-7	1
Canopy	10	n/a	1[B]

[A] Surface and near surface strata are assumed to be in the same fuel cell

[B] Assuming 100% foliage cover

Table 1.6. Suggested bulk density Woodland

Fuel Strata	Bulk Density in tonnes per hectare		Suggested Bulk Density in kg/m³ (Overlap will occur between strata if height is less than 1m)
	AS3959	(Hines et al., 2010)	
Surface		2-20	
Near Surface		1-8	10[A]
Elevated		0-8	2
Bark	15	0-7	1
Canopy	10	n/a	0.3[B]

[A] Surface and near surface strata are assumed to be in the same fuel cell

[B] Assuming 30% foliage cover

Table 1.7. Suggested bulk density Scrub

Fuel Strata	Bulk Density in tonnes per hectare (AS3959)	Suggested Bulk Density in kg/m³
Surface		
Near Surface		
Elevated		15[A]
Bark	25	0
Canopy	0	10[B]

[A] Surface, near surface and elevated strata are assumed to be in the same fuel cell

[B] Assuming 100% foliage cover

Table 1.8. Suggested bulk density Shrub

Fuel Strata	Bulk Density in tonnes per hectare (AS3959)	Suggested Bulk Density in kg/m³
Surface		
Near Surface		
Elevated		10[A]
Bark	15	0
Canopy	0	5[B]

[A] Surface, near surface and elevated strata are assumed to be in the same fuel cell

[B] Assuming 100% foliage cover

1.7 Implications for frontline firefighters and IMT's

Vegetation structure plays a critical role in the development and severity of wildfires. During periods of elevated fire weather conditions, mega-wildfires in through continuous vegetation structures (particularly in forest and woodlands), no amount of resources or water (see Chapters 4-6) will be able to suppress the head fire. Firefighting strategies in these situations should therefore focus on areas of opportunity where vegetation structure, particularly surface, near surface and elevated fuels are limited and the vegetation geometry does not support a continuous wildfire front. The removal of fuel immediately adjacent to assets and communities through 'dry' firefighting strategies such as backburning (see Chapter 4) may need to be considered early in firefighting campaigns.

1.8 Implications for frontline fire behaviour specialists and urban planners

To partially address the issues identified in AS3959 and increase the accuracy of modelled wildfire outputs the following is recommended:

i. Classification of vegetation based solely on qualitative descriptors should not over-ride the wildfire behaviour model applied to the scenario without due consideration of the wildfire behaviour expected to occur through the vegetation. Using the case study previously provided as an example, whilst the vegetation could reasonably be classified as Class A Forest or Class B Woodlands, applying the Noble et al wildfire behaviour model to either of these options without modifying the deemed fuel loads would significantly result in over-estimation of wildfire outputs. In urban areas where vegetation geometry restricts wildfire growth, a more appropriate and accurate approach is to assess the fuel load utilising Vesta Fuel Hazard Scores and apply the correct vegetation availability factor. Further guidance on this can be found in Chapters 2 and 3; and

ii. Practitioners (both from fire services and land use planning perspectives) involved in modelling wildfire and calculating potential impacts require a sound understanding of the respective models and their limitations. Caution should be applied when attempting to 'simplify' complex equations, models or engineering concepts in standards, guidance material or documents for use by lay persons or in land use planning decisions. The profession of wildfire engineering is in its infancy and job titles do not necessarily equate to the knowledge and skills required to complete the required technical analysis or make informed and accurate decisions. This can be in part be remedied by professionalization / accreditation of the sector and greater recognition of the role of fire safety engineers with wildfire backgrounds in it.

2. Modelling Wildfire Behaviour

2.1 Introduction

Understanding how wildfire behaves and how this behaviour is modelled is the next step for frontline firefighters, fire behaviour specialists IMT's and urban planners. Figure 2.1 illustrates the relationship between wildfire inputs and the empirical wildfire behaviour models and the radiation view factor model adopted throughout Australia. This chapter discusses each of the empirical wildfire components, whilst the radiation model is explored in the next chapter. Accurately modelling wildfire behaviour is important as it is used to assist determine the suitability of wildfire suppression strategies and tactics (Chapter 4), as well as for determining the suitability of development in bushfire prone areas.

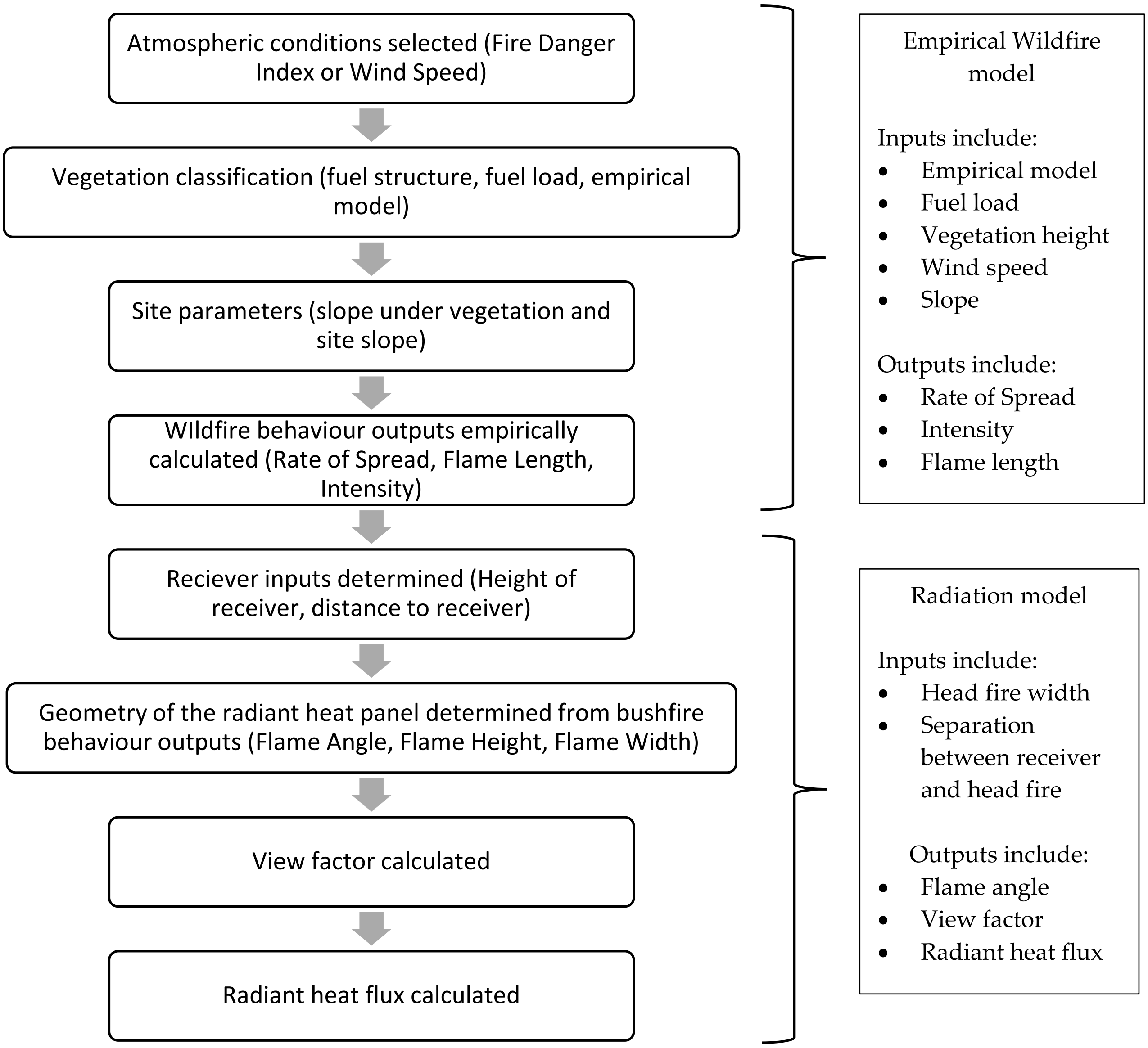


Figure 2.1. Relationship between bushfire and radiation models

2.2 Fire Weather

The influence of weather on wildfire behaviour and the potential difficulty of wildfire suppression is considered through the use of fire danger indices (Dowdy et al., 2009). In

Australia, the McArthur Forest Fire Danger Index (FDI) is used to account for the effect of weather on forest wildfires. The FDI is calculated by (Nobel et al, 1980):

$$FDI = 2e^{(-0.45+0.987ln(DF)-0.0345RH+0.0338T+0.0234V)} \quad (2.1)$$

Where:

DF is drought factor (given as a number between 0 and 10 representing the influence of recent temperatures and rainfall events on fuel availability)

RH is relative humidity (%)

T is temperature (C)

V is wind speed at 10m (kph)

For grassfires, the Grassland Fire Danger Index (GFDI) is calculated by (Cruz et al, 2015)

$$GFDI = 2\exp\left(-23.6 + 5.01\,ln(C) + 0.0281T - 0.266\sqrt{RH} + 0.633\sqrt{U_{10}}\right) \quad (2.2)$$

where:

C is degree of curing (%)

T is air temperature (°C)

RH is relative humidity (%)

U_{10} is average wind speed at 10m above ground (kmh^{-1})

Whilst Dowdy et al. (2009, Figure 2, p10) report the 95th and 99th percentile FDI's throughout Australia from 2000 to 2007, future projected changes in FDI forecast widespread increases in the severity of near-surface fire weather throughout Australia (Dowdy, 2018; Dowdy et al., 2019) as illustrated in Figure 2.2. Alternatively, AS3959 provides alternate FDI datasets, summarised in Table 2.1.

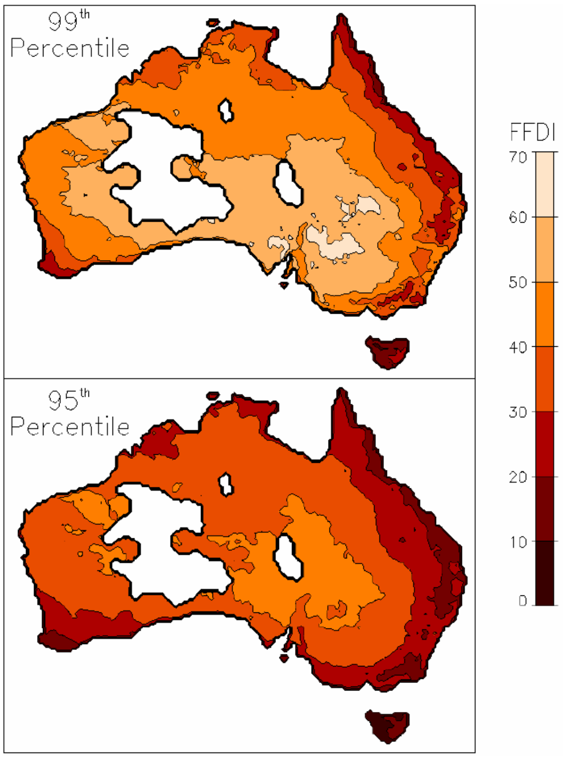


Figure 2.2. The 99th (upper panel) and 95th (lower panel) percentiles of the FDI. (image from Dowdy et al. 2009, used with permission from the Bureau of Meteorology)

Table 2.1: FDI and GFDI (excluding alpine areas)

Jurisdiction	Forest Fire Danger Index	Grassland Fire Danger Index
Australian Capital Territory	100	130
New South Wales	80-100	110-130
Northern Territory	40	50
Queensland	40	50
South Australia	80	110
Tasmania	50	70
Victoria	100	130
Western Australia	80	110

During extreme wildfire events strong and deep convection can occur within the fire plume (Dowdy et al., 2019). This phenomenon is termed pyroconvection. Condensation of moisture within the fire plume can release latent heat, resulting in enhanced convection and the formation of clouds known as pyrocumulus. In severe cases thunderstorms, (known as pyrocumulonimbus), and pyrogenic lightning may result in multiple additional wildfire ignitions. The feedback processes involved in such extreme weather events includes significant variations in surface wind speed and direction that results in unpredictable and dangerous wildfire behaviour and directional changes (Peace et al. 2017; Potter, 2012). The Continuous Haines index (CH) is a numerical index between 0-13 which provides an indication of how dry and unstable the atmosphere is above the surface and therefore the potential for the formation of dangerous pyroconvective processes (Dowdy et al, 2019; Mills & McCaw, 2010; Potter, 2012; Potter, 2018). Values of 10 or more are considered significant and require additional vigilance to be exercised during wildfire suppression efforts.

The CH is calculated by (Dowdy et al, 2019; Mills and McCaw, 2010):

$$CH = CA + CB \tag{2.3}$$

$$CA = 0.5(T850 - T750 - 4) \tag{2.4}$$

$$CB = \frac{(DD850 - 3)}{3} \tag{2.5}$$

$$\text{if } CB > 5, \text{then } CB = 5 + 0.5(CB - 5) \tag{2.6}$$

Where:

CA is the Stability Score based on the temperature difference T850 – T700, where T850 and T700 are the temperatures at 850 hPa and 700 hPa, respectively.

CB is the Humidity Score based on the 850hPa dew point depression (DD850): equal to T850 – DP850, where DP850 is the dew point temperature at 850 hPa.

2.3 Rate of Spread

During the initial stages of a wildfire only a few particles on the top of the surface fuels will be involved, with flame spread influenced by the direct contact of the flames with surrounding unburned fuel (Cheney & Gould, 1997). As the fire size grows, convective preheating of surrounding fuels occur and flame height increases resulting in more fuel becoming available. McAlpine (1988) suggests that, influenced by both the wind and topography, the fire continues to grow in size and accelerate until it achieves a quasi-steady rate of spread (RoS).

In point source accelerating fire scenarios, whereby the developing fire originating from a single ignition point is yet to grow sufficiently to reach the quasi-steady RoS required to support the assumptions used in landscape scale wildfire behaviour, the accelerating head fire rate of spread RoS_a (km/h) in forest and woodland fuels is given by (McAlpine, 1998; Van Wagner, 1985):

$$RoS_a = RoS(1 - e^{-\beta t}) \tag{2.7}$$

where RoS is the equilibrium/potential head fire rate of spread (km/h), t is the time since ignition (h), and β (h−1) is a constant related to how rapidly the head fire accelerates. A reasonable first estimate for β can be established using the assumption that the fire will accelerate to 90% of the equilibrium rate of spread in 30 minutes (i.e., 0.5 h) for treed vegetation structures, including forest and woodlands. The attainment of the 90% equilibrium rate of spread 30 minutes post ignition within treed fuel structures is supported by the findings of Gould et al (2007); Kucuk et al (2007); Van Wagner (1985); and Cheney (1981).

Stevenson (Penney & Stevenson, 2019) identified that applying this to Equation (1) gives $\frac{RoS_a}{RoS} = 0.9$ and t = 0.5, as illustrated below to solve the fire acceleration parameter (β):

$$\begin{aligned} 0.9 &= 1 - e^{-\frac{\beta}{2}} \\ \Rightarrow \quad e^{-\frac{\beta}{2}} &= \frac{1}{10} \\ \Rightarrow \quad \beta &= 2\ln(10) \\ &\approx 4.605. \end{aligned}$$

It is worth noting that the value of $\beta = 0.0768$ stated in previous work by McAlpine (1998) is in units of (min^{-1}). This would only be appropriate in the current setting if the RoS were considered in km/min rather than km/h.

For modelling purposes, the time since ignition may not be known, therefore the ability to determine the rate of spread of an accelerating fire in terms of distance travelled since ignition is required. As RoS_a is the rate of change of distance D (km) with respect to time, it follows that

$$\frac{dD}{dt} = RoS_a .$$

By integrating Equation (2.7) with respect to time, and setting D(0) = 0, the distance travelled post ignition can be expressed as:

$$D = RoS\left(t + \frac{e^{-\beta t}}{\beta} - \frac{1}{\beta}\right) \tag{2.8}$$

From Equation (7) we know that

$$t = -\frac{1}{\beta}\ln\left(1 - \frac{RoS_a}{RoS}\right),$$

which when inserted this into Equation (2), enables distance travelled post ignition to be written as:

$$D = -\frac{RoS}{\beta}\left(\frac{RoS_a}{RoS} + \ln\left(1 - \frac{RoS_a}{RoS}\right)\right) \tag{2.9}$$

or alternatively as:

$$\frac{\beta D}{RoS} = -\left(\frac{RoS_a}{RoS} + \ln\left(1 - \frac{RoS_a}{RoS}\right)\right) \tag{2.10}$$

Equation (10) can be used to determine the RoS of an accelerating head fire RoS_a at a specified distance D from the point source ignition with the equilibrium rate of spread. The problem is that it is not possible to re-arrange Equation (10) to express RoS_a as a function of D. To resolve this issue a plot of $\frac{RoS_a}{RoS}$ is numerically generated against $\frac{\beta D}{RoS}$ which can be used to approximate the ratio $\frac{RoS_a}{RoS}$ (and hence RoS_a) for a given value of the ratio $\frac{\beta D}{RoS}$. Such a plot is given in Figure 2.3.

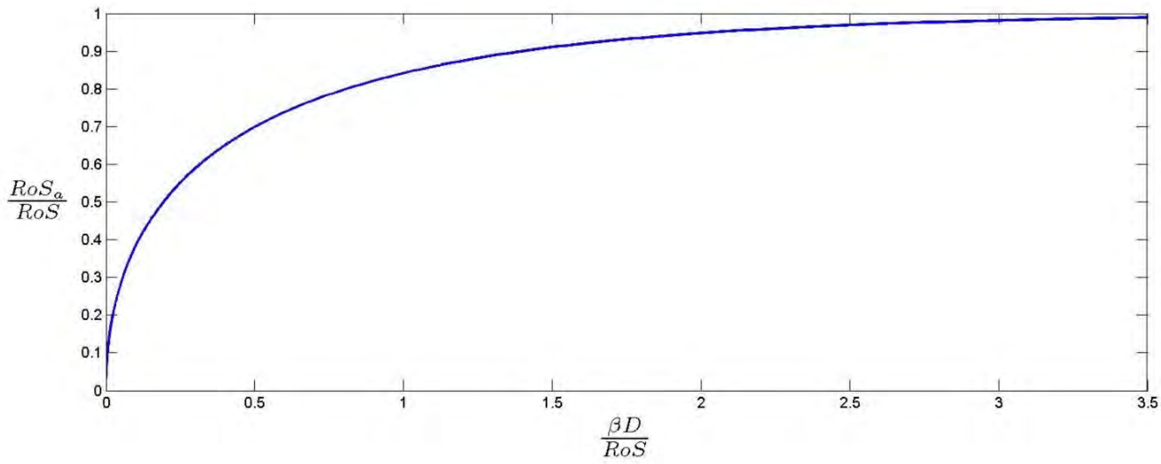


Figure 2.3. Plot of the ratio $\frac{RoS_a}{RoS}$ against $\frac{\beta D}{RoS}$.

Head fire spread distance at a given time can be calculated using the equation McAlpine (1988, Eqn 5):

$$D = RoS\left(t + \frac{e^{-0.0768t}}{0.0768} - \frac{1}{0.0768}\right) \quad (2.11)$$

Where:
D is the head fire spread distance at time t
RoS is the potential head fire rate of spread
t is the elapsed time since ignition

The fire will continue to accelerate with an increasing forward RoS until it attains a quasi-steady rate. Whilst Cheney and Gould (1997) report this may not occur in forest fuels until a head fire width of approximately 150m is reached, Penney (2017) identifies the more conservative figure of 100m, which is subsequently consistent with the calculations of Van Wager, is adopted for modelling purposes by both AS3959-2009 Construction of buildings in bushfire prone areas (AS3959) and NSWFRS (2016). During catastrophic bushfires, the scale and intensity of the bushfire itself can result in air-flow and wind conditions generated by the fire itself (Dold & Zinoviev, 2009) and subsequently 'explosive' bushfire behaviour similar to flashover phenomena experienced in structural firefighting response (Chatelon, Sauvagnargues, Dusserre, & Balbi, 2014).

2.3.1 *Forest, woodland and rainforest*

RoS is calculated in treed fuel structures of forest, woodland and rainforest using (Noble et al, 1980 cited in AS3959):

$$RoS = 0.0012 \times FDI \times w \quad (2.12)$$

Where:
RoS is the potential rate of spread (kph), also simply referred to as rate of spread
FDI is Fire Danger Index (dimensionless)
w is surface fuel load (t/ha)

Alternatively, for dry eucalypt forest, potential quasi-steady rate of spread (R_{SS}) can be calculated using the Vesta Fuel Hazard Scores (Gould et al, 2007) discussed in Chapter 1:

$$R_{ss} = \left[R_t + b_0(V_{10} - V_t)^{b1} exp\left(b_2 S_{hfs} + b_3 NS_{fhs} + b_4 NS_h\right)\right](\emptyset\dot{M}_f)(\emptyset\dot{S}_f) \quad (2.13)$$

where:
R_{ss} is the potential quasi-steady rate of spread (m/h)
R_t is the threshold rate of spread of 5kph at the threshold wind speed (U_t)
V_{10} is mean wind speed at 10m in the open (kph)
V_t is threshold wind speed 5kph
S_{fhs} is surface fuel hazard score
NS_{fhs} is near surface fuel hazard score
NS_h is near surface fuel height
$b_0 – b_4$ are regression constants $b_0 = 1.132$; $b_1 = 0.904$; $b_2 = 0.279$; $b_3 = 0.611$; $b_4 = 0.013$
$\emptyset M_f$ is fine fuel moisture function
$\emptyset S_f$ is slope function

And (Gould et al., 2007, Eqn. 5)

$$\emptyset M_f = \left({M_f}^{-1.495}\right)/0.0545 \quad (2.14)$$

where:
M_f is fine fuel moisture content (%)
And $\emptyset S_f$ is calculated by (Gould et al., 2007, Eqn. 6)

$$\emptyset S_f = exp(0.069\theta) \quad (2.15)$$

where:
θ is slope of the ground (degrees)

2.3.2 *Shrubland and scrub*

For shrubland and scrub, RoS is calculated by Anderson et al, (2015):

$$RoS = 5.67(0.67\ U_{10})^{0.91}\ \mathrm{H}^{0.22}\ e^{(-0.076\mathrm{MC})} \quad (2.16)$$

where:
H is height of the fuel bed (m)
U10 is average wind speed at 10m out in the open
MC is moisture content

Alternatively, it may be calculated using Cruz et al (2013):

$$RoS = 0.023V^{1.21}VH^{0.54} \quad (2.17)$$

where:
VH is the average height of the classified vegetation (m)
V is average wind speed at 10m above ground (kmh^{-1})

2.3.3 *Grassland*

For grassland, RoS is calculated by Putron (1982):

$$RoS = 0.13GFDI \quad (2.18)$$

Corrections for slope

When using equations 8 and 12-14, RoS can be corrected for the effects of slope by (AS3959):

$$R_{slope} = Re^{(0.069\, slope)}\ for\ fires\ burning\ uphill \quad (2.19)$$

$$R_{slope} = Re^{(-0.069\, slope)}\ for\ fires\ burning\ downhill \quad (2.20)$$

where:
R_{slope} is the forward rate of spread corrected for slope (km/h)
R is the forward rate of spread determined
slope is the slope (degrees)

Cruz et al (2015) however suggest this approach will grossly over-estimate the effect of slope and subsequently will result in an under-prediction of downslope RoS. To address this downslope RoS should be corrected by:

$$R_{slope} = R\frac{\exp\left(-0.069slope\right)}{2\exp(-0.069slope) - 1} \quad (2.21)$$

where:
R_{slope} is the forward rate of spread corrected for slope (km/h)
R is the forward rate of spread determined
slope is the slope (degrees)

2.4 Flame front residence time

Residence time is defined as the time the flaming zone takes to pass over a given point. There is some variance in the literature regarding typical residence time in forest fuels. Fire service literature (DFES, 2014) suggests in forest fuels a figure of between 45 to 60 seconds can be expected. During the development of firefighting vehicle crew protection systems, Nichols, Canderle, Knight and Leonard (2003, p2) identified it was reasonable to expect “residence times of several minutes,” however the peak of the burover intensity will last between 15-30 seconds as the fine bushfire fuels are consumed. This is consistent with the findings of Linton (2016) in her report into the burnovers experienced during the 2012 Black Cat Creek Fire. Wotton, Gould, McCaw, Cheney and Taylor (2012, p270) reported longer periods as the “average flame-front residence time for eucalypt forest fuels was 37 seconds and did not vary significantly with fine fuel moisture, fuel quantity or bulk density.” Poon (2003) describes a significantly longer flame residence time as lasting 1-2 minutes and mainly involving the fine fuels of twigs, ground litter and foliage, yet in the same report he identifies a residence time of 60 seconds as being appropriate for modelling purposes. Smith (2013) identifies residence time may be calculated using:

$$TR = \frac{D}{RoS} \quad (2.22)$$

Where:
TR is residence time (minutes)
D is flame depth (m)
RoS is rate of spread (m/hr)

2.5 Flame length and height

Flame length (L_f) will increase as the fire develops from ignition to a bushfire of landscape proportions. It is also affected by numerous other factors influencing the fire behaviour including fuel structure, wind speed and topography. Flame height is the vertical height of the flame above the ground as illustrated in Figure 2.4 and will vary depending on the inclination of the ground, the flame length and the flame angle. Whilst Linton (2016) reports flame heights of between 8-10m during the fatal Black Cat Creek bushfire, Cruz et al. (2012) reports flame heights 10-20m above the crowns of trees were experienced during the Black Saturday Kilmore East fire. The flame heights experienced by crews on Black Saturday are also consistent with reports of flames encountered by crews during the 2016 Yarloop Waroona fire in Western Australia.

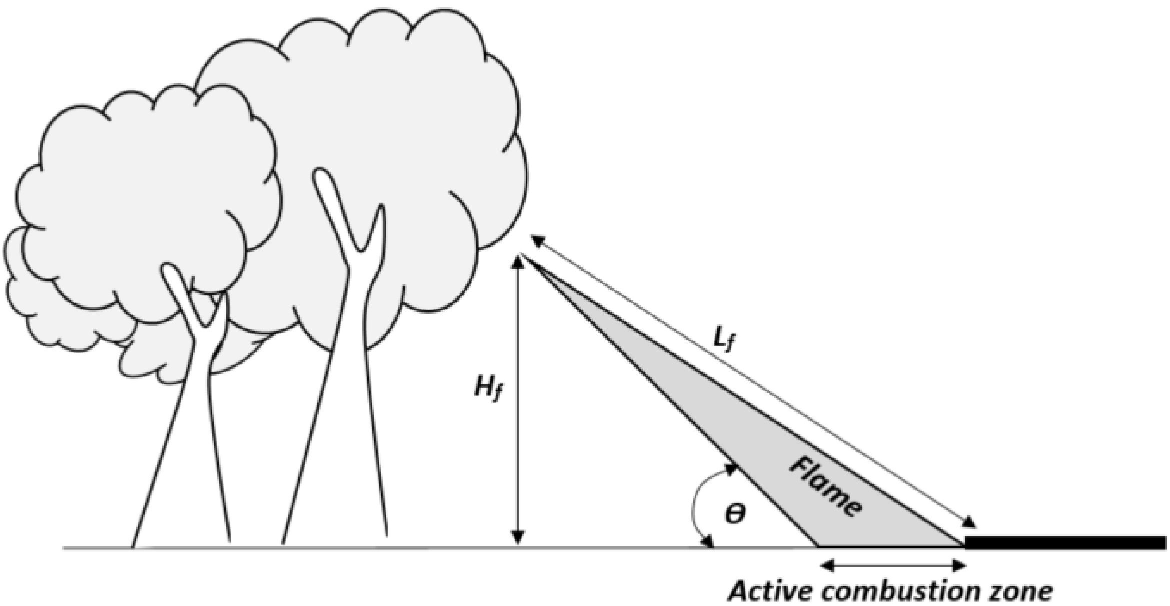


Figure 2.4. Flame length and height

Flame length (L_F) in treed fuel structures including those involved in Australian bushfire events can be calculated using the equation (AS3959, Eqn B2):

$$L_f = \frac{13R_{slope} + 0.24W}{2} \tag{2.23}$$

where:
L_f is flame length (m)
W is the total fuel load (t/ha)
R_{slope} is the forward rate of spread corrected for slope (km/h)

Flame height can also be calculated using the assigned hazard scores (Gould, 2007, Eqn. 7):

$$H_f = 0.0193 \times R^{0.723} \times exp(0.64E_{fh}) \tag{2.24}$$

where:
H_f is flame height (m)
R is head fire rate of spread
E_{fh} is elevated fuel height (m)

2.6 Fire line intensity

Current vehicle protection systems utilised in Western Australian fire service vehicles have been tested against fire line intensities of between 2.5-10MW/m and designed to withstand 7.5MW/m (Nichols, Gould, Knight, Leonard, & Brown, 2005). Comparatively, Cruz, et al. (2012) report average fire line intensities experienced during the Black Saturday Kilmore East Fire in 2009 of 88MW/m. Dold, Zinoviev and Leslie, (2011) describe bushfires as eruptive and unstable combustion involving a process of dynamic interaction between RoS and fire line intensity (*I*). A critical component of the fireline intensity is the heat of combustion, defined as the amount of heat released when a unit quantity of fuel is oxidised completely to yield stable end products (SFPE, 1-93). Common values for H are identified in Table 2.2. AS3959 details that *I*, in kW/m and corrected for slope, is calculated using Byram's fireline intensity equation.

$$I = HWR_{slope}/36 \quad (2.25)$$

Where:
H is the heat of combustion (kJ/kg), shown in table 2.2
W is total fuel load (t/ha)

Table 2.2. Heat of Combustion

Fuel	Heat of Combustion (kJ/kg)	Source
Wood (European Beech)	19500	SFPE Table 1-5.3
Wood (Ponderosa Pine)	19400	SFPE Table 1-5.3
Australian vegetation	18600	AS3959

2.7 Implications for frontline firefighters, fire behaviour specialists and IMT's

This chapter covers the basic modelling of wildfire development and behaviour. As the suitability of firefighting strategies are gauged against these inputs it is essential that all firefighters, fire behaviour specialists and IMT's alike not only understand the presented models, but are effective in accurately applying them. Incorrect predictions may result in inappropriate strategies being devised, leaving frontline personnel exposed to overwhelming wildfire conditions with potentially fatal consequences (see Chapters 5 and 7). Whilst fire behaviour specialists are required to accurately and competently predict wildfire behaviour, all personnel from firefighters to the IMT should be able to verify predictions thereby increasing the margin for safety for both firefighters and the community.

2.8 Implications for urban planners

Perhaps the greatest implications for urban planners apply to assessments of potential wildfire behaviour in urban areas where the landscape scale wildfire behaviour assumed in AS3959 and many of the planning guidelines is not possible. Where vegetation fuel bed geometry (refer back to Chapter 1) prevents the development of a quasi-steady RoS (refer to section 2.3 of this chapter), as reported in recent studies (Penney & Stevenson, 2019), failure to adequately adjust inputs may result in the significant over-calculation of potential wildfire behaviour. This can be in part be remedied by deference in such instances to suitably qualified fire safety engineers with wildfire backgrounds that can provide quantified analysis and an appropriate level of fire safety engineering rigor to design solutions.

3. Wildfire radiant heat flux

3.1 Introduction

Thermal radiation is the energy emitted from a body due to the internal temperature of the surface that is transported by photons capable of traveling through a perfect vacuum (Massoud, 2005). The rate of transfer of radiation across a given surface is known as radiant heat flux. Humans can only be exposed to relatively small levels of radiation before feeling pain and suffering other debilitating effects, hence it becomes a crucial factor in determining tenability on the fireground (see Chapter 5). Even prior to the attainment of a quasi-steady Rate of Spread (RoS), radiation quickly becomes the primary mechanism of heat transfer from a bushfire and impacts the receiving body well before direct flame impingement occurs (Leonard, 2009; Sullivan, Ellis, & Knight, 2003; Wotton, Gould, McCaw, Cheney, & Taylor, 2012). This chapter builds upon Chapter 2, discussing the calculation of radiant heat flux from wildfires and other vegetation fires occuring in small fuel beds. Understanding wildfire radiant heat flux is critical as it has impacts on firefighter and civilian tenability, as well as signficant implications for land use planning and construction in areas prone to wildfire in Australia.

3.2 Radiant heat flux

In order to empirically calculate the radiant heat flux during a bushfire event the chaotic flame front is geometrically represented by a uniform parallelepiped black body radiant heat panel (Sullivan, Ellis & Knight, 2003; Tan, Midgley & Douglas, 2005; Mendham, 2013) as illustrated in Figure 3.1. The horizontal position of the panel in relation to the flame is determined to be directly below the middle of the extended flame panel (Sullivan, Ellis & Knight, 2003) as shown in Figure 2. Both the flame temperature and emissivity are assumed to be consistent across the panel, whilst AS3959 also assumes the receiving body is perpendicular to the approaching fire front.

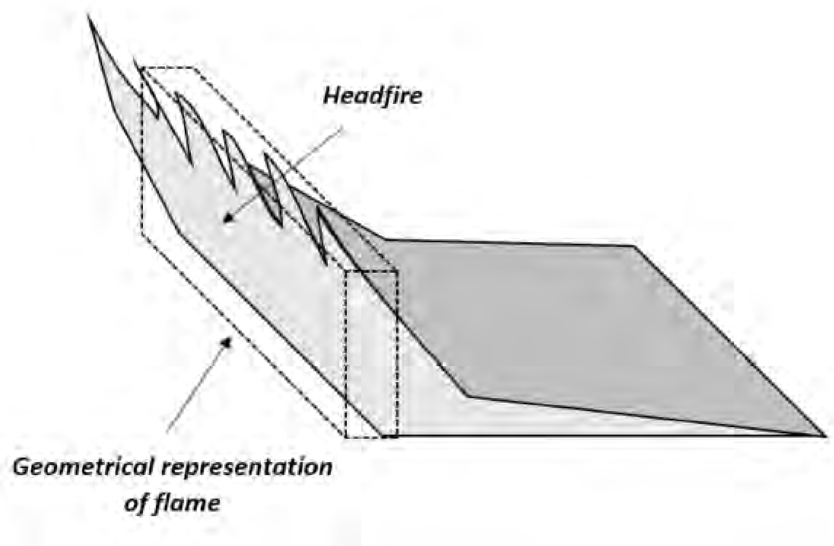


Figure 3.1: Geometrical representation of the flame front.

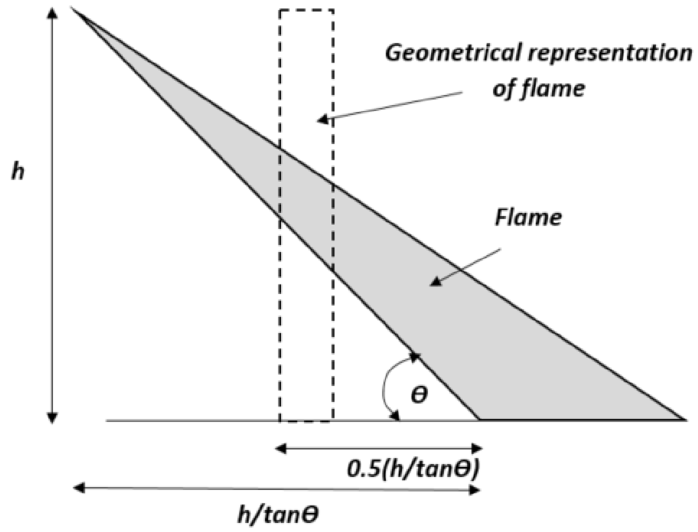


Figure 3.2: Geometrical representation of the flame front – side view.

Radiant heat flux is calculated using the equation:

$$q = \tau\phi E \tag{3.1}$$

where q is the radiant heat flux in kW/m^2, τ is the atmospheric transmissivity, E is the flame emissive power in kW/m^2 and ϕ is the view factor.

3.3 Atmospheric transmissivity

With reference to Figure 3.3, atmospheric transmissivity (τ) is calculated using the following steps:

Calculate path length (L):

$$\text{If } d \leq 0.5L_f cos\alpha, \text{ then } L = 0 \tag{3.2}$$

or

$$\text{If } d > 0.5L_f cos\alpha, \text{ then } L = d - 0.5L_f cos\alpha \tag{3.3}$$

where d is the distance between the fuel bed and the receiver (m), L_f is the flame length (m) and α is the flame angle (in degrees) that maximizes the view factor, calculated in accordance with the algorithm shown in Figure 3.4 (AS3959).

The atmospheric transmissivity is then calculated as follows:

$$\text{If } L = 0, \text{ then } \tau = 1$$

or

$$\text{If } L \neq 0, \text{ then } \tau = a_0 + a_1L + a_2L^2 + a_3L^3 + a_4L^4 \tag{3.4}$$

where L is the path length and a_n is the coefficient calculated by

$$a_n = C_{1n} + C_{2n}T_a + C_{3n}T_f + C_{4n}RH \tag{3.5}$$

where T_a is the ambient temperature, T_f is the flame temperature, RH is the relative humidity; and C_{1n}, C_{2n}, C_{3n} and C_{4n} are constants defined in Table 3.1 (AS3959, Table B3, reproduced with the permission of SAI Global on behalf of Standards Australia).

Table 3.1: Constants used in Equation 3.5.

n	C_{1n}	C_{2n}	C_{3n}	C_{4n}
0	1.486	-2.003×10^{-3}	4.68×10^{-5}	-6.052×10^{-2}
1	1.225×10^{-2}	-5.900×10^{-5}	1.66×10^{-6}	-1.759×10^{-3}
2	-1.489×10^{-4}	6.893×10^{-7}	-1.922×10^{-8}	2.092×10^{-5}
3	8.381×10^{-7}	-3.823×10^{-9}	1.0511×10^{-10}	-1.166×10^{-7}
4	-1.685×10^{-9}	7.637×10^{-12}	-2.085×10^{-13}	2.350×10^{-10}

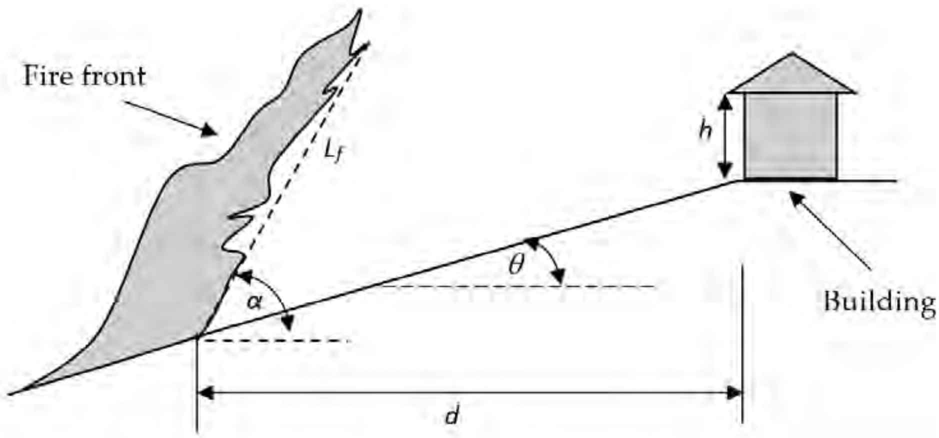


Figure 3.3: Typical building and fire front configuration.

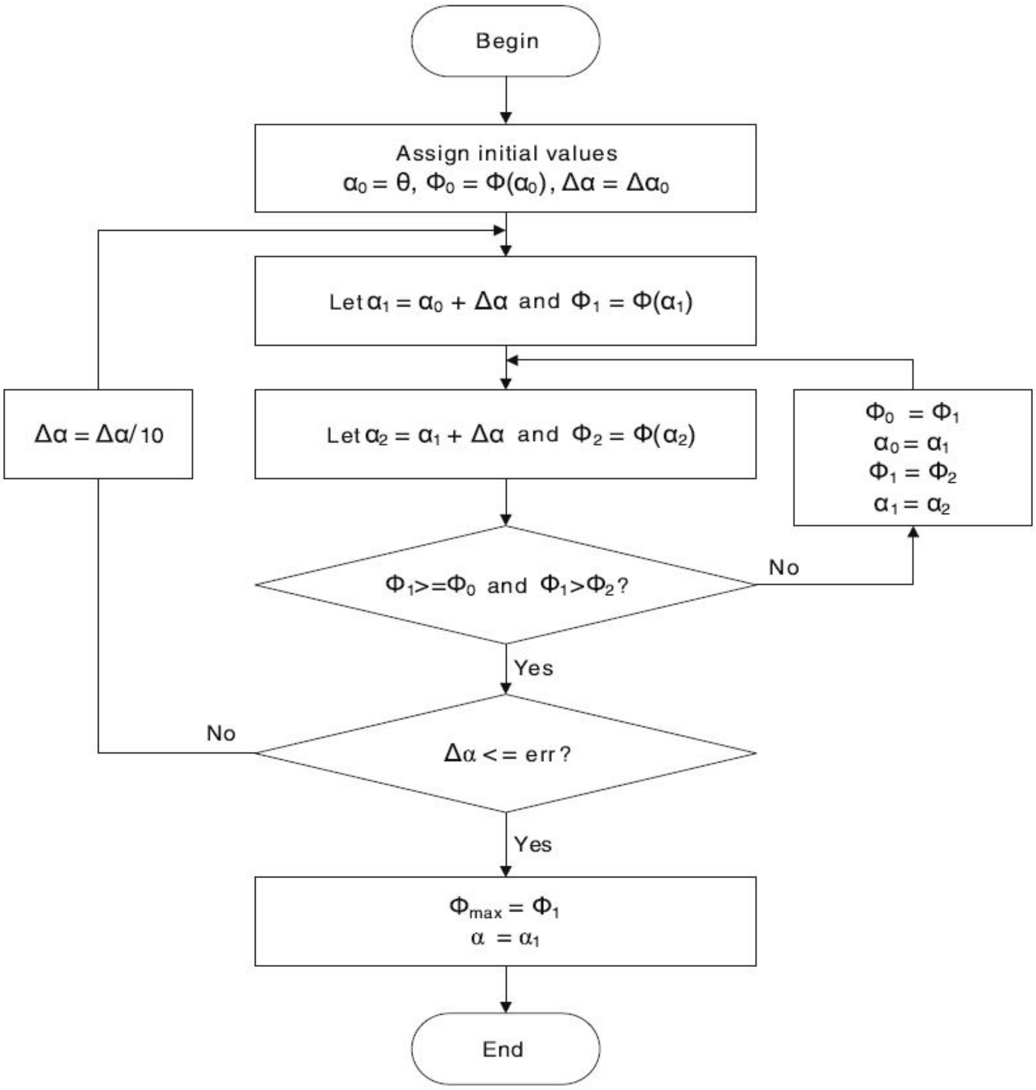


Figure 3.4: Flame angle algorithm (Copied by Greg Penney with the permission of SAI Global on behalf of Standards Australia).

3.4 Flame temperature

Drysdale (2011) identifies that flames emit radiation within the visible spectrum with a dull red glow at approximately 823K. As the flame temperature (T_f) increases, the flame colour changes as detailed in Table 3.2. Poon (2003) identifies that the predominantly 'reddish-orange' colour of bushfire flames suggests a flame temperature of approximately 1273K, which is supported by Rossi, Simeoni, Moretti and Leroy-Cancellieri (2011) who report a flame temperature of 1200K is appropriate for large wildland fires. AS3959 (2009) adopts a flame temperature of 1080K and assumes a uniform temperature across the flame surface. Conversley, the approximate maximum flame temperature reported in the research by Wotton, Gould, McCaw, Cheney and Taylor (2012) was 1373K.

Table 3.2: Visual colour of flame.

Temperature (K)	Appearance
823	Red glow
973	Dull red
1173	Cherry red
1373	Orange
1673	White

3.5 Emissivity

Emissivity (ε) is the ratio of the energy of radiated from a material's surface to that radiated from a blackbody (perfect emitter) at the same temperature and wavelength and under the same conditions (NPL, 2014). It is a dimensionless number between 0 (a perfect reflector) and 1 (a perfect emitter). During small scale experiments representative of a bushfire in the early stages of development, Boulet et. al. (2009) reported emissivity of up to 0.74 in flames lengths of 4m. AS3959 (2009, CB10.2) adopts a flame emissivity of 0.95 across the flame surface using the justification that "bushfire flames under design[2] fire weather scenarios are generally optically thick (ε~1)." This value is consistent with the findings of Agueda, Pastor and Perez, cited in Rossi, Simeoni, Moretti and Leroy-Cancellieri (2011) who report the emissivity of large wildland fires as being able to be considered close to the emissivity of a perfect emitter and assigned an emissivity of 0.90. Poon (2003, p26) however, suggests the use of "an emissivity close to 1 may not be a reasonable approximation of the emissive power from the flame front" and subsequently assumes a flame emissivity of 0.6 justifying this figure as "equivalent to a flame depth of about 5m" (Poon, 2003, Table 12, p38).

The flame emissive power (E) is calculated by:

$$E = \sigma \varepsilon T_f^{\,4} \tag{3.6}$$

where σ is the Stefan-Boltzman constant of 5.67x10^{-11} kWm^{-2}K^{-4}, ε is the flame emissivity and T_f is the flame temperature.

3.6 View factor

The view factor (ϕ) is a geometrical factor ranging from 0 to 1 which is related to the extent that the fire front fills the field of view looking from the site toward the flame. A value of $\phi = 1$ indicates that the entire field of view consists of flame (i.e. not even sky), while a value of $\phi = 0$ indicates that the fire front is completely out of view. As such, it is the view factor that must incorporate the impact of non-combustible obstructions on the radiant heat flux. To address this issue, this section proposes an alternate view factor model to that presented in AS3959.

In the absence of shielding bodies and referring to Figure 3.3, calculation of the view factor in the wildfire context is expressed as:

If $d \leq 0.5 L_f \cos(\alpha)$ then

$$\phi = 1 \tag{3.7}$$

otherwise, if $d > 0.5 L_f \cos(\alpha)$ then

[2] A design fire scenario is a specific fire scenario on which the analysis will be conducted, and a design fire is a quantitative description of assumed fire characteristics within the design fire scenario.

$$\phi = \frac{1}{\pi}\left\{ \begin{array}{c} \frac{X_1}{\sqrt{1+X_1^2}}\tan^{-1}\left(\frac{Y_1}{\sqrt{1+X_1^2}}\right) + \frac{Y_1}{\sqrt{1+Y_1^2}}\tan^{-1}\left(\frac{X_1}{\sqrt{1+Y_1^2}}\right) + \\ \frac{X_2}{\sqrt{1+X_2^2}}\tan^{-1}\left(\frac{Y_2}{\sqrt{1+X_2^2}}\right) + \frac{Y_2}{\sqrt{1+Y_2^2}}\tan^{-1}\left(\frac{X_2}{\sqrt{1+Y_2^2}}\right) \end{array} \right\} \tag{3.8}$$

where

$$X_1 = \frac{L_f \sin(\alpha) - 0.5 L_f \cos(\alpha)\tan(\theta) - d\tan(\theta) - h}{d - 0.5 L_f \cos(\alpha)} \tag{3.9}$$

$$X_2 = \frac{h + \left(d - 0.5 L_f \cos(\alpha)\right)\tan(\theta)}{d - 0.5 L_f \cos(\alpha)} \tag{3.10}$$

$$Y_1 = Y_2 = \frac{0.5 W_f}{d - 0.5 L_f \cos(\alpha)} \tag{3.11}$$

L_f is the flame length (m), W_f is the flame width/head fire width (m), α is the flame angle (degrees), θ is the slope of the land between the site and vegetation fuel bed (degrees), d is the horizontal distance between the site and the base of the vegetation fuel bed (m), and h is the elevation of the receiver (m). Figure 3.3 provides an illustration of these variable in relation to a typical site and fire front. In order to consider the worst case scenario, the view factor is maximised with respect to the flame angle α. To do this, the optimization algorithm in Figure 4 (AS3959) is used.

3.6.1 *Modelling radiant heat flux at the urban interface*

Within the urban environment, substantial non-combustible structures may stand between the receiving body and the fire front. For modelling purposes, these structures include significant walls or buildings, but not tin fencing or the like. Ignoring the impact of these structures on view factor may result in significant over estimation of wildfire impacts (Penney & Richardson, 2019). In order to incorporate the impact of non-combustible obstructions, the total combined view factor of the obstructions must be calculated and then subtracted from the unobstructed view factor given by Equations (3.7–3.11). This approach may be suitable for empirical calculation of radiant heat flux when firefighters are seeking shelter behind a substantial structure, however it is not suitable for use where firefighters are sheltering behind a fire appliance as the fire front will be significantly wider than the shielding body. Flames may also travel underneath and over the top of an appliance, drawn down the far side by an eddy caused by flame and air movements (Mangan, 1997).

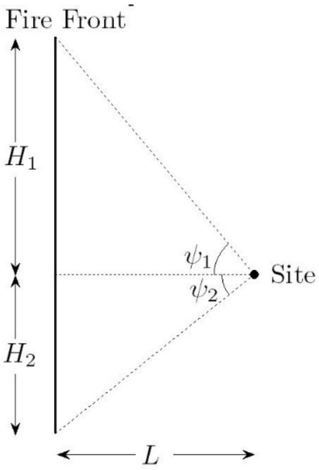
In describing the details of this approach, Penney and Richardson (2019) generalise Equations (3.7–3.11) and re-write them as follows:

1. Equations (3.8) and (3.11) impose the assumption that the site is horizontally central with respect to the fire front. This assumption will be relaxed to allow the calculation of view factors for obstructions and fire fronts which are not centrally aligned to the site.
2. Equations (3.7–3.11) are formulated in terms of parameters specifically referencing the fire front (not an obstruction). Furthermore, although convenient from a computational perspective, they are not presented in a means that offers significant geometrical insight. The equations will be reformulated in terms of view angles from the site to the fire front or obstruction(s).

The first step is to generalise and amend the existing view factor model. The second step is to consider the effect of shielding obstructions.

3.6.1.1 Generalisation and Reformulation of the View Factor Formulae

Figure 3.6 displays a generalised geometrical representation of the side view of a fire front and site. Consistent with the view factor calculation assumptions of AS3959, an inclined flame is approximated by a vertical flame with the same height as the inclined flame (height measured vertically from the highest point of the flame to the ground directly below) and located in the middle of the inclined flame.



$$H_1 = L_f \sin(\alpha) - \frac{1}{2} L_f \cos(\alpha)\tan(\psi_1) - d\tan(\psi_1) - h$$

$$H_2 = d\tan(\psi_1) - \frac{1}{2} L_f \cos(\alpha)\tan(\psi_1) + h$$

$$L = d - \frac{1}{2} L_f \cos(\alpha)$$

Figure 3.6: Geometrical representation of the side view of the site and vertical approximation of a fire front.

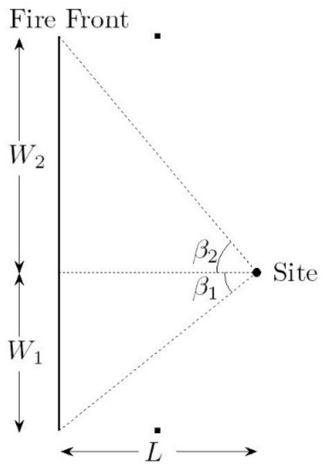
With reference to Figure 6, and Equations (9) and (10), it becomes evident that:

$$X_i = tan(\psi_i)$$

$$\sqrt{1 + X_i^2} = \sec(\psi_i)$$

for $i = 1,2$.

Figure 3.7 displays a generalised geometrical bird's-eye view of the fire front and site. Equation (8) enforces the assumption that the site is horizontally central with respect to the fire front by setting $W_1 = W_2 = \frac{W_f}{2}$, however wildfires may not be centered with respect to the receiving structure. To reflect this, Figure 9 represents a generalised asymmetrical case.



$$W_1 = W_2 = \frac{W_f}{2} \text{ (in the case of horizontal symmetry)}$$

$$L = d - \frac{1}{2} L_f \cos(\alpha)$$

Figure 3.7: Geometrical representation of the birds-eye view of the site and vertical approximation of a fire front.

With reference to Figure 7, and Equation (11), it becomes evident that:

$$Y_j = tan(\beta_i)$$

$$\sqrt{1 + Y_j^2} = \sec(\beta_i)$$

for $j = 1,2$.

Figure 3.8 displays a three dimensional representation of the upper-left quadrant of the fire-front relative to the site, and the four angles ψ_i, β_j, γ_{ij}, and ν_{ij}, $i = 1,2$, $j = 1,2$. The indexing of quadrants is summarised in Table 3.3.

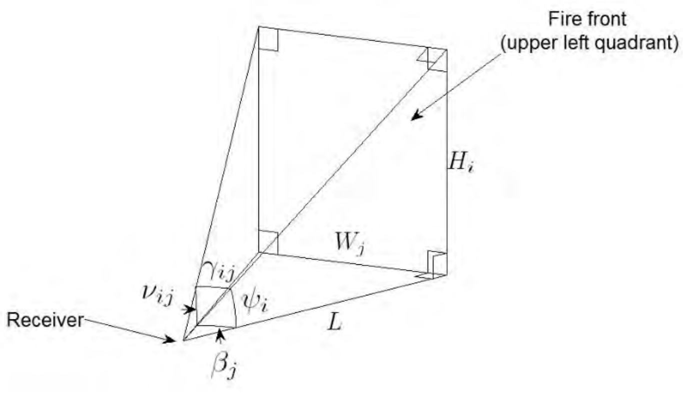


Figure 3.8: Geometrical representation of the upper-left quadrant of the fire front relative to the site.

Table 3.3: Indexing of quadrants.

i	j	Quadrant
1	1	Upper-left
1	2	Upper-right
2	2	Lower-right
2	1	Lower-left

With reference to Figure 3.8, it becomes evident that:

$$\frac{Y_j}{\sqrt{1+X_i^2}} = \frac{\tan(\beta_j)}{\sec(\psi_i)} = \tan(\gamma_{ij})$$
$$\frac{X_i}{\sqrt{1+Y_j^2}} = \frac{\tan(\psi_i)}{\sec(\beta_j)} = \tan(\nu_{ij})$$

for $i = 1,2$.

Accordingly, the generalised view factor for a rectangular approximation to a fire front or obstruction that does not pass through the site can be expressed as:

$$\begin{aligned}\phi &= \frac{1}{2\pi}\sum_{i=1}^{2}\sum_{j=1}^{2}\left(\frac{X_i}{\sqrt{1+X_i^2}}\tan^{-1}\left(\frac{Y_j}{\sqrt{1+X_i^2}}\right) + \frac{Y_j}{\sqrt{1+Y_j^2}}\tan^{-1}\left(\frac{X_i}{\sqrt{1+Y_j^2}}\right)\right)\\ &= \frac{1}{2\pi}\sum_{i=1}^{2}\sum_{j=1}^{2}\left(\frac{\tan(\psi_i)}{\sec(\psi_i)}\tan^{-1}\left(\tan(\gamma_{ij})\right) + \frac{\tan(\beta_j)}{\sec(\beta_j)}\tan^{-1}\left(\tan(\nu_{ij})\right)\right)\\ &= \frac{1}{2\pi}\sum_{i=1}^{2}\sum_{j=1}^{2}\left(\sin(\psi_i)\gamma_{ij} + \sin(\beta_j)\nu_{ij}\right)\end{aligned} \tag{3.12}$$

where the angles ψ_i, β_j, γ_{ij}, and ν_{ij}, $i = 1,2$, $j = 1,2$ are as defined in Figures 3.8–3.10. Consistent with Equation (3.7), if the vertical approximation to the flame front lies on or behind the site (relative to the direction of travel of the fire front) the view factor is assigned the value $\phi = 1$.

3.6.2 *Calculating the View Factor Subject to Shielding Obstructions*

The method for calculating the view factor of a flame front that is at least partially obstructed by non-combustible structures incorporates greater complexity than the existing model of AS3959 which does not consider the impact of obstructions on radiant heat flux. To assist with the discussion we describe the method with reference to the (r, β, ν) coordinate system illustrated in Figure 3.9.

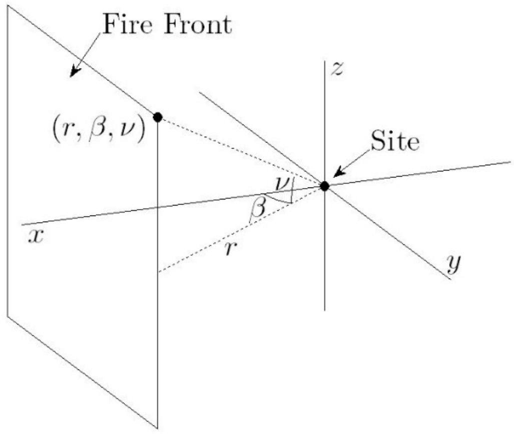


Figure 3.9: The (r, β, ν) coordinate system.

The r component is the distance from the site measured in the $x - y$ plane, β is the angle in the $x - y$ plane measured anticlockwise from the positive x-axis when viewed from above (i.e. $z > 0$), and ν is the vertical angle measured from the $x - y$ plane with positive values for $z > 0$, and negative values for $z < 0$.

The view factor calculation method is based on a discretisation of the fire front with respect to β as illustrated in Figure 3.10.

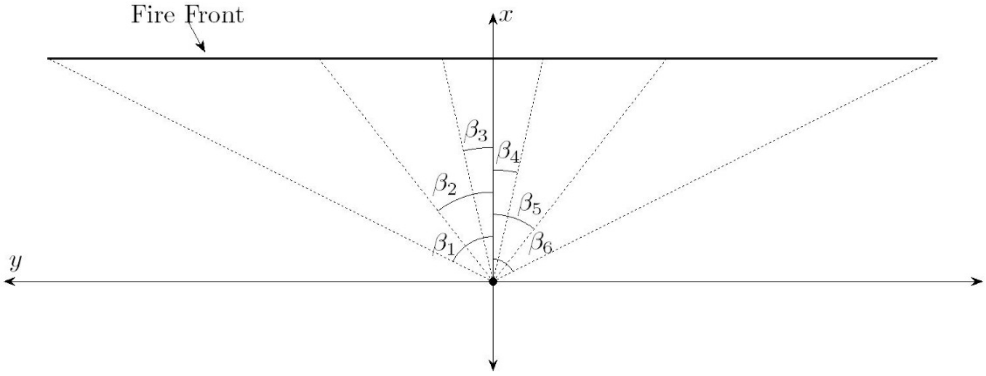


Figure 3.10: The discretisation of the fire front with respect to β using 6 uniformly distributed values $\{\beta_i\}_{i=1}^{6}$ looking from above. Note that $\beta_1, \beta_2, \beta_3 > 0$ while $\beta_4, \beta_5, \beta_6 < 0$.

The discretisation consists of a total of n uniformly distributed values $\{\beta_i\}_{i=1}^{n}$, with minimum value β_1 corresponding to the leftmost edge of the flame front (looking from above), and maximum value β_n corresponding to the rightmost edge.

Consider the vertical rectangle illustrated in Figure 3.11.

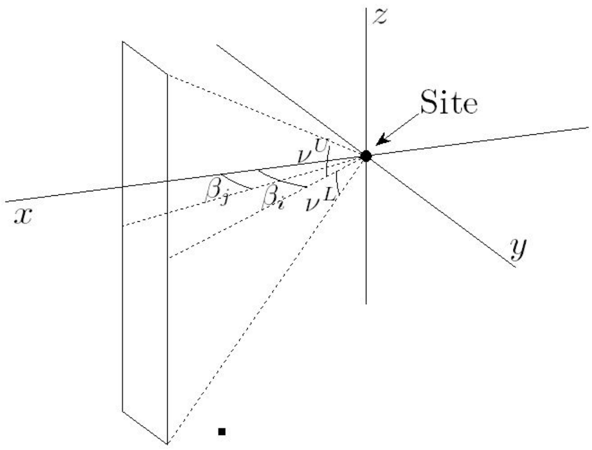


Figure 3.11: Any rectangle specified by a set of angles β_i, β_j, ν^U, and ν^L will have the same view factor relative to the site. Note that $\nu^U > 0$ and $\nu^L < 0$, while $\beta_i > 0$ and $\beta_j > 0$.

In order to calculate the view factor of the Figure 3.11 rectangle using Equation (3.12), the angles are set as follows:

$$\begin{array}{ll}
\psi_1 = \tan^{-1}\left(\dfrac{\tan(\nu_i^U)}{\cos(\beta_i)}\right), & \psi_2 = -\tan^{-1}\left(\dfrac{\tan(\nu_i^L)}{\cos(\beta_i)}\right) \\
\beta_1 = \beta_i, & \beta_2 = \beta_j \\
\gamma_{11} = \tan^{-1}(\tan(\beta_i)\cos(\psi_1)), & \gamma_{21} = \tan^{-1}(\tan(\beta_i)\cos(\psi_2)) \\
\gamma_{12} = -\tan^{-1}(\tan(\beta_j)\cos(\psi_1)), & \gamma_{22} = -\tan^{-1}(\tan(\beta_j)\cos(\psi_2)) \\
\nu_{11} = \nu_i^U, & \nu_{21} = -\nu_i^L \\
\nu_{12} = \tan^{-1}\left(\dfrac{\tan(\nu_i^U)\cos(\beta_j)}{\cos(\beta_i)}\right), & \nu_{22} = -\tan^{-1}\left(\dfrac{\tan(\nu_i^L)\cos(\beta_j)}{\cos(\beta_i)}\right)
\end{array} . \quad (3.13)$$

A single flame front with top edge coordinates denoted $\{(r_i^F, \beta_i, \nu_i^{FU})\}_{i=1}^n$ and bottom edge coordinates denoted $\{(r_i^F, \beta_i, \nu_i^{FL})\}_{i=1}^n$ is illustrated in Figure 3.12.

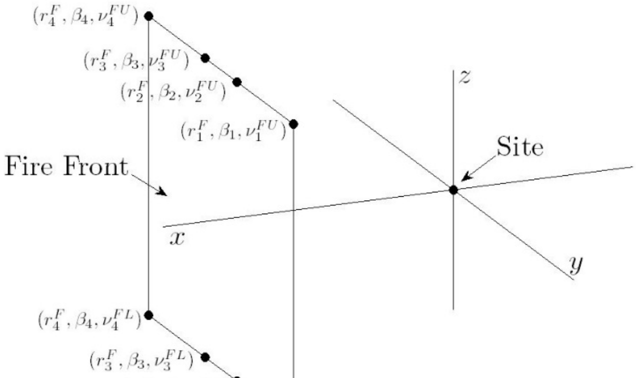


Figure 3.12: A flame front with top and bottom edge coordinates $\{(r_i^F, \beta_i, \nu_i^{FU})\}_{i=1}^4$ and $\{(r_i^F, \beta_i, \nu_i^{FL})\}_{i=1}^4$ respectively.

We now consider a collection of M obstructions with top edge coordinates denoted $\{(r_i^j, \beta_i, \nu_i^{jU})\}_{i=n_1^j}^{n_2^j}$ and bottom edge coordinates denoted $\{(r_i^j, \beta_i, \nu_i^{jL})\}_{i=n_1^j}^{n_2^j}$ for $j = 1,2,\ldots,M$. Note that $1 \le n_1^j \le n_2^j \le n$ for $j = 1,2,\ldots,M$ since the obstruction(s) may not span the full horizontal angular extent of the fire front when viewed from the site, and any part of an obstruction lying beyond the angular extent of the fire front does not impact the view factor calculation. This is illustrated in Figure 3.13.

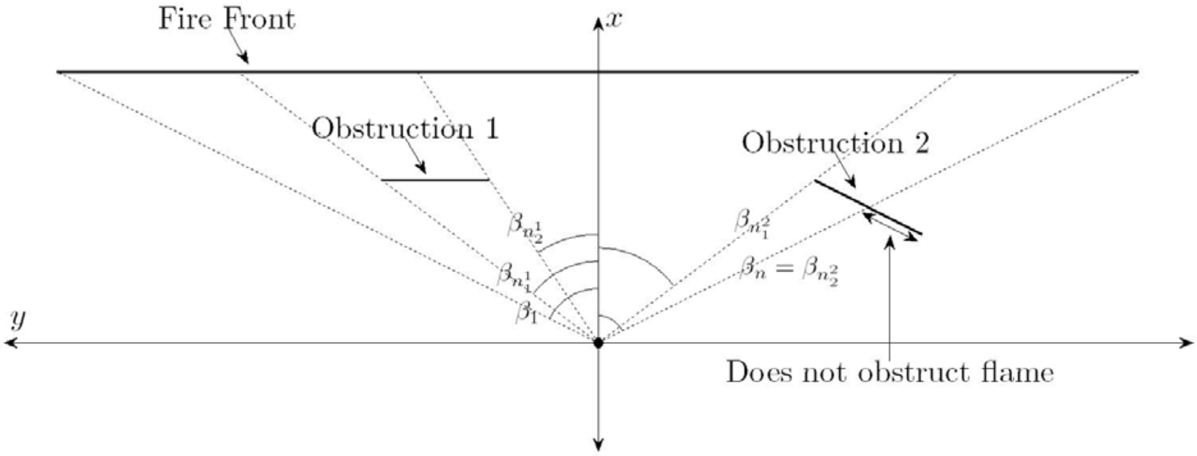


Figure 3.13: An obstruction may only partially obstruct the fire front and will only obstruct the fire front if it lies within the angular region.

The calculation of the view factor ϕ subject to shielding obstructions proceeds as follows: If $d \leq 0.5L_f \cos(\alpha)$ (i.e. the center of the inclined flame is directly above or behind the site, so the vertical approximation to the fire front is on top of the site) then

$$\phi = 1,$$

otherwise

1. Calculate the view factor ϕ_F of the unobstructed vertical approximation to the fire front by setting $i = 1$, $j = n$, $\nu_i^U = \nu_1^{FU}$ and $\nu_i^L = \nu_1^{FL}$ in Equation (3.13), and then substituting the resulting angles into Equation (3.12).
2. In order to accommodate non-rectangular obstructions, the obstructed view factor ϕ_O is calculated by approximating the obstructions using thin rectangles defined within the angular increments from β_i to β_{i+1} for $i = 1,2,\ldots,n-1$. For each angular increment, the obstructed view factor ϕ_O^i is calculated by determining the maximum value of ν_i^{jU} and minimum value of ν_i^{jL} for the obstructions that lie between the flame front and the site. If $\nu_i^{jU} > \nu_i^{FU}$, then ν_i^{FU} is used to denote the top of the obstructing rectangle, as any part of the obstruction extending above the flame front does not actually block the view of the flame front. This is illustrated in Figure 3.14.

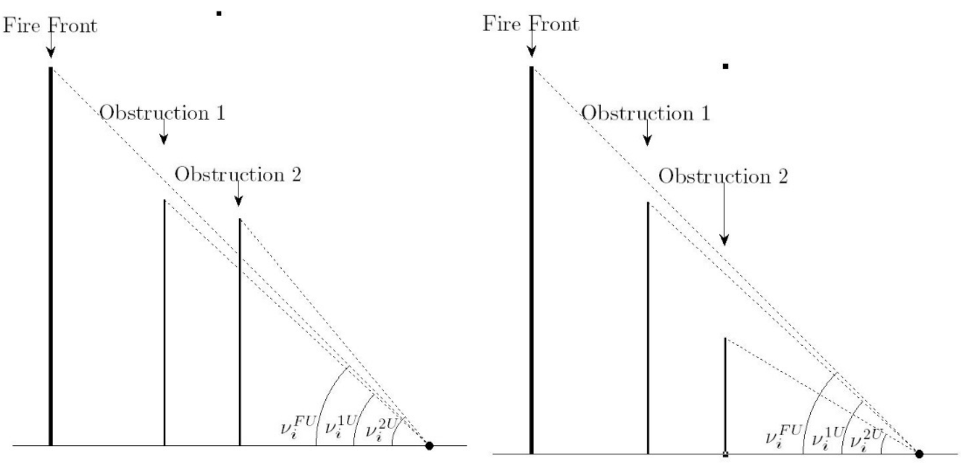


Figure 3.14. (Left) Obstruction 2 completely blocks the fire front from the site, so $v_i^U = v_i^{FU}$ as the part of Obstruction 2 that extends above the view line of the top of the fire front does not contribute to blocking the fire front. (Right) Obstruction 1 partially blocks the fire front from the site, so $v_i^U = v_i^{1U}$.

Similarly, if $v_i^{jL} < v_i^{FL}$, then v_i^{FL} is used to denote the bottom of the obstructing rectangle. Denoting the angle to the top and bottom of the obstructing rectangle on increment i as v_i^U and v_i^L respectively, it follows that

$$v_i^U = min\{v_i^{FU}, v_i^{OU}\}$$

$$v_i^L = min\{v_i^{FL}, v_i^{OL}\}$$

where

$$v_i^{OU} = \max\{v_i^{jU} u(r_i^F - r_i^j) : j \in N_i\}$$
$$v_i^{OL} = \max\{v_i^{jL} u(r_i^F - r_i^j) : j \in N_i\}$$
$$u(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases}$$
$$N_i = \{j : n_1^j \leq i \leq n_2^j\}$$

The obstructing view factor ϕ_O^i for each angular increment $i = 1,2, \dots, n-1$ is calculated by setting $j = i + 1$ in Equation (3.13), and then substituting the resulting angles into Equation (3.12).

3. Calculate the total obstructed view factor

$$\phi_O = \sum_{i=1}^{n-1} \phi_O^i$$

4. Calculate the view factor of the partially obstructed flame front

$$\phi = \phi_F - \phi_O.$$

3.6.2.1 Modifications to the Optimisation Algorithm

In order to consider the worst case view factor with respect to the flame angle in this approach, four modifications need to be made to the optimisation algorithm illustrated in Figure 4:

1. In the original algorithm the initial value (lowest value) of the flame angle considered in is the site slope θ. This is not a valid angle in the case that an obstruction exists between the flame front and the site, as it effectively allows the fire front to penetrate the obstruction. To avoid this situation it is necessary to set the initial flame angle such that the fire front would clear the obstruction. This amounts to setting

$$\alpha_0 = \tan^{-1}\left(\tan(\theta) + \max\left\{\frac{h_O^j(\beta_i)}{x - x_O^j(\beta_i)} : n_1^j \leq i \leq n_2^j, j = 1,2, \dots, M\right\}\right)$$

when $x > \min\{x_O^j(\beta_i) : n_1^j \leq i \leq n_2^j, j = 1,2, \dots, M\}$. Note that θ denotes the site slope, and $h_O^j(\beta_i)$ and $x_O^j(\beta_i)$ denote the maximum height and x component of obstruction j at angle β_i relative to the site.

A further complication could arise if the center of the fire front lies in front of the obstruction when the base of the fire front lies behind the obstruction. The issue in this instance is that the obstruction would not have an impact on the view factor. To avoid this situation the minimum flame angle is required to satisfy

$$\alpha_0 \geq \max\left\{\cos^{-1}\left(\frac{2\left(x - x_O^j(\beta_i) - \varepsilon\right)}{L_f}\right) : n_1^j \leq i \leq n_2^j, j = 1,2,\dots,M\right\}$$

when $x > \min\{x_O^j(\beta_i) : n_1^j \leq i \leq n_2^j, j = 1,2,\dots,M\}$. Note that L_f is the flame length, and ε is a small positive number (e.g. 10^{-6}).

2. If the fire front is positioned on top of an obstruction, the flame angle α_0 is set to 90 degrees to effectively consider the fire front as being behind the obstruction. In this case, the algorithm is not required to proceed further to determine an optimal value of α_0.
3. Since the algorithm does not start with the flame angle α_0 equal to the site slope θ, it is possible that the initial value of α_0 could turn out to be the flame angle that optimises the view factor. The standard optimisation algorithm of AS3959 terminates or refines its search increment when the view factors ϕ_0, ϕ_1, and ϕ_2, which correspond to the flame angles $\alpha_0 < \alpha_1 < \alpha_2$ satisfy $\phi_1 \geq \phi_0$ and $\phi_1 > \phi_2$, however, if $\phi_0 > \phi_1$ at the first step the algorithm will not terminate. Hence the additional termination or refinement criteria, $\phi_0 > \phi_1$ must be added to the algorithm in addition to the existing criteria (i.e., ($\phi_1 \geq \phi_0$ and $\phi_1 > \phi_2$) or $\phi_0 > \phi_1$).
4. In the case that the obstruction completely obscures the line of sight from the building site to the top of the flame front, the optimisation algorithm will never terminate as it will not be able to identify a non-zero view factor no matter how much the flame angle (α) is increased. In order to avoid this situation, an additional condition is added to both loops of the algorithm. Specifically, if $\alpha_1 > 90^o$ during the iteration then the algorithm will terminate immediately, and the flame angle will be set to $\alpha_1 = 90^o$. This measure is only required to avoid an infinite loop, and will not affect the outcome of the calculation.

3.7 Fire in isolated vegetation and fuel beds that restrict wildfire growth

In urban environments the failure to consider the effect of vegetation geometry on restricting wildfire growth can lead to significant overestimation of potential radiant heat impacts (Penney & Richardson, 2019). In turn, this may result in:

1. Firefighters not being deployed to suppress wildfires and defend homes as a result of over-estimation of wildfire behaviour that indicates suppression efforts are not suitable, resulting in avoidable house loss and impacts on communities. This may occur as firefighting suppression thresholds are related to wildfire behaviour parameters throughout jurisdictions internationally (Penney et. al., 2019). Where inappropriate predictions fail to consider vegetation geometry that does not support the assumptions of landscape wildfire modelling, otherwise defendable areas may be left unguarded due to inappropriate evaluation of suppression strategies;
2. Inappropriate modelling of wildfire through landscaped gardens, public open space, road reserves, and residential areas within urban areas. In turn, land that is actually suitable for development may be identified as being subject to overestimated wildfire impact which restricts or prohibits development altogether. Typically, this may occur in urban settings where a small unmanaged vacant residential lot is modelled as supporting a landscape scale wildfire, in turn restricting or prohibiting development on adjacent and near-by lots; and
3. Unnecessary requirements for over engineering and wildfire resistant construction standards of affected dwellings and structures that hinders development through either misidentification of land as being subject to unacceptable levels of wildfire

impact, or through making development cost-prohibitive as a result of the level of wildfire resistant engineering and construction required.

3.7.1 *Modelling of wildfire through fuel beds that restrict wildfire growth and spread*

As detailed by Penney and Richardson (2019), within the urban environment in road reserves, urban parklands and similar scenarios, correction of the wildfire models can be achieved through the application of:

1. The Vegetation Availability Factor (refer to Chapter 2);
2. Calculation of accelerating RoS from a point source (refer to Chapter 2);
3. Consideration of shielding structures when calculating view factor; and
4. Calculating the final radiant heat flux.

3.7.2 *Modelling of radiant heat flux in isolated vegetation structures*

Methods of calculating radiant heat flux that rely of a defined RoS cannot be applied to fires occurring in isolated vegetation structures, including individual trees, bushes or small garden beds (Figure 3.14) or other situations where there is an absence of a sustained forward RoS. AS3959 provides some provisions for the exclusion of defined 'low threat vegetation', where these exclusions do not apply or modelling is required for other purposes. In such instances the RoS will be zero, a vertical flame (flame angle of 90°) should be modelled (i.e. $L_f = H_f$) and a reduction in emissivity is appropriate compared to landscape scale wildfire environments.

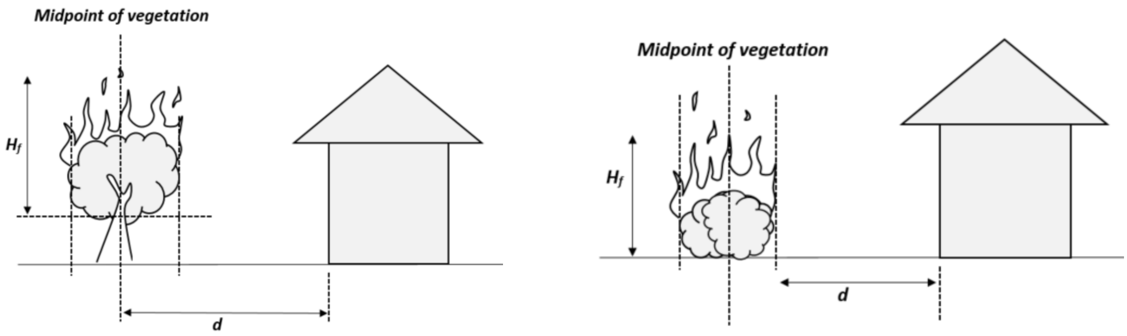


Figure 3.14: Modelling of isolated trees (left) and shrub/scrub (right).

To calculate radiant heat flux in this situation, flame height (H_f) is calculated by (Dupuy, Marechal & Morvan, 2003)

$$H_f = 0.2Q_f^{\frac{2}{5}} \tag{3.14}$$

where H_f is the flame height (m) and Q_f is the maximum heat release rate (kW). The maximum heat release rate is given by

$$Q_f = H_C MLR \tag{3.15}$$

where H_C is the heat of combustion and MLR is the Mass Loss Rate. Finally, the Mass Loss Rate is given by

$$MLR = \frac{W_i}{t} \tag{3.16}$$

where W_i is the total fuel load consumed in the isolated vegetation structure (kg), calculated using the Vegetation Availability Factor in the absence of other available datasets, and t is time (s), assumed to be 37 seconds as reported by Wotton et. al. (2012) reflective of flaming residence times and greater than the duration of tall flames, being a maximum 22 seconds.

Once H_f is known, the view factor, flame emissive power and final radiant heat flux can be calculated as previously described.

3.8 Case Studies

A number of case studies are presented to illustrate the application and implications of the approaches described previously to consider radiant heat flux from a fire front while accounting for fuel loading, non-combustible obstruction(s), or accelerating fire fronts. These case studies, as well as the alternative view factor calculations were originally published in Penney and Stevenson (2019).

3.8.1 *Case Study 1*

The first case study considers a semi-rural environment in which a row of single and two story brick houses backs onto forest type bush land with a fuel bed of unrestricted geometry and V_F=1. Suppose that the radiant heat flux of a fire in the bush land behind the houses is to be estimated at a site or house on the opposite side of the street. The geometry of the specific case considered here is provided in Figure 3.15.

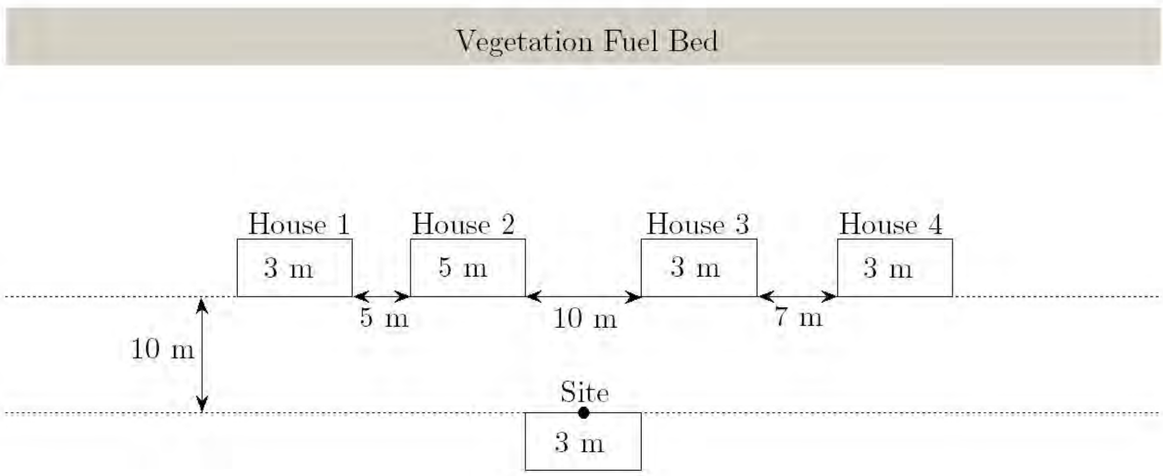


Figure 3.15. A bird's-eye view of the case study 1 scenario. The measurements within the house boxes denote the height of each house.

The parameter values used in the calculation as described in AS3959 are summarised in Table 3.3.

Table 3.3. Parameter values used in the Case Studies.

Parameter	Value	Parameter	Value
Effective slope	0°	Flame temperature (T_f)	1090 K
Site slope (θ)	0°	Ambient temperature (T_a)	308 K
Vegetation class	Forest	Relative humidity (RH)	25%
Fire Danger Index (FDI)	80	Flame width (W_f)	100 m
Surface fuel load (w)	25 t/ha	Flame emissivity (ε)	0.95
Overall fuel load (W)	35 t/ha	Stefan Boltzman constant (σ)	5.67×10^{-11} kW/m²/K⁴
Heat of Combustion (H)	18600 kJ/kg		

The radiant heat flux was calculated for a range of distances from the site to the vegetation fuel bed ranging from 10 m to 100m. For the sake of comparison, the radiant heat flux at the site was estimated using four calculation methods:

1. The method outlined in AS3959, ignoring the obstructions presented by the houses located between the site and vegetation fuel bed.
2. The method outlined in AS3959 with the receiver height h set to 3 m (instead of the mid-level of the flame front).
3. The method outlined in this paper, where each of the four houses is considered to reduce the view factor of the flame front.
4. A simplified method in which the four obstructions are considered as a single rectangular obstruction with height 5 m (i.e., the height of the tallest house), and width equal to the combined width of the four houses. The combined width is the distance from the westernmost edge of the westernmost structure to the easternmost edge of the easternmost structure.

Figure 3.16 provides a plot of the radiant heat flux at the site as a function of the distance to the vegetation fuel bed using each of the methods 1–4 outlined above.

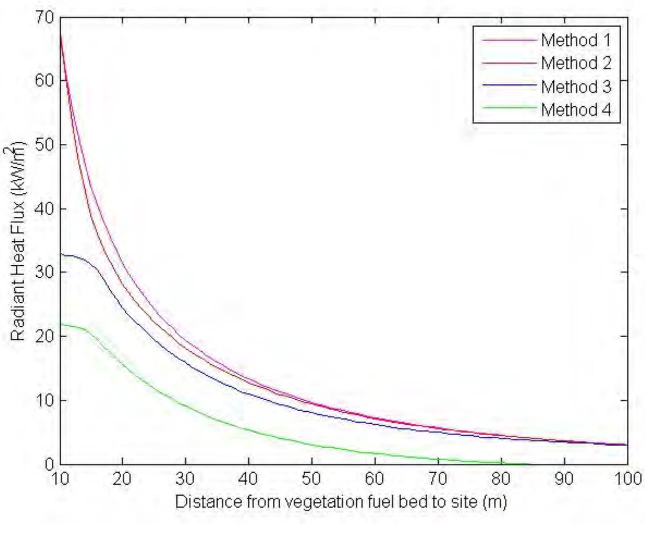


Figure 3.16. The radiant heat flux at the site as a function of the distance to the vegetation fuel bed.

As expected, the methods that did not consider the shielding effect of the houses (magenta and red lines) provided higher estimates for the radiant heat flux compared to the methods that did consider the shielding effect (blue and green). For small distances to the vegetation fuel bed, the approaches that did not consider shielding significantly over-estimated the radiant heat flux compared to the method presented in this paper (blue line). As the distance to the vegetation fuel bed increases, the difference between the AS3959 approach and shielding approach presented here becomes small. This is most likely because the 10m gap between house 2 and 3 becomes the most significant zone for heat flux for a more distant fire front, so the impact of the obstructions becomes less significant.

Method 4 (green line) provided the lowest estimates of radiant heat flux as expected. As the distance to the vegetation fuel bed increased, the radiant heat flux estimated using this approach tended to zero far more rapidly than the other methods. This was most likely due to the significant gap between house 2 and house 3, which was not blocked in methods 1–3, but was blocked when the four houses were approximated as a single rectangular obstruction. This highlights the importance of considering multiple obstructions individually to ensure that the impact of radiation through significant gaps is not diminished.

3.8.2 *Case Study 2*

The second case study considers an accelerating fire front burning within a 20m wide treed forest style bushland zone within the road reserve between the edge of a freeway or highway and a 3m brick wall separating the freeway from housing. The geometry of the vegetation fuel bed prevents the fire attaining its maximum potential rate of spread. There is a row of houses located 10m on the other side of the brick wall, one of which will be considered the site at which the radiant heat flux from the fire will be considered. The geometry of the specific case considered here is provided in Figure 3.17.

The parameters used in the calculation are summarised in Table 3.3. In addition, the vegetation factor V_f = 0.2 scales back the surface and overall fuel loads as defined in Chapter 2. The fire is assumed to ignite from a point source at the edge of the Freeway, 30 m from the site/receiver. The fire is assumed to spread perpendicular to the Freeway at an accelerating rate RoS_a, which is related to the distance from the ignition point *D*. The rate parameter $\beta = 2\ln(10)$ h^{-1}, as suggested by McAlpine (1988), is utilised. Figure 3.18 provides a plot of the accelerating rate of spread RoS_a and the equilibrium rate of spread RoS against the distance from the ignition point *D*.

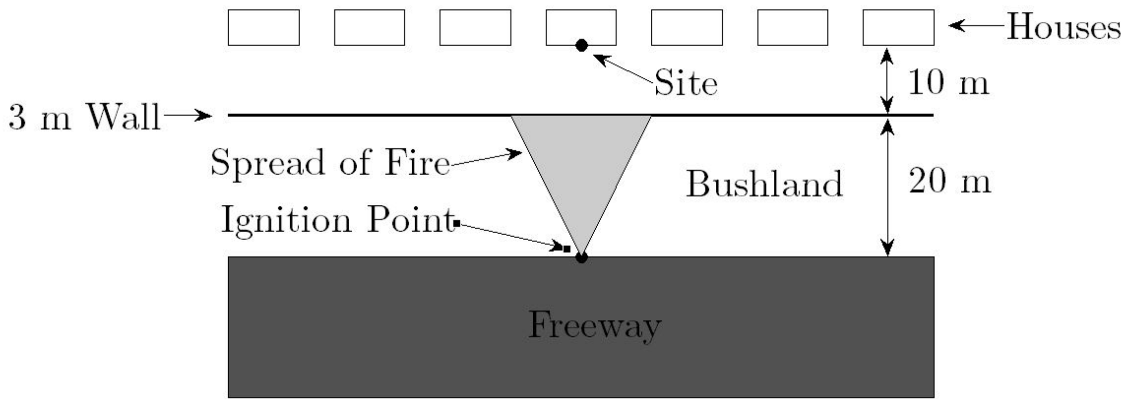


Figure 3.17. A bird's-eye view of the case study 2 scenario.

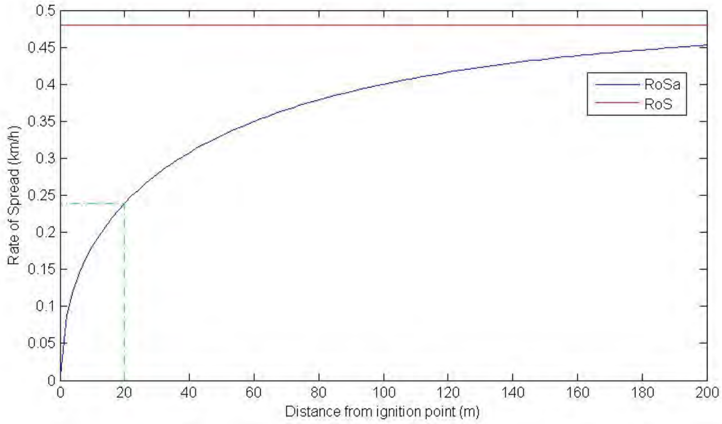


Figure 3.18. The accelerating rate of spread $RoSa$ and the equilibrium rate of spread RoS against the distance from the ignition point D.

From Figure 3.18 it is apparent that over 20 m (i.e., the distance from the ignition point to the obstructing wall) the rate of spread reaches approximately half of its equilibrium value. The rate of spread perpendicular to the forward direction is assumed to be half the forward rate of spread, so the flame width is given by $W_f = \frac{D}{2}$.

The impact of incorporating the acceleration of a fire front and an obstruction into the heat flux model has been highlighted by comparing the above scenario with an additional seven modelling variants. The eight scenarios are summarised as follows:

1. The fire front is modelled with a constant (equilibrium) rate of spread from the ignition point, a width of 100m, a vegetation factor of V_f = 1, and the obstruction (wall) is ignored (the model of AS3959).
2. The fire front is modelled with a constant (equilibrium) rate of spread from the ignition point, a width of 100m, a vegetation factor of V_f = 0.2, and the obstruction (wall) is ignored.
3. The fire front is modelled with an accelerating rate of spread from the ignition point, a vegetation factor of V_f = 1, and the obstruction (wall) is ignored.
4. The fire front is modelled with an accelerating rate of spread from the ignition point, a vegetation factor of V_f = 0.2, and the obstruction (wall) is ignored.
5. The fire front is modelled with a constant (equilibrium) rate of spread from the ignition point, a width of 100 m, a vegetation factor of V_f = 1, and the obstruction (wall) is included.
6. The fire front is modelled with a constant (equilibrium) rate of spread from the ignition point, a width of 100 m, a vegetation factor of V_f = 0.2, and the obstruction (wall) is included.
7. The fire front is modelled with an accelerating rate of spread from the ignition point, a vegetation factor of V_f = 1, and the obstruction (wall) is included.
8. The fire front is modelled with an accelerating rate of spread from the ignition point, a vegetation factor of V_f = 0.2, and the obstruction (wall) is included (i.e., the Case Study 2 scenario).

The radiant heat flux for the above scenarios are plotted against the distance from the site in Figures 3.19 and 3.20.

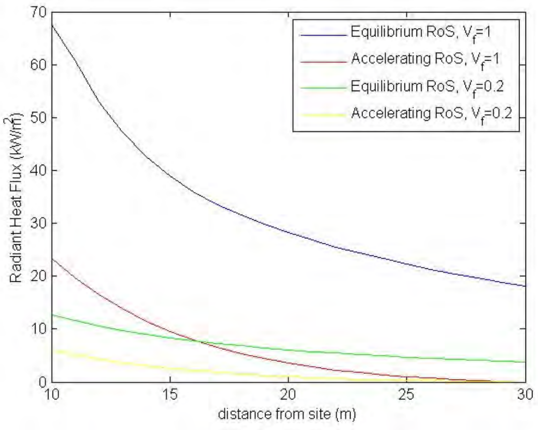


Figure 3.19. The radiant heat flux for models ignoring the 3m obstructing wall. The yellow line represents the Case Study 2 scenario.

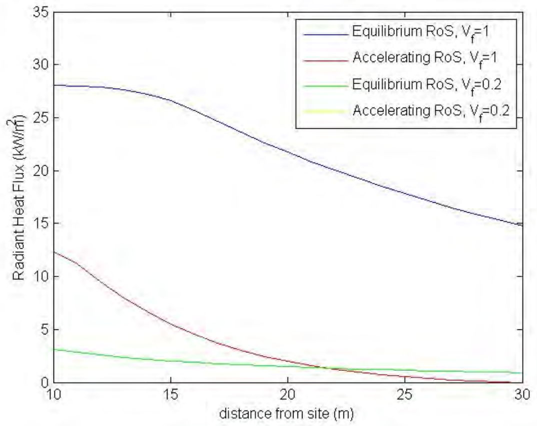


Figure 3.20. The radiant heat flux for models including the 3m obstructing wall. The yellow line represents the Case Study 2 scenario.

As expected, the heat fluxes when the wall is ignored are all greater than the corresponding fluxes when the wall is incorporated into the model to provide shielding. Furthermore, the fluxes with $V_f = 1$ exceeded those with $V_f = 0.2$. All of the models that include the modelling of acceleration start from a flux of zero, which increases as the rate of spread, length, and width increase (in addition to the increase from the larger view factor as the front closes on the site). Significantly, in Figure 3.20 the yellow line corresponding to the Case Study 2 scenario is not visible as the heat flux at the site remains zero. This is because the fuel load and rate of spread are not sufficient to create a front with sufficient height to be visible above the 3m obstruction after 20m of spreading, with the flame height reaching only 2.4 m.

The progression of the flame front over the bush region between the freeway and obstructing wall is illustrated in Figure 3.21 for scenarios 5 to 8.

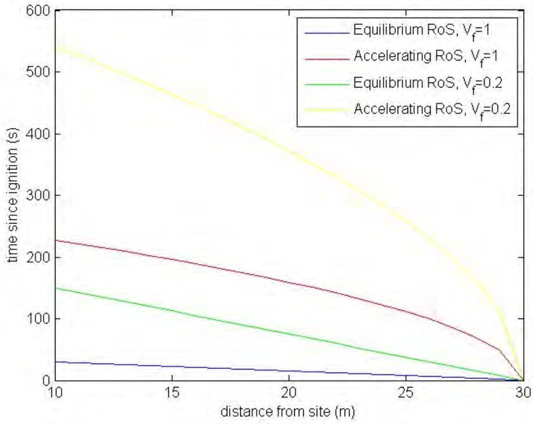


Figure 3.21. The progression of the fire front for modelling scenarios 5 through to 8. The yellow line represents the Case Study 2 scenario.

The model of AS3959, which assumes the wildfire is established and has attained a quasi-steady rate of spread, estimates the time taken for the ignited fire to travel from the freeway to the wall (20 m) is 30 seconds, while the model incorporating the acceleration of the spreading front and the reduced vegetation density estimates the time at 9 minutes, consistent with the findings of McAlpine (1988) and Kucuk, Bilgili and Baysal (2007).

3.9 Implications for frontline firefighters, fire behaviour specialists and IMT's

The case studies presented indicate potential significant over-estimation of radiant heat flux using the approach outlined in AS3959 in cases involving non-combustible obstructions and point-source ignition fires for a minimum of 20m separation from the fire front. This is significant as it is in this distance that wildfire flame radiation is considered to have its greatest impact (Cohen & Butler, 1996; Newman et al, 2013). Such situations are common in urban environments. The results demonstrate the importance of appropriately considering fuel geometry, wildfire behaviour, and the effect of shielding structures when calculating radiant heat impacts on buildings and emergency responders within urban environments where vegetation fuel bed geometry prevents wildfires reaching landscape proportions.

Over estimation of potential radiant heat flux impacts could, in turn, result in firefighters not being deployed to suppress wildfires and defend homes as a result of over-estimation of wildfire behaviour that indicates suppression efforts are not suitable, resulting in avoidable house loss and impacts on communities. This may occur as firefighting suppression thresholds are related to wildfire behaviour parameters throughout jurisdictions internationally. Where inappropriate predictions fail to consider vegetation geometry that does not support the assumptions of landscape wildfire modelling, otherwise defendable areas may be left unguarded due inappropriate evaluation of suppression strategies.

When considering the suitability of fire suppression strategies, there are factors other than radiant heat flux that also require consideration. These are addressed in Chapters 4-7.

3.10 Implications for urban planners

Whilst a precautionary approach to development in areas prone to wildfire is necessary, inappropriate modelling of wildfire through landscaped gardens, public open space, road reserves, and residential areas within urban areas. In turn, land that is actually suitable for development may be identified as being subject to overestimated wildfire impact which restricts or prohibits development altogether. Typically, this may occur in urban settings where a small unmanaged vacant residential lot is modelled as supporting a landscape scale wildfire, in turn restricting or prohibiting development on adjacent and near-by lots.

Unnecessary requirements for over engineering and wildfire resistant construction standards of affected dwellings and structures that hinders development through either misidentification of land as being subject to unacceptable levels of wildfire impact, or through making development cost-prohibitive as a result of the level of wildfire resistant engineering and construction required.

In addition to the inherent safety factor incorporated within the vegetation availability factor previously discussed, the methodologies proposed also retain the assumption of a flame emissivity $\varepsilon = 0.95$, being representative of a landscape scale wildfire with an active uniform flame front depth greater than 2m, and even potentially greater than 10m (Poon, 2003; Sullivan, 2009). In cases where the active flame front will not reach this depth, it may also be suitable to reduce the emissivity. It is important to note that whilst the vegetation factor and modified view factor model are applicable to all fuel types (forest, woodland, shrub, scrub, grassland, etc.), the point source acceleration model presented in this Chapter is suitable for treed forest and woodland structures only, as fire growth in other fuel structures may be significantly faster.

The models presented in this Chapter are not intended to address the potential radiant heat flux arising from surrounding buildings being involved in fire. In part, this is inherently considered within AS3959 through the requirement that associated structures on the same parcel of land and within 6m of the dwelling subject to enhanced construction standards, must also be constructed to that same standard. In new estates, all dwellings within the land development should be constructed to the required standard of wildfire resistance, in theory significantly reducing the potential for mass conflagration spreading between multiple houses. Due to the differences in wildfire and structural fire behaviour and radiation models as well as the difference in building and structure performance once impacted by wildfire, it is suggested that a high level of technical expertise is required to complete this process.

4. Wildfire suppression

4.1 Introduction

Where wildfires occur yet pose no threat to life, critical infrastructure, private assets or cultural and environmental areas of significance it is possible to simply allow the fire to self-extinguish once it runs out of available fuel or rainfall occurs. Unfortunately this is rarely possible in populated areas common throughout developed nations and significant intervention is required by fire and emergency services to suppress wildfires and minimise their impacts. This chapter discusses wildfire suppression strategies and presents evidence and analysis of available options to assist Incident Controllers to make critical incident decisions during chaotic and large wildfire incidents.

4.2 Strategies

Whilst offensive strategies involve actively combatting the fire, defensive strategies are employed when the fire behaviour is too intense to be safely attacked. Defensive strategies utilise tactics that do not involve active fire suppression including building containment lines and focusing on evacuation of people or livestock (DFES, 2012). When attempting to suppress severe wildfire, a combination of strategies may be necessary depending on the fire behaviour, availability of resources, accessibility and fuel structure. When incorrect strategies are applied firefighting crews may find themselves overrun by wildfire, known as a burnover. In such instances, unless the wildfire behaviour is particularly mild, the results can be fatal.

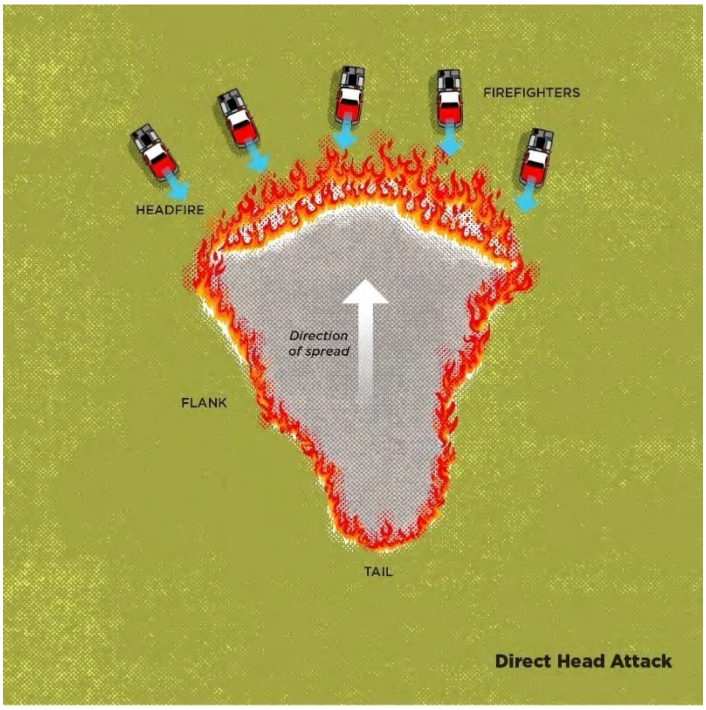
4.3 Offensive tactics

4.3.1 *Direct Attack*

Direct firefighting attack involves firefighters (including personnel, firefighting appliances, machines and aircraft) directly attacking the wildfire using the tactics of either head attack or flank attack. A direct head attack (see figures 4.1-4.3) involves firefighting efforts directly against the head fire before moving down either flank once the head fire is suppressed; a direct tail attack involves attacking the bushfire from the rear and working along the flanks towards the head fire; and a direct flank attack involves attacking the side of the fire and working around the head and tail. The direct tail attack is the "preferred method of suppression" (DFES, 2012, p11) as it reduces the potential for crews to be caught in a burnover due to a wind change that turns the flank into the greater head fire. Direct head attacks expose firefighters to the most severe wildfire behaviour, which reduces towards the tail. All tactics require firefighters to be able to access the fire edge in order to extinguish the fire. In dense forest fuels or in difficult terrain, this may be problematic and result in firefighters attempting to extinguish bushfire wherever they can in a patchwork manner. Where this occurs suppression efforts are likely to be less than optimal and result in unrestrained wildfire propagation as well as placing firefighters in unnecessary danger. Advantages and disadvantages of a direct attack reported in DFES (2012) are summarised in Table 4.1.

Table 4.1: Advantages and disadvantages of a direct attack

Advantages	Disadvantages
Minimises the area burnt.	Only possible on low intensity fires with flame heights <1.5m to 2m.
Reduces the likelihood of fire gaining momentum with changes in weather, fuel or topography factors.	Crews are more exposed to heat-related illnesses such as heat stroke, heat exhaustion, heat cramps and smoke inhalation.
Uses any dead edge of the fire to get the fire contained quickly.	If fire behaviour changes or there is a weakness in the control line, the fire can quickly escape.
May allow safe night work.	It may produce an irregular, winding control line.
Usually allows retreat onto burnt ground.	



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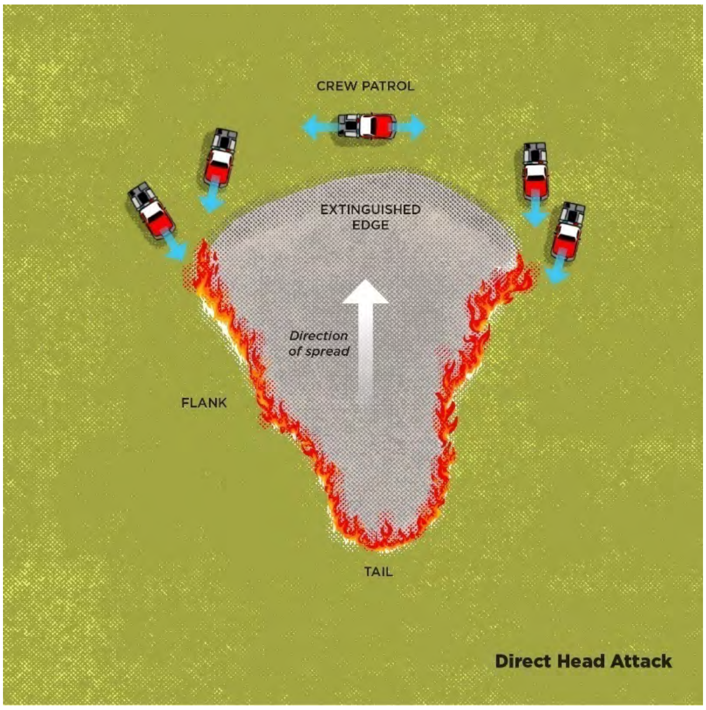

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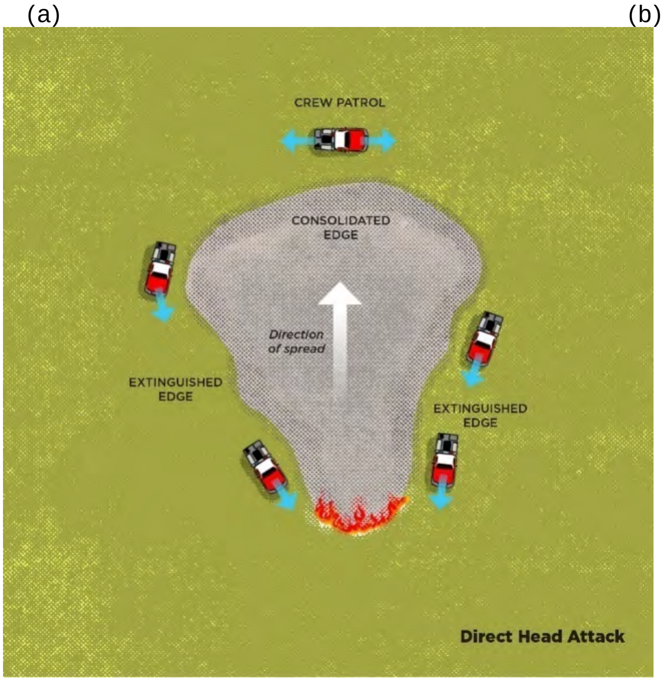


(c)

Figure 4.1: Direct head attack - commencement (a), ongoing (b), near completion (c)

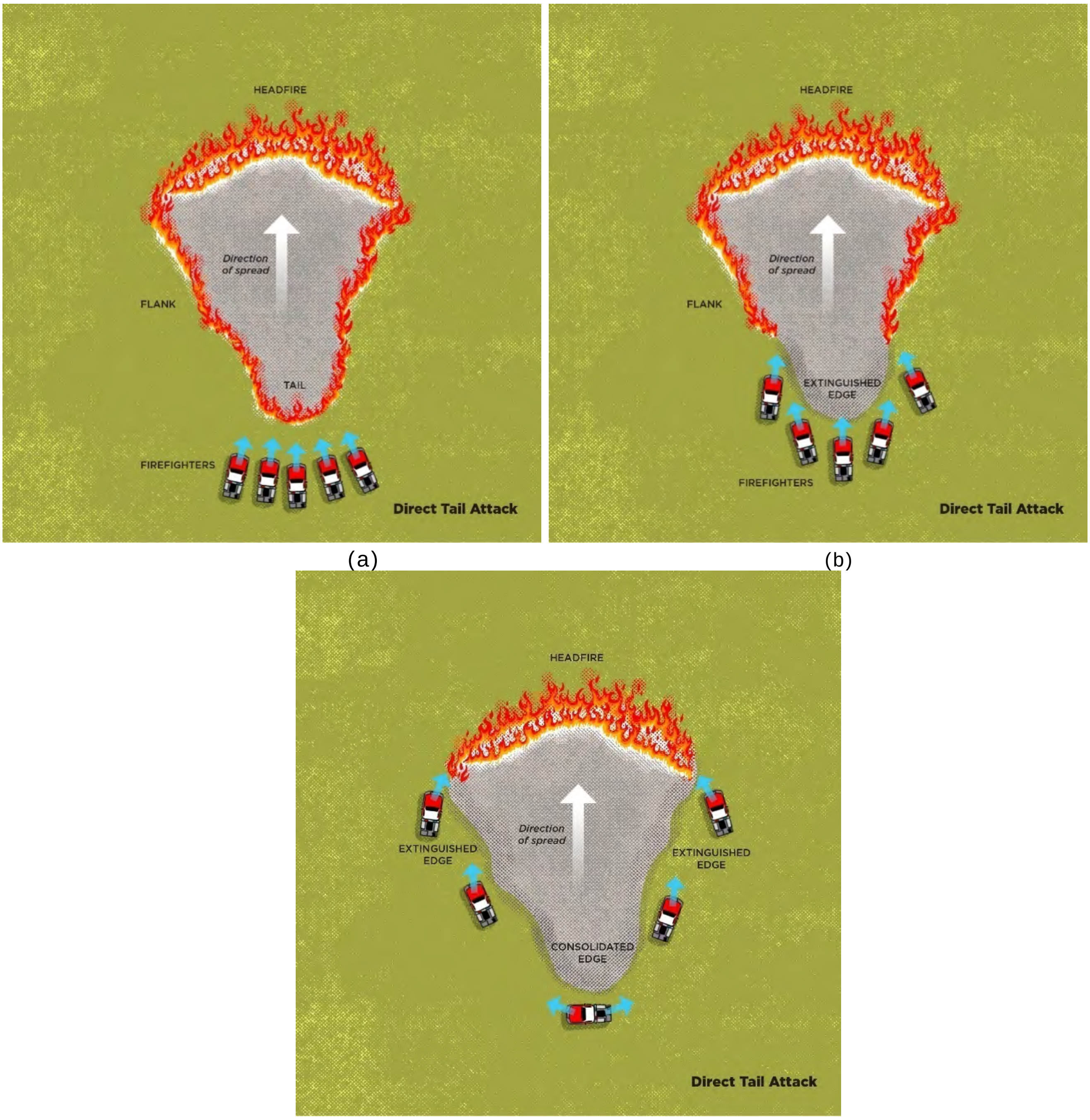
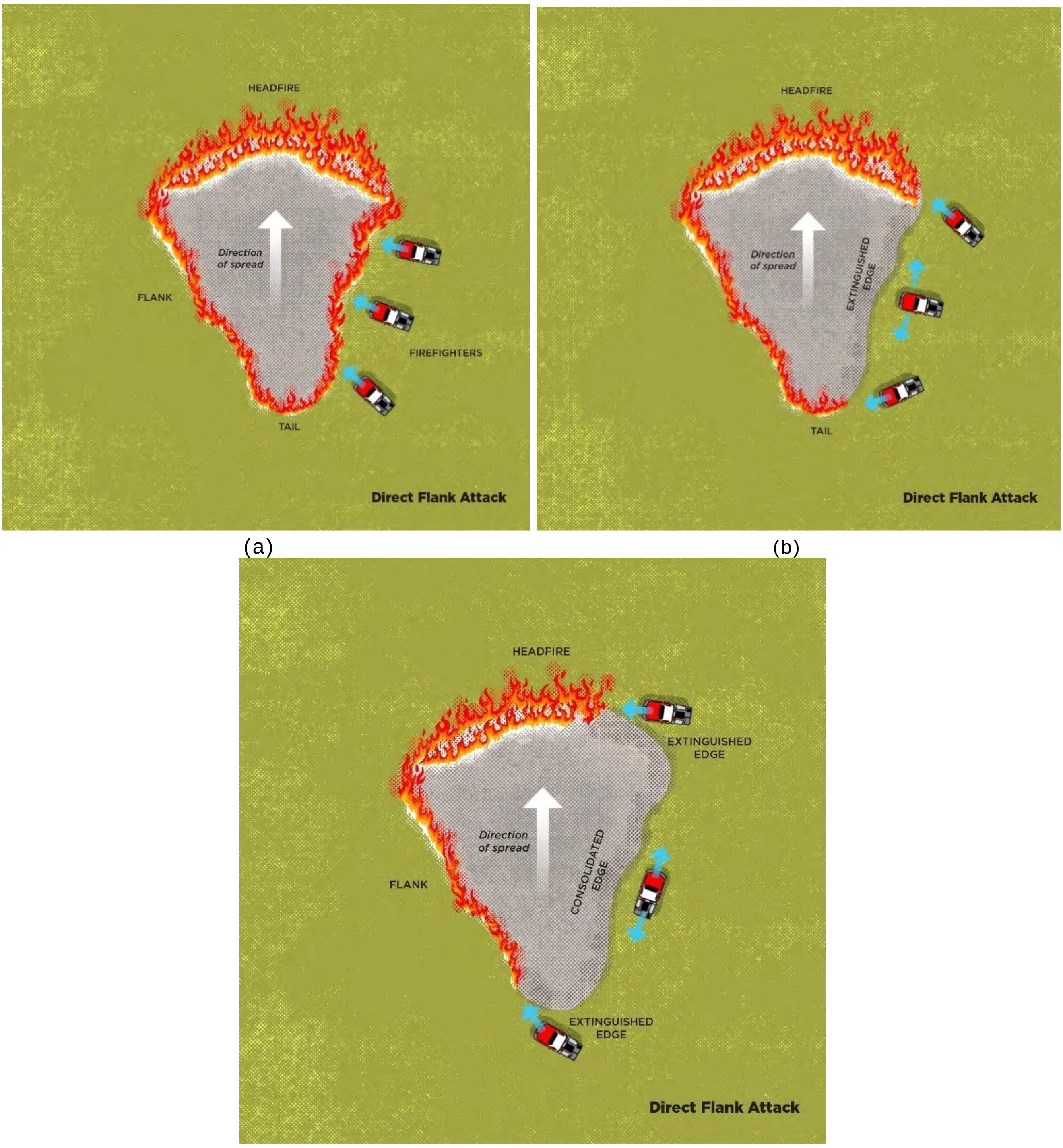


Figure 4.2: Direct tail attack - commencement (a), ongoing (b), near completion (c)



(a) (b) (c)

Figure 4.3: Direct flank attack - commencement (a), ongoing (b), near completion (c)

4.3.2 *Indirect Attack*

Parallel attacks involve construction of control lines by personnel using hand tools or machines as close as possible to the flanks of the bushfire (Figure 4.4). The intent of the parallel attack is to establish fuel-free containment boundaries that the fire cannot cross. Retardant drops by firefighting aircraft may be used to reduce wildfire behaviour approaching containment line to increase the potential for containment lines to hold. When considering the establishment of parallel control lines or breaks, both the production rates of firefighters with hand tools and machinery, as well as the required break width need to be considered as the production of control lines must exceed the bushfire's rate of spread in order for the fire to be contained. Whilst supporting literature regarding these factors is limited, fire line potential rates of construction are detailed in Tables 4.3-4.5, (McCarthy, Tolhurst and Wouters ,2003 cited in FESA, 2011). Required fire break widths in low intensity grassfire events where spotting is a possibility are detailed in Table 4.6 (Cheney and Sullivan, 1997 cited in FESA, 2011). In more extreme forest wildfires where flame lengths may reach 40-50m and spotting of several hundred meters is possible (Gould et al, 2007) control lines will likely be inneffective against an established headfire. Advantages and disadvantages of a parallel attack reported in DFES (2012) are summarised in Table 4.2.

Table 4.2: Advantages and disadvantages of a parallel attack

Advantages	Disadvantages
Control line may be shorter and straighter than in a direct attack.	There is an increased chance of fire escaping.
Crews may be less exposed to heat and smoke.	Total fire area will be greater.

Table 2.3: Rates of fireline construction using handtools (FESA, 2011)

Elevated Fuel	Construction rate (meters per person per hour)	Construction rate when 0.5m flames within 5m of crew
Low	24	16
High	19	13
Very high / extreme	14	10

Table 4.4: Rates of fireline construction by machines (FESA, 2011)

Machine	Flat production rate (m/hr)	15° slope production rate (m/hr)	Comments
D4 & Wheeled Loader	700	420	No debris
	630	380	Some debris – can handle
	470	200	Some debris – can manage
	300	60	Substantial – D6 required
		10° slope production rate (m/hr)	
D6-D9	900	730	Little debris
	700	550	Some debris – D4 can manage
	450	375	Significant debris – D6+ required
	350	270	Very significant debris – D6+ has difficulty

Table 4.5: Fireline construction rates (McCarthy, Tolhurst & Wouters, 2003)

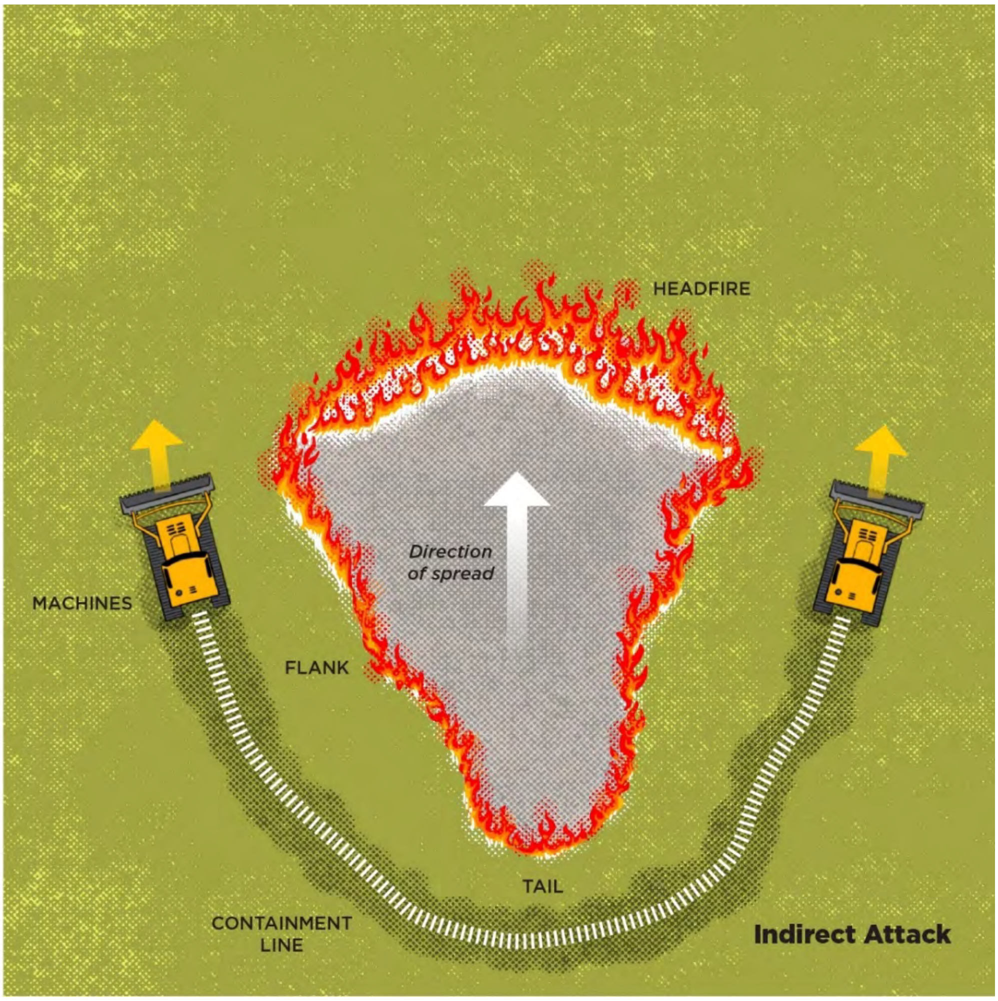
Method / Appliance	Mean production rate (meters per hour)	Note
Firefighters using hand tools	**13.7 per person**	**A total of 34 incidents were reviewed and average firefighter experience was high (reported as a mean of 0.8 out of 1). Minimum crew of 5, maximum of 60 firefighters.**
D4	505	A total of 34 D4 performances were reviewed.
D6	640	A total of 16 D6 performances were reviewed.
D7	570	A total of 9 D7 performances were reviewed.
D9	560	A total of 7 D9 performances were reviewed.

Notes regarding the study:

1. Maximum flame height for the 103 incidents reviewed for the study was 5m; and
2. The study does not specify the width of the fire line created.

Table 4.6: Required firebreak width for spotting vegetation (FESA, 2011)

Fire line intensity (kW/m)	Firebreak width	Anticipated success
1000	10	High
	7.5	Moderate



(a)

Figure 4.4: Parallel attack - commencement

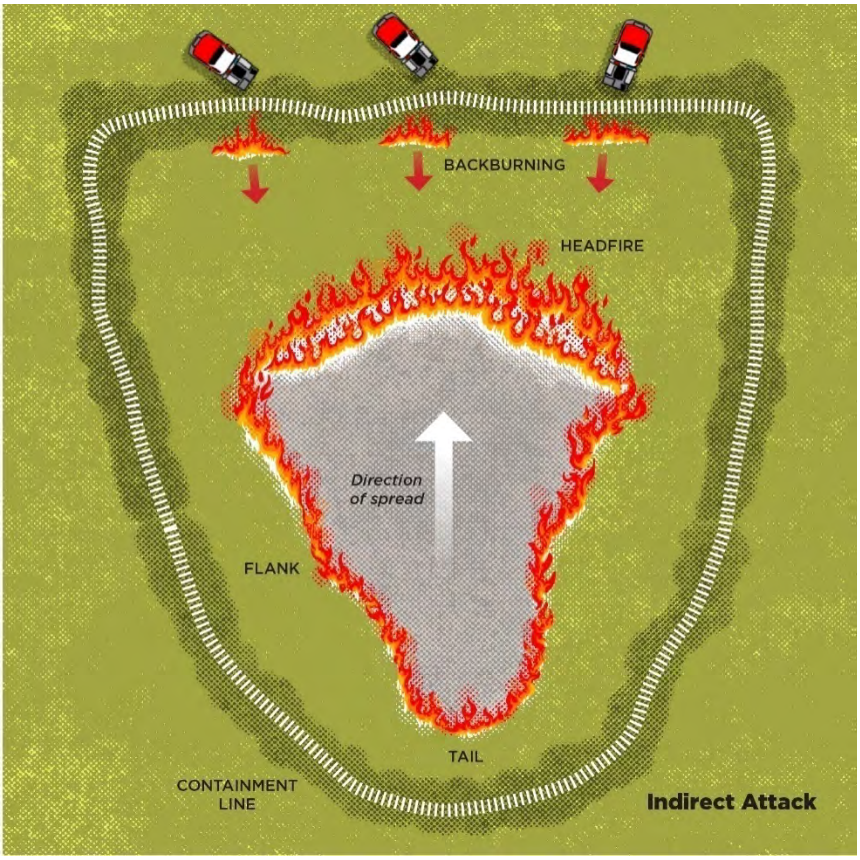
4.3.3 *Backburning*

Identified as one of the most difficult strategies to implement properly in the face of wildfire impact at the urban interface, backburning is the only potentially successful tactic available for combatting large, fast moving or intense and inaccessible fires (DFES, 2012). As illustrated in Figure 4.5, it involves the deliberate burning out of vegetation fuel between established control lines and the approaching fire front and must be undertaken with extreme care to avoid the creation of additional uncontrollable fire fronts. Advantages and disadvantages of backburning reported in DFES (2012) are shown in Table 4.7, however it is again noted no supporting research or justification was provided to substantiate the statements. Due to the nature of backburning, DFES (2014) identifies several conditions that prohibit backburns being utilised, listed as:

1. The fire is running under extreme conditions;
2. Long distance spotting is occurring;
3. The location of the fire edge is not known;
4. There are no adequate or existing control lines;
5. There are insufficient resources to construct and hold the backburn;
6. There is not enough time to allow penetration of the backburn to a safe depth; and
7. The forecast weather conditions will lead to extreme fire behaviour before the backburn can be secured.

Table 4.7: Advantages and disadvantages of backburning

Advantages	Disadvantages
May stop the progress of a rapidly moving bushfire.	Increased total fire area.
May be the most practicable method of bushfire suppression for difficult terrain.	If the backburn escapes control, the progress of the main fire is accelerated.
	It can endanger the lives of firefighters
	It may produce intense fire behaviour at the junction between the backburn and the main fire front.
	It requires considerable time to effectively establish.
	It requires substantial resources to light and patrol.



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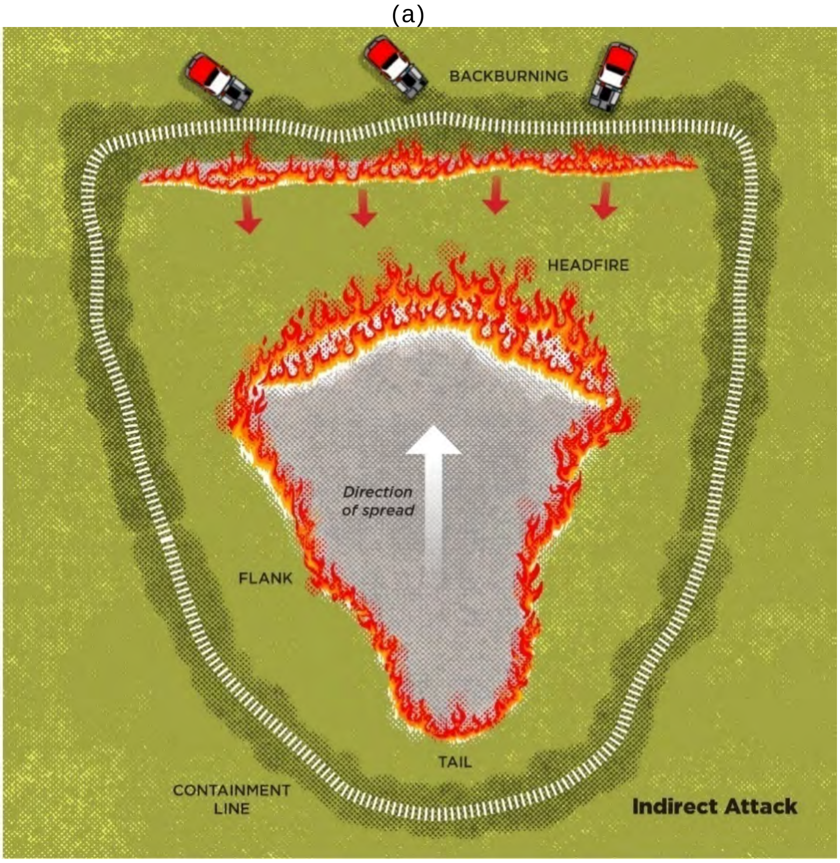


(b)

Figure 4.5: Backburning – point source ignition (a) and line ignition (b)

4.3.3.1 Utilising previous wildfire scars and Hazard Reduction Burns

Although the use of fire through hazard reduction burns (HRB's) and backburning are utilised internationally for conservation, to reduce uncontrolled wildfire behaviour and to enhance the potential for successful suppression (Boer et al., 2009; Grant & Wouters, 1993; Marsden-Smedley, 2011; Stratton, 2004; VBRC, 2010; Wimberly et al., 2009; Ingalsbee, 2015), the effectiveness of these strategies in specifically reducing wildfire impact on communities remains uncertain (Fernandes & Herminio, 2003; Florec, 2016; McCarthy & Tolhurst, 2001; Oliveras & Bell, 2008; Penman et al., 2011). Even studies which report potential economic benefits of prescribed burn programs from a suppression perspective (Kuzenko, 2000; Florec, 2016; Silva & Gozalez-Caban, 2010), do not provide comparison of the total economic or life loss from wildfires where HRB's were, or were not present. Whilst HRB's remain an essential part of Australian wildfire related risk mitigation (AFAC, 2016; McCarthy & Tolhurst, 2001), and backburning remains an important aspect of wildfire suppression (DFES, 2014; Ingalsbee, 2015; Penney et al., 2019a) the effectiveness of these programs in relation to the specific objective of protecting people and buildings from the effects of wildfire is unknown.

Illustrated in equation 4.1, the concept of effectiveness is described as a product of efficacy and reliability (Thomas, 2002) and facilitates a numerical measure of effectiveness allowing firefighting measures to be quantitatively compared. Efficiency of HRB's (Eff_{HRB}) can then be calculated to provide a numerical measure against which to evaluate HRB's against the set objectives.

$$Eff_{HRB} = efficacy \times reliability \qquad (4.1)$$

As Thomas (2002) explains efficacy is the degree to which a system/process achieves an objective given it operates / is executed. The efficacy the process will be different depending on the objective. For example, if HRB's are intended to eliminate house damage at the rural urban interface (RUI) from wildfire impacts its efficacy is:

- One (1) if there were no houses damaged whenever prescribed burns were present and a wildfire occurred that would have otherwise impacted the houses;
- Between zero (0) and one (1) if the rate of houses damaged whenever prescribed burns were present and a wildfire occurred that would have otherwise impacted the houses was reduced compared to otherwise identical situations where prescribed burns were not present;
- Zero (0) if the rate of damaged houses remained the same whether prescribed burns were present or not; and
- Negative if the rate of damaged houses increased when prescribed burns were present and a wildfire occurred that would have otherwise impacted the houses.

HRB's work to reduce the severity of wildfire behaviour by reducing the understory (and potentially bark) fuels available for consumption during a subsequent wildfire event. Depending on the rate of vegetation regrowth, HRB's may reduce subsequent wildfire behaviour in the same area for up to ten years post burn completion (McCarthy & Tolhurst, 2001; Penman et al., 2011; VBRC, 2010). However, a HRB may potentially stop a wildfire head fire for only the first two years (VBRC, 2010) and even then only under certain conditions. Firstly, the HRB must be suitably placed in order for the uncontrolled wildfire to impact it (in other words they are reliable). Secondly, as reported by McCarthy and Tolhurst (2001), as fire weather conditions worsen the probability of a HRB having any impact on an established wildfire significantly decreases. As illustrated in Figure 4.6 (McCarthy & Tolhurst, 2001, Figure 6), even with a moderate overall fuel hazard score, once the Fire Danger Index reaches 50 the efficacy of the HRB slowing the wildfire head fire drops to below 0.6. At increased overall hazard scores and higher Fire Danger Indices, the efficacy of a previous HRB slowing the wildfire head fire rapidly drops below 0.2. During a study of a different area by the same authors involving 2425 wildfires on public land, the overall efficacy of HRB's assisting suppression efforts was reported to be even lower at 0.11. In some instances HRB's have even been reported to have negative efficacy (McCormick, 2002) where 30% of forest HRB's studied in the Blue Mountains in NSW had a negative effect. This negative effect was reported to occur due to the curing of scrub fuels greater than 0.5m above the ground, even if understorey fuels below that height were consumed.

The efficacy of a HRB in reducing spotting and new fire behaviour is dependent on its ability to remove bark, particularly of stringy bark fuels which contribute significantly to spotting behaviour and the ignition of new fires (Grant & Wouters, 1993). Where spotting occurs there is the potential for those spot fires to grow into uncontrolled wildfires having attaining a quasi-steady rate of spread in their own right. Depending largely on vertical fuel understory fuel structure and wind penetration (McRae, 1999), in forest fuels this may take in excess of 30 minutes (Finney & McAllister, 2011; Kucuk, Bilgili & Baysal, 2007; McAlpine, 1988; Penney & Stevenson, 2019) and may not occur until a head fire width of approximately 150m is reached (Cheney & Gould, 1997). The potential result of this may be that whilst the size of the final wildfire that impacts urban areas may be less than that of the original wildfire, this does not necessarily mean the wildfire impacts on life or property may actually be reduced. Recent work into the effect of fuel bed geometry on wildfire growth (Penney & Stevenson, 2019), firefighter tenability during wildfire suppression (Penney at al, 2019a) and critical flow rates for wildfire extinguishment (Penney et al., 2019b) suggests that there will be little if any difference in the ability for firefighters to suppress the 'new' headfire/s without substantial aerial suppression once they attain a quasi-state of spread and an active head fire depth of more than 2m. In such instances the efficacy of the HRB's would be close to zero if the objective was defined as reducing wildfire behaviour that would facilitate active suppression of the head fire by firefighter direct attack using machinery.

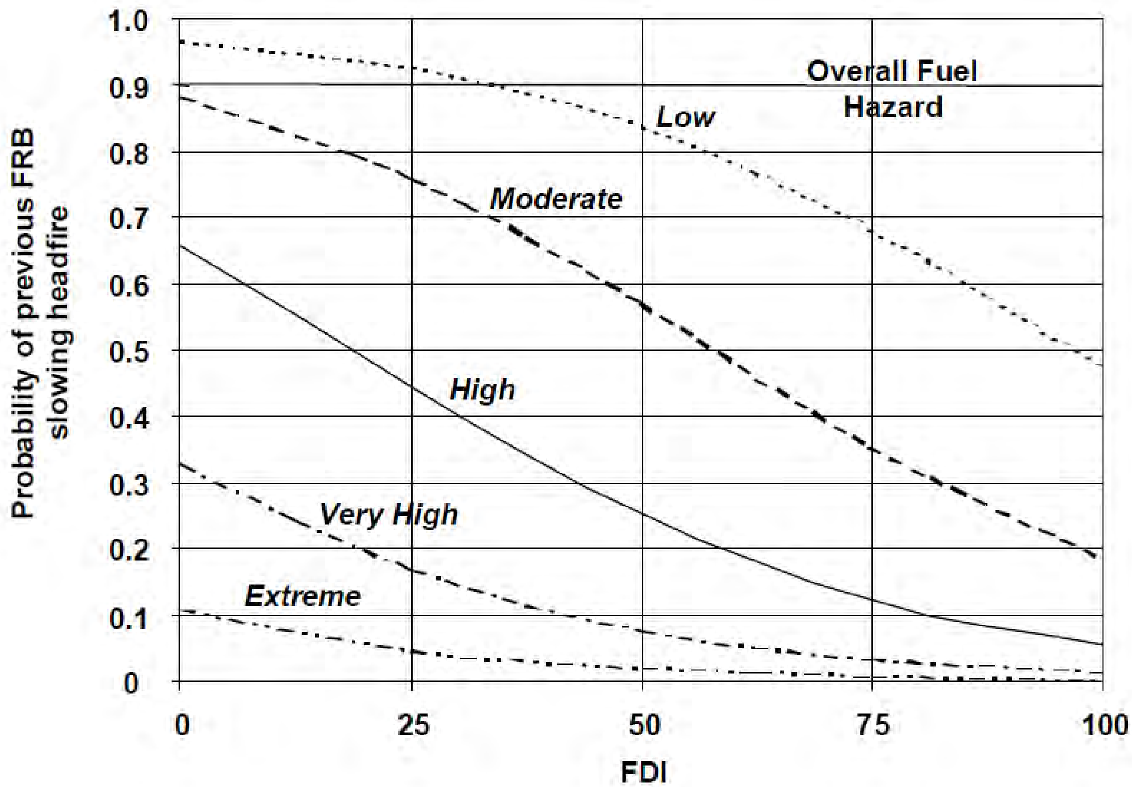


Figure 4.6. Probability of previous prescribed burn slowing the headfire of a subsequent wildfire as a function of Overall Fuel Hazard and Fire Danger Index. (Probability of "1.0" means "certain", probability of "0" means "not possible".) Reproduced with permission of the Department of Environment, Land, Water and Planning Victoria

In this same context, reliability is the probability that prescribed burns are in the correct place when required, in other words they are intentionally positioned so that they will be impacted by wildfire. For example, if the area affected by prescribed burns are always impacted by wildfires the reliability is one (1). If the area affected by prescribed burns are impacted by wildfires only half the time then the reliability is 0.5. In a study of 114 wildfires between 1990 to 1998, McCarthy and Tolhurst (2001) reported only 69 of all wildfires analysed encountered a HRB, equivalent to a reliability of 0.61. This figure increased 0.92 to when only fires within “Zone 1” were assessed. Zone 1 was identified as the most proximal to development where the objective was to protect human life, property and assets and therefore subject to significantly reduced overall fuel hazard scores compared to outer lying zones. The same authors reported this figure dropped to less than 0.25 in Zone 1 areas during a study of a different area involving 2425 wildfires on public land. This variance is not unexpected, with as the reliability of HRB’s is highly dependent on the area being examined.

4.3.4 *Wildfire behaviour suppression thresholds*

Fire services throughout Australia, America, Canada, Europe and New Zealand consider predicted and reported wildfire behaviour including head fire *RoS*, fire line intensity (*I*) and flame length (L_F) when determining the suitability of suppression strategies and tactics. Penney et al. (2019a) reported that out of the literature reviewed from the various jurisdictions, only Western Australia utilised RoS as a marker for wildfire suppression strategies in forest or woodland fuel structures. The reported thresholds were readily suppressed (<0.06kph); hand tool attack possible (<0.14kph); direct machine attack possible (<0.4kph); direct attack not possible / unlikely to succeed (>0.4kph); and indirect attack likely to fail (>0.8kph).

Even within fire services some variance exists between strategy thresholds as detailed in Tables 4.8 (DFES, 2014) and 4.9 (Smith, 2013) which show values for forest fuels. DFES (2014, p79) also identifies that for tall eucalypt forest, “aerial suppression is of limited effect with fire intensities over 2000kW/m”. International literature revealed marked variance between jurisdictional thresholds. Thresholds for the United States of America are identified in Tables 4.10 and 4.11 (Deeming et al., 1978 cited in Hirsch and Martell, 1996; Andrews and Rothemel, 1982 and Rothemel, 1983, also cited in Hirsch & Martell, 1996). Canadian thresholds, Alexander and DeGroot (1988) cited in Hirsch and Martell (1996) are shown illustrated in Table 4.12. European thresholds (EuroFire, 2012) are identified in Table 4.13 whilst thresholds adopted by New Zealand (Alexander, 2000) are detailed in Table 4.14.

Table 4.8: Fire behaviour and firefighting strategies in Western Australia

Fire Danger	Flame Height (m)	Intensity (kW/m)	Significance
Low	0-0.5	0-50	Fires generally self-extinguish
Moderate	0.5-1.5	50-500	Hand tool line should hold the fire. Direct attack possible.
High	1.5-3.0	500-2000	Fire too intense for direct attack. Parallel attack recommended.
Very high	3.0-10.0	2000-4000	Crown fire at upper intensities. Indirect attack recommended.
Extreme	>10	>4000	Crowning, spotting and major runs likely. Control efforts probably ineffective. Defensive strategy recommended.

Table 4.9: Head fire behaviour and firefighting strategies in Western Australia

Rate of Spread (m/hr)	Intensity (kW/m)	Significance
<60	<800	Readily suppressed.
<140	<800	Hand tool attack possible.
<400	<2000	Direct machine attack possible.
>400	>2000	Direct attack not possible / unlikely to succeed.
>800	>4000 or >5000*	Indirect attack likely to fail.

*both values are cited in the same table and category

Table 4.10: Head fire behaviour and strategies - USA (Deeming et al. 1978)

Flame Length (m)	Intensity (kW/m)	Significance
0.9	<173	Behaviour associated with most prescribed burns.
1.2	346	Limit of control for manual attack methods.
2.4	1730	The prospects for control by any means are poor above this limit.
2.8	2422	The "heat load" on people within 30 feet of the fire is dangerous
3.3	3460	Spotting, fire whirls and crowning should be expected.

Table 4.11: Head fire behaviour and strategies - USA (Andrews & Rothemal, 1982; Rothemel, 1983)

Flame Length (m)	Intensity (kW/m)	Significance
<1.2	<346	Manual attack on the head fire possible.
1.2-1.4	346-1730	Machine attack on the head fire possible.
2.4-3.4	1730-3460	Control efforts at the head fire will probably be ineffective.
>3.4	>3460	Crowing, spotting and major fire runs are probable. Control efforts at the head fire are ineffective.

Table 4.12: Head fire behaviour and strategies - Canada

Flame Length (m)	Intensity (kW/m)	Significance
<0.2	<10	Readily suppressed.
0.2-1.4	10-500	Direct manual attack possible.
1.4-2.6	500-2000	Direct machine attack possible.
2.6-3.5	2000-4000	Control efforts at head fire may fail.
>3.5	>4000	Intermittent crown fire to active crown fire development (at >10000kW/m). Suppression efforts must be restricted to fire flanks. Violent fire behaviour at intensities >30000kW and suppression activities should not be attempted until burning conditions ameliorate.

Table 4.13: Head fire behaviour and strategies - Europe

Flame Length (m)	Significance
<0.5	Fires generally self extinguish.
0.5-1.5	Direct hand tool attack possible.
1.5-2.5	Direct machine attack possible. Flank / parallel attack recommended.
2.5-3.5	Too intense for direct attack.
3.5-8	Indirect attack possible.
>8	Extreme fire behaviour. Defensive strategies recommended.

Table 4.14: Head fire behaviour and strategies - New Zealand

Intensity (kW/m)	Significance
<500	Direct hand tool attack possible.
500-2000	Direct machine attack possible.
2000-4000	Helitanks and airtankers using chemical fire retardants.
>4000	Very difficult if not impossible to control.

4.3.4.1 Rate of spread thresholds

Applying the Noble et al (1980) forest model, as illustrated in Figure 4.7, Penney et al (2019a) reported the operational *RoS* thresholds identified by Smith (2011) are exceeded in all but the sparsest of understorey (w) fuel loads and mildest fire weather conditions associated with an FDI less than 20. Hand tool attack is not considered possible once available understory fuel loads exceed 5 t/ha, regardless of FDI, whilst the direct machine attack threshold is also rapidly exceeded once the FDI exceeds 20 for understory fuel loads exceeding 15 t/ha. Indirect attack thresholds are exceeded once an FDI of 45 is reached in understory fuel loads of 15 t/ha. At an understory of 25 t/ha, identified as the standard fuel load in AS3959 (2019), direct machine attack is only suitable at FDIs ≤10 and the indirect attack threshold is exceeded once the FDI exceeds approximately 23.

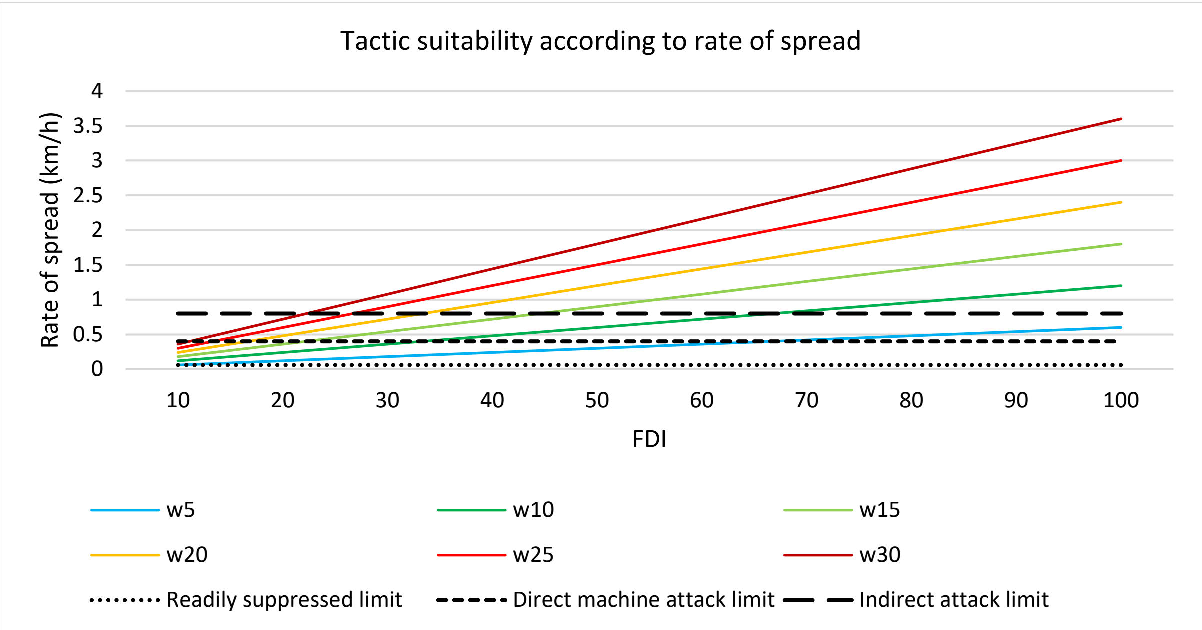


Figure 4.7. Tactic suitability according to RoS

4.3.4.2 *Fire line intensity thresholds*

When considering fire line intensity (*I*) thresholds, Penney et al. (2019a) found that whilst there is general agreement across international jurisdictions regarding direct attack tactical thresholds in forest or woodland fuel structures, discrepancy occurs between direct machine attack thresholds as well as when the head fire is considered uncontrollable. Western Australian, New Zealand and Canadian thresholds are the most aggressive, identifying direct machine attack on the headfire suitable to 2000 kWm^{-1} and indirect attack suitable to 3000-4000 kWm^{-1} compared to the United States which considers the headfire control limit to be 1730 kWm^{-1}, dangerous conditions present within 30 feet (9.14m) of the head fire at 2422 kWm^{-1} and the head fire to be undefendable at 3460 kWm^{-1}. Only Canada identified a limit for suppression efforts to cease, being 10,000 kWm^{-1} almost three times higher than the undefendable threshold set by the United States.

Illustrated in Figure 4.8, Penney et al. (2019a) reported that once understory fuel loads exceed 20 t/ha headfire behaviour is recognised as undefendable across all jurisdictions regardless of the FDI. Utilising American thresholds, *I* is recognised as resulting in dangerous conditions within 30 ft of the head fire at all FDIs once a surface fuel load of 15 t/ha is exceeded. The lower Canadian intensity threshold of 10,000 kWm^{-1} to cease all wildfire suppression activities can be exceeded under the right fire weather conditions once surface fuel loads reach 10 t/ha, and can be breached at an FDI as low as 30 when surface fuels exceed 20 t/ha. The higher Canadian *I* threshold of 30,000 kWm^{-1} is breached once surface fuels exceed 20 t/ha and the FDI exceeds 80.

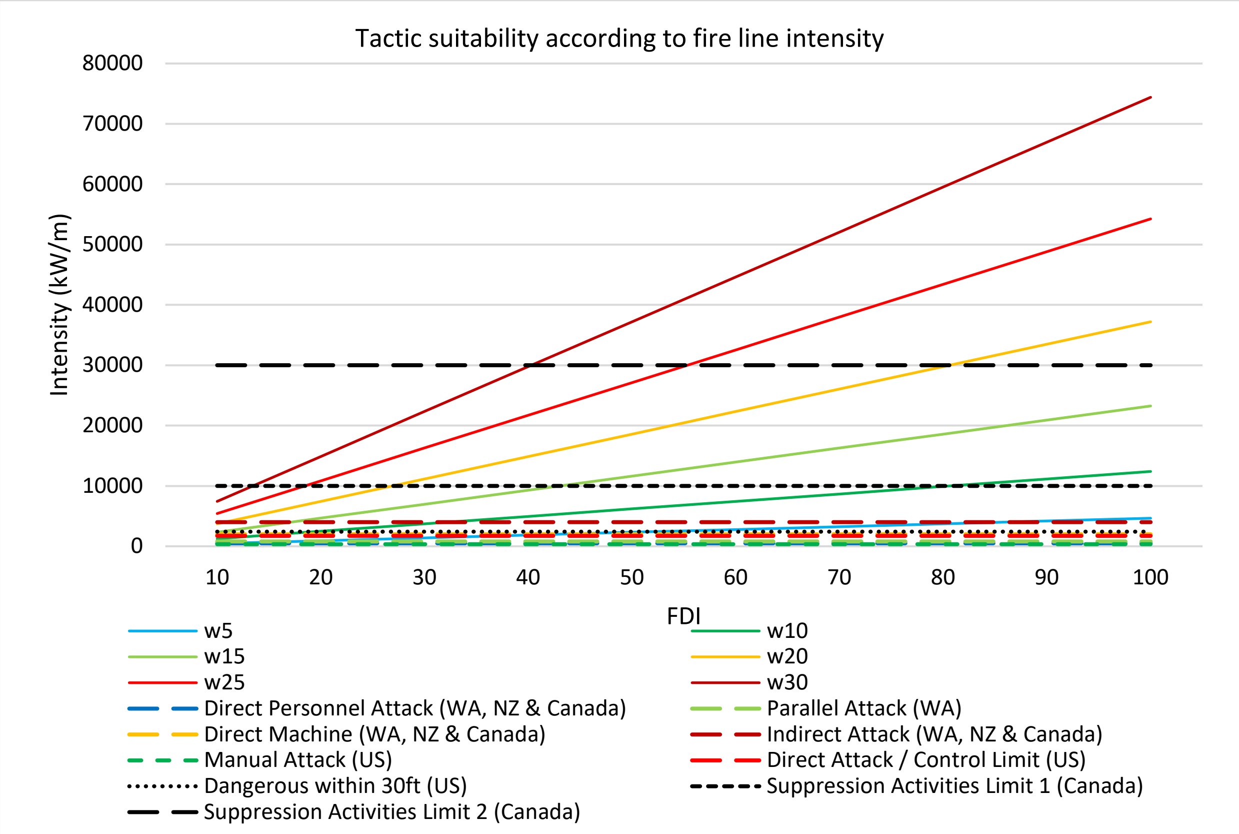


Figure 4.8. Tactic suitability according to fire line intensity

4.3.4.3 *Flame length thresholds*

Penney et al. (2019) reported Western Australia adopted the most aggressive L_F tactical thresholds in forest or woodland fuel structures. Whilst there is again general agreement at lower flame length, there is increased variance as L_F increases. Western Australia's Parallel Attack L_F threshold of 3 m is greater than both the 2.5m European limit for Parallel Attack and the 2.8m L_F the United States recognises as creating dangerous conditions within 30ft of the head fire, whilst the Western Australian indirect attack limit of 10 m is almost three times greater than the head fire undefendable threshold of 3.4m set by the United States.

As detailed in Figure 4.9 (Penney et al, 2019a), when L_F thresholds are used, offensive suppression strategies are considered unsuitable or dangerous for all landscape scale wildfires burning in understory fuel loads exceeding 15t/ha regardless of fire weather conditions. Further, fire behaviour is recognised as dangerous within 30ft of the head fire in all understory fuel loads once an FDI of 30 is attained. There is strong agreement between direct personnel attack thresholds between jurisdictions with direct personnel attack / manual attack on the head fire identified as inappropriate due to L_F across all scenarios regardless of understory fuel loads and at all FDIs. Only two jurisdictions suggest a direct machine attack on the head fire is suitable, and only in the mildest head fire behaviour arising from understory fuel loads of 5 t/ha and at an FDI of 5 (USA) and 10 (Canada).

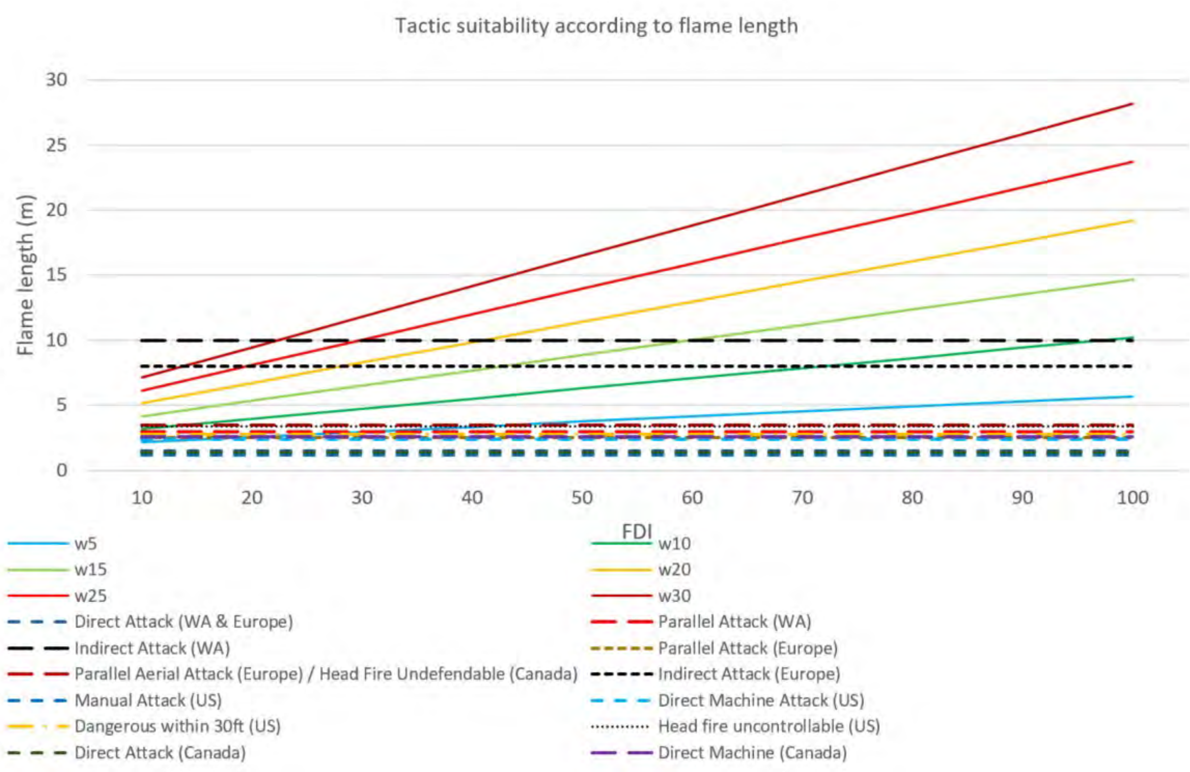


Figure 4.9. Tactic suitability according to flame length

4.3.4.4 *Dry Eucalypt Forest Fire Model (DEFFM)*

Penney et al (2019a) reported little agreement between the results of the Dry Eucalypt Forest Fire Model (DEFFM) and Noble model analysis. In comparison to Noble, DEFFM analysis under predicted *RoS*, *I* and L_F across all geographic regions once fuels reached three to four years in age and a FDI of 30 to 40 was attained. Applying DEFFM alone, direct machine attack RoS thresholds were reached across all geographical jurisdictions when fuels reached four to five years of age, direct machine attack *I* thresholds were reached at five to nine years of age whilst direct machine attack L_F thresholds were reached across all geographical jurisdictions at fuel ages between three to nine years.

Comparative Nobel and DEFFM modelling across all fire weather conditions and utilising typical forest fuel loads in Western Australia (a sample of these results is illustrated for RoS in Jarrah Mosaic -Figure 4.10; *I* in Jarrah South - Figure 4.11; and L_F in Jarrah East - Figure 4.12) revealed DEFFM analysis typically over estimated wildfire behaviour below an FDI of 30 to 50, above this range DEFFM analysis typically significantly underestimated wildfire behaviour across all fuel ages and jurisdictions. . Fire line intensity suppression thresholds were typically exceeded across all jurisdictions once fuel ages reached 3 to 4 years and an FDI of 30 was reached, with the United States 'dangerous within 30ft' threshold rapidly exceeded under the same conditions. *LF* suppression thresholds were typically exceeded with most jurisdictions considering the head fire to be undefendable due to fire behaviour once fuels reached 3 to 5 years of age and an FDI of 30 attained. Only Western Australia and Europe considered head fires to be defendable above these limits, albeit using indirect suppression tactics.

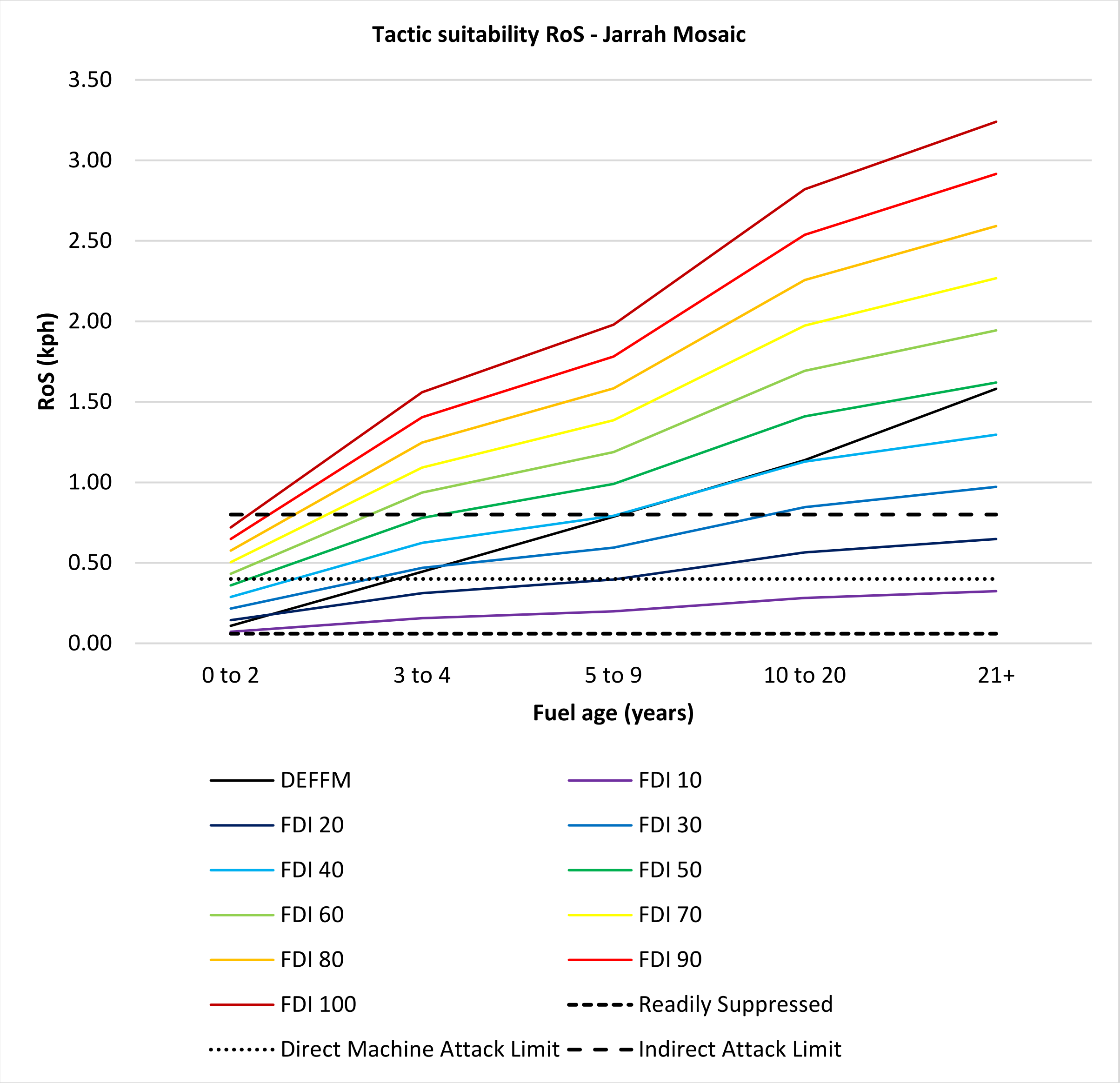


Figure 4.10. Tactic suitability – the relationship between rate of spread, fuel age and various suppression tactic thresholds for fire in jarrah forest fuels (Jarrah Mosaic)

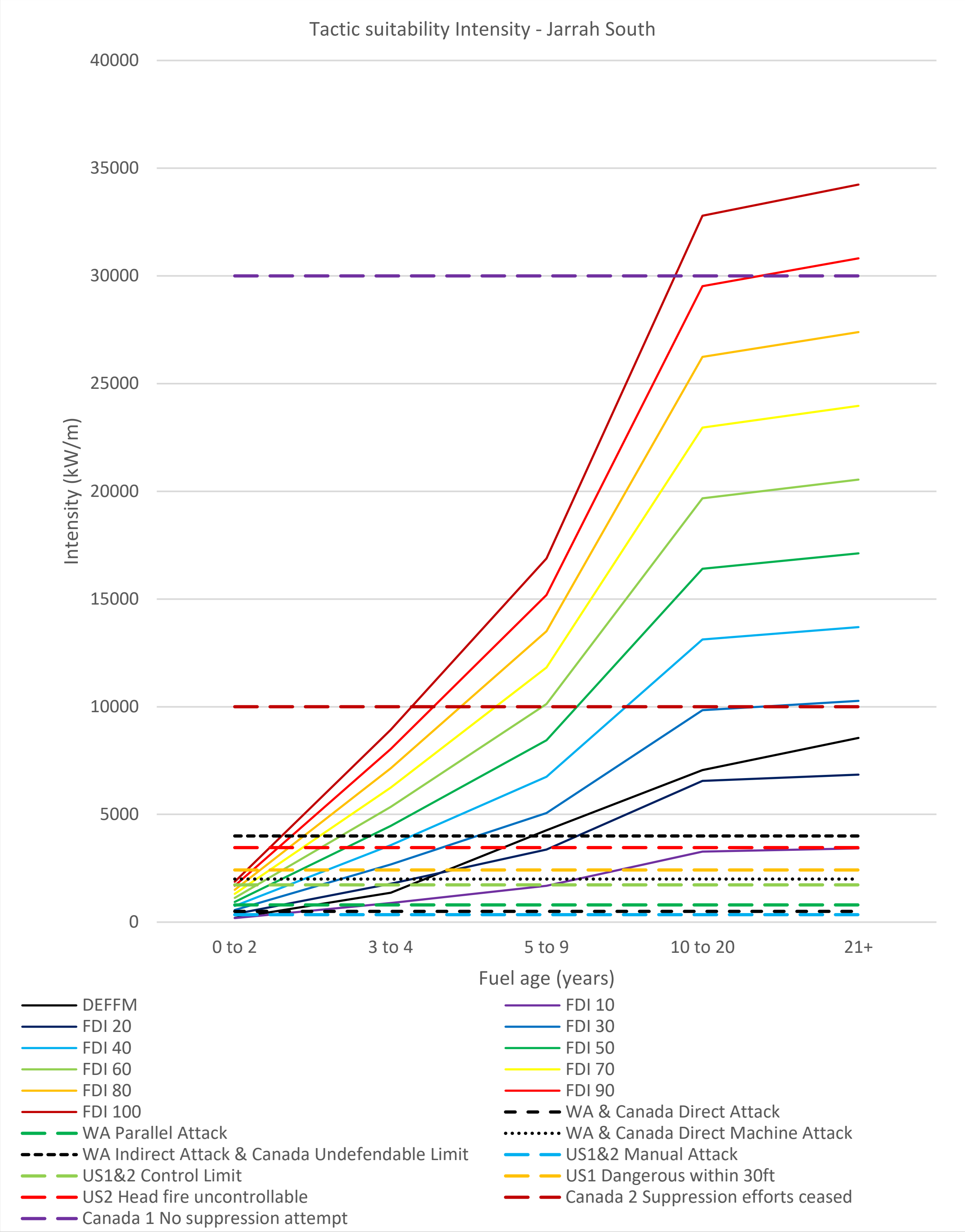


Figure 4.11. Tactic suitability – the relationship between fire line intensity, fuel age and various suppression tactic thresholds for fire in jarrah forest fuels (Jarrah South)

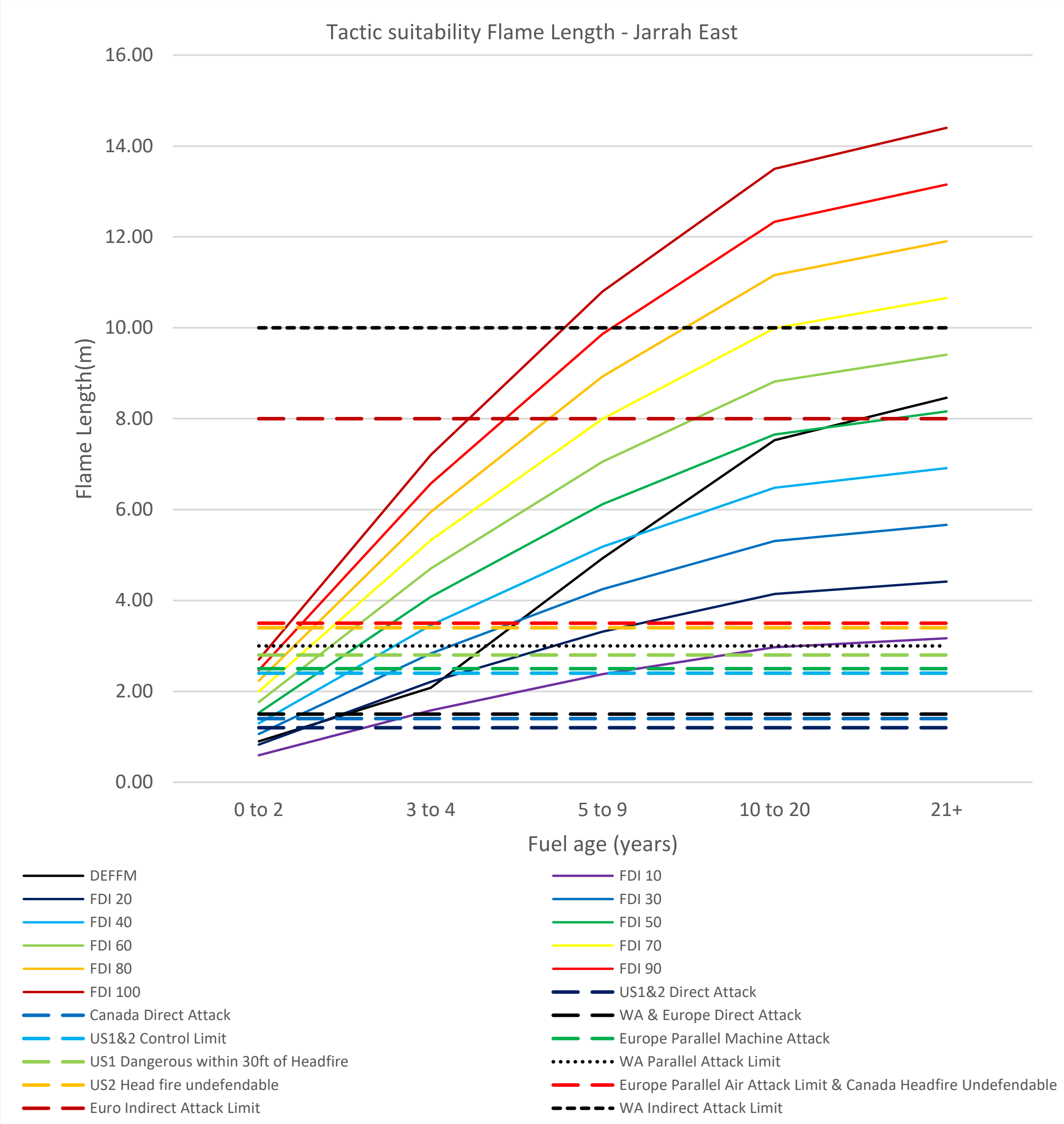


Figure 4.12. Tactic suitability – the relationship between flame length, fuel age and various suppression tactic thresholds for fire in jarrah forest fuels (Jarrah East)

4.3.5 *Holistic guidance for suitability of wildfire suppression*

Comparing the calculated fire behaviour outputs (RoS, I_{FL} and L_F) with the associated base inputs of FDI, w and fuel age and comparing the results to international wildfire suppression thresholds a single strategic guidance table can be produced (Penney et al., 2019). As shown in Table 4.15, the result is that safe offensive strategies on the head fire are identified as appropriate in only the mildest of conditions or where fuel structure does not facilitate significant head fire propagation (Penney & Stevenson, 2019). It is important to note this guidance is intended for established siege wildfires of significant proportion such as those reviewed by Keelty (2011, 2012), Ferguson (2016) and the Victorian Bushfires Royal Commission (2010). As discussed in Chapters 2 and 3, smaller wildfires such as those experienced within closed urban environments do not achieve the same Heat Release Rates or produce the same behaviour outputs as established wildfires which may subsequently allow more aggressive offensive suppression strategies and tactics. In these instances, as opposed to utilising Table

4.15, it is necessary to apply the Vegetation Availability Factor as appropriate when predicting potential wildfire behaviour and manually determining whether suppression and tenability thresholds are exceeded.

Table 4.15: Wildfire head fire suppression guide

Siege Wildfire Head Fire Suppression						
FDI/w (t/ha)	5	10	15	20	25	30
10	DM Fuel Age < 5yrs	IA Fuel Age < 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
20	IA Fuel Age < 10yrs	IA Fuel Age < 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
30	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
40	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
50	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
60	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
70	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
80	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
90	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs
100	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs	DEF Fuel Age ≥ 10yrs

Legend

DM – Direct machine attack

IA – Indirect attack

DEF – Defensive strategy adopted for head fire. Consider flank and tail attacks where suitable.

Note: For DEFFM Modelling refer to fuel age. For McArthur use FDI/w

4.4 Defensive tactics

Defensive tactics are utilised when fire behaviour is too intense to be safely or effectively attacked. As opposed to offensive tactics, defensive tactics do not attempt to suppress the bushfire itself, but rather limit the consequences of its impacts through evacuation, community information and the protection in place of vulnerable communities and critical infrastructure.

4.4.1 *Rural Urban Interface Defense*

The protect-in-place / shelter-in-place defensive Rural Urban Interface (RUI) firefighting tactic is typically utilised where communities and infrastructure are located within or immediately adjacent to vegetation that will support landscape scale bushfire behaviour, (DFES, 2013). It can be a high risk approach as not all homes are defensible (Cova, 2005) or constructed to withstand wildfire impacts. Illustrated in Figure 4.13, RUI defense essentially requires firefighting crews to position themselves between an identified asset and the approaching bushfire front (DFES, 2013). As detailed in Penney, et al. (2019a) however, it should be noted that this type of suppression tactic may expose firefighters to untenable conditions well in advance of the wildfire front itself and may be ineffective due to insufficient water flow rates. These factors are explored further in Chapters 5 and 6. As an alternative RUI defense to this high risk tactic, particularly where buildings are constructed in accordance with AS3959 (SAI Global, 2018), protection of houses and the sheltering population may be achieved by firefighters sheltering inside the buildings until after the passage of the head fire and they can safely extingish spot fires and reminant flames. Where evacuations of large vulnerable communities are not possible, as may be the case for hospitals, schools, aged care facilities and trapped communities etc, the shelter-in-place defense remains a necessary approach. In such instances sheltering in the safest possibly buildings distal from the fire front should be considered. Preemptive retardent line building from fixed wing and rotary firefighting aircraft, coupled with enhanced direct aerial suppression of the section of the head fire impacting the protected structures should also be undertaken wherever possible.

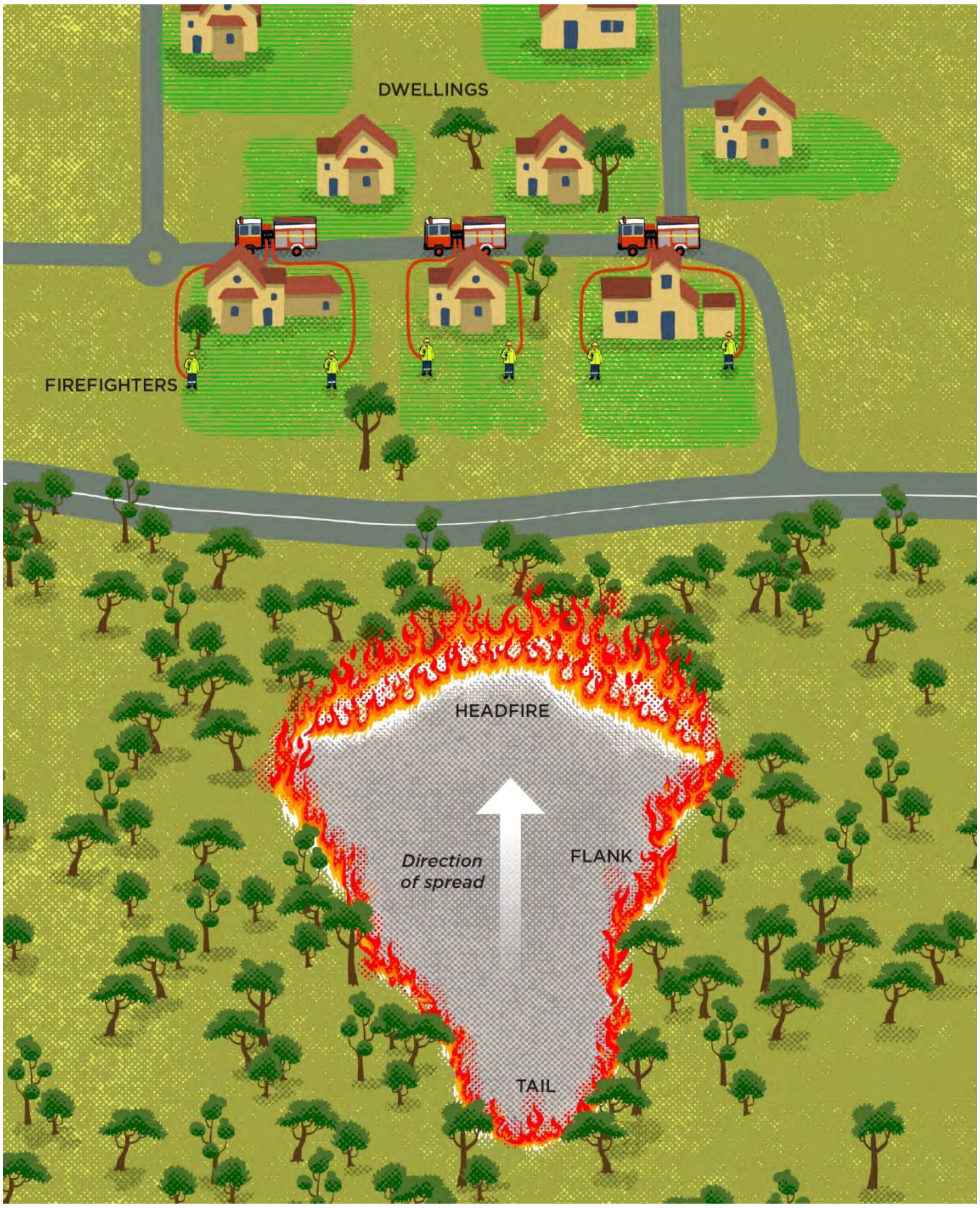


Figure 4.13: RUI defense

4.4.2 *Rural Urban Interface Model (RUIM)*

Published in Penney et al. (2020a), the Rural Urban Interface Model (RUIM) can be used when considering whether there is sufficient time to set up RUI defense prior to the impact of the head fire. Based on Australian and international RUI wildfire fighting strategies and tactics, the RUIM represents the expansion of the Fire Brigade Intervention Model (AFAC, 2004) to the specific context of firefighting defense at the RUI. When completed, the RUIM assists the Incident Management Team determine whether there is sufficient time for taskforce's assigned to protect life, property and critical infrastructure at the RUI, subsequently known as RUI taskforce's, to safely mobilise, prepare for, and find shelter prior to the arrival of the wildfire and the untenable conditions which can occur well in advance of the headfire front. deterministic analysis of Available Safe RUI Preparation Time (ASRPT) versus Required Safe RUI Preparation Time (RSRPT) can be applied:

$$ASRPT > RSRPT \tag{4.2}$$

ASRPT is calculated by:

$$\frac{Distance\ between\ headfire\ and\ RUI}{Headfire\ rate\ of\ spread} \tag{4.3}$$

Where the distance between the headfire and RUI is the lineal separation between the headfire and the structures under threat; and the headfire rate of spread is calculated using appropriate equations for the vegetation type and fuel structure involved, such as those described in (Gould et al, 2007, SAI Global 2018, Cruz et al., 2015).

Illustrated in figure 2, RSRPT is calculated by:

$$RSRPT = (T_R + T_T + T_{HL} + T_S) \tag{4.4}$$

Where T_R is the time taken for the RUI taskforce to respond; T_T is travel time (to a base, staging area and/or the RUI itself); T_{HL} is time to complete and assessment of the immediate area and set up hose lines; T_S is the time taken for crews to seek shelter within a structure prior to the arrival of untenable conditions associated with the wildfire front. Safety factors (F_S) are included at each stage of the process. Each of these components are discussed separately in this manuscript.

The main differences between the RUIM and FBIM are:

1. FBIM requires the firefighting strategy and associated tactics to be determined. In RUI firefighting, the strategies are limited to either 'backstop defense' or sheltering within the structures. The RUIM reflects this accordingly;
2. Wildfire suppression during large campaign wildfires such as those in California (CAFS, 2018; USFD & CDFFP, 2003), Greece (CBS, 2018) or Victoria (BCRC, 2009) required the mobilization of military, interstate and even international firefighting assistance. Suppression efforts are protracted, lasting weeks and firefighting crews will be drawn from many regions and are likely to be unfamiliar with the operational area, particularly during the escalation phases of the incident. This results in greater uncertainty compared to metropolitan structural fire response, therefore some of the decision points and pathways of the FBIM are not appropriate to the wildfire context;
3. RUI firefighting does not involve crews committing to internal structural firefighting as structures actively on fire are identified as undefendable (DFES, 2013 & 2014). Therefore external suppression of structures only is considered in the RUIM; and
4. The RUIM also allows for Available Safe Time to Critical Points or ASTCP to be calculated, enabling critical components of the response including wildfire impacts on access routes, evacuations and other aspects to be deterministically assessed. This further enhances firefighter safety when responding to areas involving active wildfire.

Similarities between the RUIM and FBIM are:

1. Both models rely on the systematic completion to determine the total time to complete the required activities;
2. Both models require the identification of the critical path, being the sequence of activities determining the minimum time required for the firefighting intervention;
3. Whilst neither model provides a definitive answer for the duration of mobilization and suppression efforts, both the RUIM and FBIM provide useful guidance for Incident Controllers when making operational decisions; and
4. Both models can be improved with enhanced data.

One limitation of the RUIM is the presence of spot fires that grow into new head fires well in advance of the original fire front are not automatically considered due to the difficulty in accurately forecasting spot fire formation. Where spotting results in new wildfires in advance of the original head fire result from spotting, the ASRPT must be revised appropriately. This is not unique to the RUIM however as new fires within an urban structure require a new timeframe to be established. As with any model, they are only one tool firefighters and Incident Controllers can utilise to assist the decision making process. Field validation and current and reliable intelligence will further assist to increase the accuracy of predictions.

For each of the RUIM stages in the boxes of Figure 4.14, separate flow charts and associated tables are required to be referred to in order to calculate the total RSRPT. Whilst firefighters will complete property protection tasks prior to seeking shelter inside the building of refuge, the time available to complete the property protection (shaded in Figure 4.14) is calculated after the other stages as it is not in the critical path of completing RUI defense. To calculate RSRPT, the Incident Controller or relevant officer should commence at Box 1 in Figure 4.15 and work their way through the RUIM until all time components have been calculated. The incorporation of safety factors and/or percentiles into the RUIM is also essential (AFAC, 2004; ICC et al., 2005; SFS, 2007) due to:

1. Fire safety engineering, especially wildfire engineering, being a discipline based on complex science which is neither exact or complete (AFAC, 2004);
2. The potential for mass fatalities associated with firefighters' convoys being caught in a burnover (Haynes et al., 2008; Handmer, O'Neil & Killalea, 2010; Blanchi et al., 2014);
3. The potential for untenable conditions occurring well in advance of the wildfire front (Penney et al., 2019); and the complexity of significant wildfire events, the incorporation of a safety factors and/or percentiles is also required.

As AFAC (2004, p26) reports

"Fire safety engineering is a discipline based upon a complex science which is neither exact nor complete. For a realistic result to be achieved, informed approximations and expert judgement must be employed. In order to ensure safety, appropriate margins are required in the analysis."

To account for firefighter fatigue, varying levels of firefighter proficiency and other uncertainties that can affect fire service response, utilising a percentile approach can also be incorporated into the RUIM. The mean values provided in this manuscript are sourced from AFAC (2004) and are representative of the particular activity being completed within the stated duration, 50% of the time. Due to the severity of the consequences of burnover, it is suitable to incorporate a greater percentile. For reference, AFAC (2004) suggests a 90^{th} percentile is suitable, meaning a particular activity will be completed within the stated duration 90% of the time. Adopting a conservative approach, the relationship between X percentile and k standard deviations can be expressed as:

$$k = \sqrt{\frac{100}{100 - X}} \qquad (4.5)$$

When the distribution is unknown, for X = 90, k = 3.17 (AFAC, 2004), however where the average time is at least several standard deviations greater than zero, it is reasonable to assume the distribution to be normal and for X = 90, k = 1.28 (AFAC, 2004). Using the example of an "officer size up" where the mean (μ) is 135 seconds and the standard deviation (σ) is 20 seconds, the 90th percentile can then be expressed as:

$$90th\ percentile = \mu + 1.28\sigma \qquad (4.6)$$

$$90th\ percentile = 135 + (1.28 \times 20) = 160.6\ seconds$$

Where the calculation involves speed as opposed to time, the equation becomes:

$$90th\ percentile = \mu - 1.28\sigma \qquad (4.7)$$

The use of safety multipliers or factors is also recommended. As AFAC (2004) describes, where the scientific basis for a well-established discipline is sound, a relatively small safety factor (F_S) as low as 1.2 may be suitable. In keeping with the recommendations of the FBIM, a safety factor of 2 should be considered for the RUIM. As opposed to applying a single safety factor at the completion of the model, the correct approach to incorporating safety factors is to apply them after each individual stage. This is demonstrated in the case study presented later in this chapter.

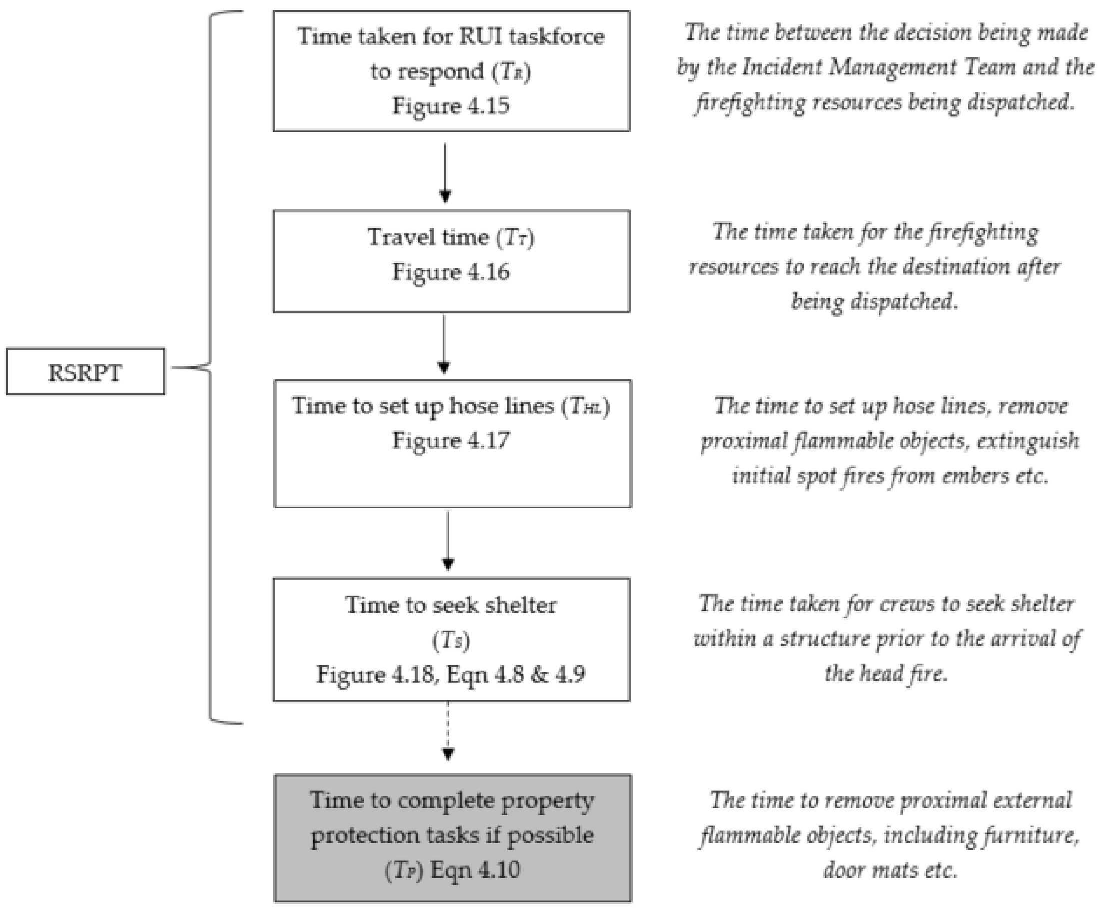


Figure 4.14: Rural Urban Interface Model (RUIM) methodology

4.4.2.1 Time taken for RUI taskforce to respond

This represents the time taken for firefighters to respond to the dispatch / turnout message and respond to either the staging area, or the RUI to be defended. It considers whether the taskforce is pre-assembled or must first mobilise to the staging area from various locations.

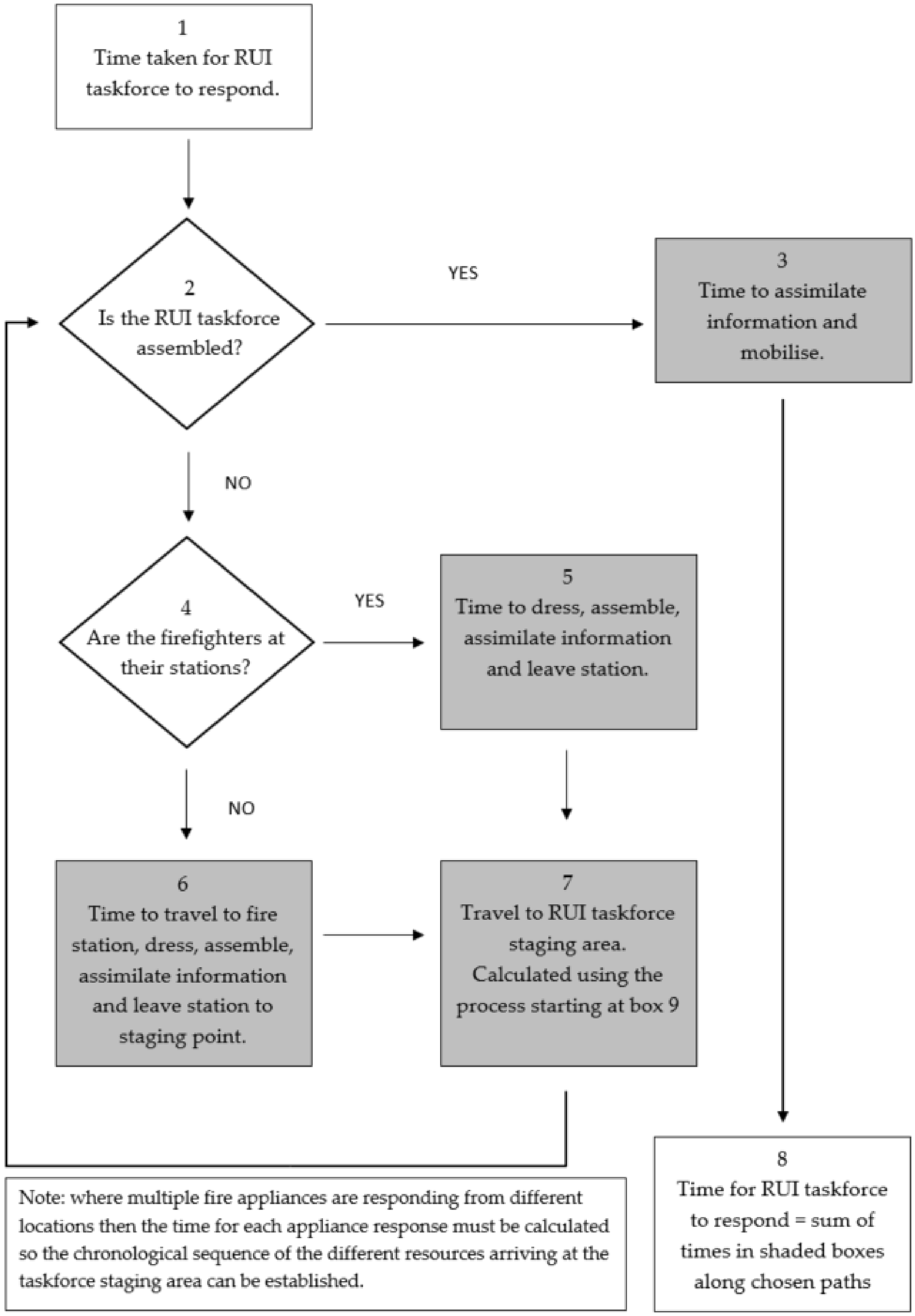


Figure 4.15: RUI taskforce dispatch time flow chart. Adapted from AFAC (2004, Chart 3, p56)

Table 4.16: RUI taskforce dispatch flow chart explanation. Adapted from AFAC (2004, Table E, p106)

Box / diamond	Description	Time (s)
1	This flowchart determines the time taken for firefighters to respond to the dispatch / turnout message. It is the time taken from activation of the turnout signal to the time when the taskforce proceeds to the RUI to be defended.	n/a
2	The RUI taskforce assembles at the staging point prior to mobilising to the RUI to be defended.	n/a
3	When assembled at the staging area and wearing PPC, firefighters receive their briefing and crew their machines immediately prior to mobilising to the RUI to be defended.	60* to 1,200**
4	If the RUI taskforce hasn't been assembled then firefighters must first mobilize to the RUI taskforce staging area from their home fire stations.	n/a
5	If firefighters are on station then they must respond to the message to proceed to the RUI staging area, don PPC and depart.	90*
6	If firefighters are not on station then (as may be the case with volunteer stations) they must first drive to the fire station prior to responding to the dispatch/turnout message. Once on station the firefighters must respond to the message to proceed to the RUI staging area, don PPC and depart.	480* to 1,200**
7	Figure 4.17 details the flowchart used for calculation of fire appliance travel times.	Fig. 4.17
8	Time for RUI taskforce to respond = sum of times in shaded boxes along chosen paths.	n/a

**Sourced from AFAC (2004, Table E, p106)*
***Suggested realistic worst case scenario*

4.4.2.2 Time taken for the taskforce to travel to the RUI

This process can be used for determining both the time it takes for individual appliances to reach the taskforce staging area (the area all crews assemble prior to being briefed and dispatched as one taskforce), and the time it takes for the assembled taskforce to reached the RUI to be defended.

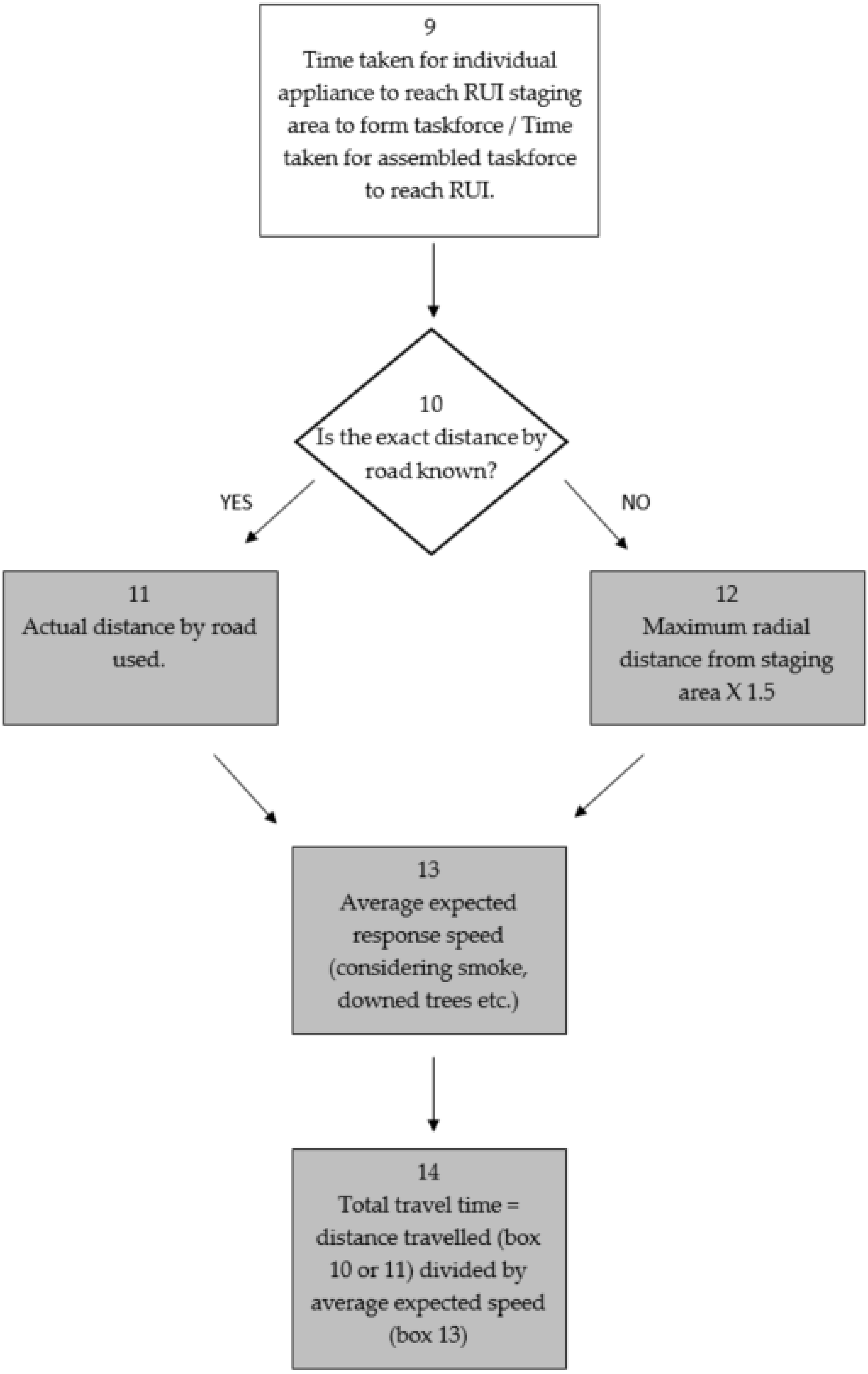


Figure 4.16: RUI taskforce travel time flow chart. Adapted from AFAC (2004, Chart 4, p60)

Table 4.17: Fire appliance and RUI taskforce travel flow chart explanation.

Box / diamond	Description	Value
9	Time taken for individual appliances to reach RUI taskforce staging area (use greatest time). Also the process used to determine the time taken for the assembled taskforce to reach the designated RUI.	n/a
10	If the response is along a defined route then the actual road distance can be used (Box 11). If the route or the exact distance of a route is unknown then the radial distance multiplier (Box 12) applies.	n/a
11	Use the actual road distance.	Actual route (km)
12	AFAC (2004, p61) reports the radial distance multiplied by 1.5 provides a reasonable approximation of actual road distance to be travelled.	Radial distance X 1.5 (km)
13	AFAC (2004, Tables F1-F5) provide typical fire service travel times for different Australian jurisdictions. The average of these times is provided in Table 4.18 and may be used where other data sets are not available (AFAC, 2004, p61).	Table 4.18
14	Total travel time = distance travelled (Box 11 or 12) divided by average expected speed (Box 13)	n/a

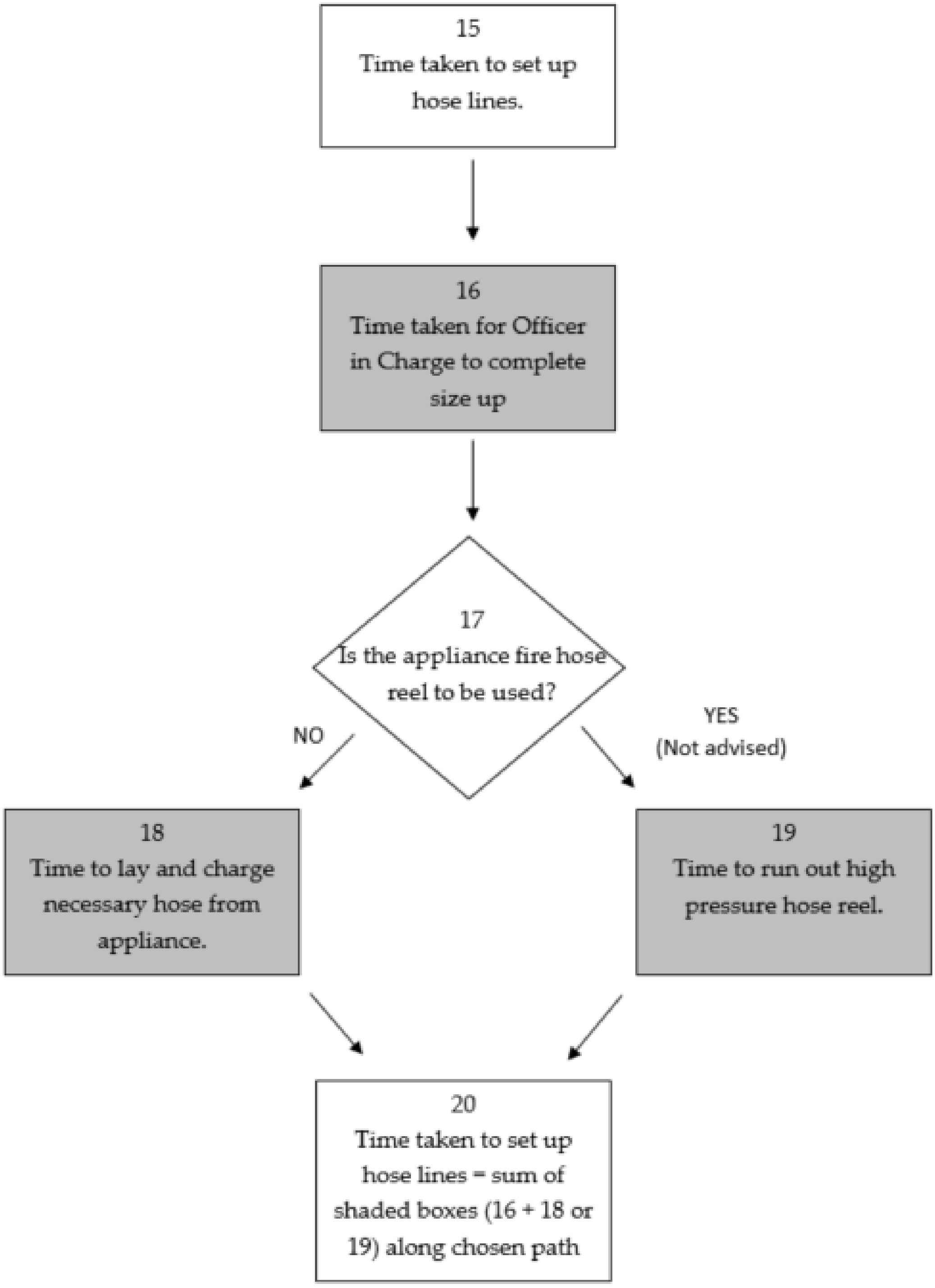
Table 4.18: Mean fire appliance travel times, in kph. Adapted from AFAC (2004, Tables F1-F5).

Context	Melbourne		Tasmania		South Australia		Average	
	μ	σ	μ	σ	μ	σ	μ	σ
Major city CBD	38.8	12.8	45.1	24.1	36.6	8.7	40.2	15.2
Major city inner suburb	44.3	12.0	51.0	20.3	41.4	7.3	45.6	13.2
Major city outer suburb	60.5	16.2	43.9	18.2	42.6	8.8	49.0	14.4
Rural town centre	-	-	54.9	25.6	-	-	54.9	25.6
Rural country	-	-	55.7	23.6	-	-	55.7	23.6
Travel through site	8	-	8	-	-	-	8	-

Note: other datasets from AFAC (2004) included firefighter response times which are considered separately in RUIM Figure 4.15

4.4.2.3 *Time taken to set up hose lines*

This process is used to calculate the time required for firefighters to set up hose lines for the RUI defense. It provides flexibility around the individual RUI tactics that individual fire services utilise.



Note: the use of high pressure hose reels is not advised as firefighters must be able to 'drop and run'. The use of lay flat hose enables firefighters to quickly disconnect the branch from the hose and retreat. Hose reels must be dropped intact, meaning that the branch will be lost if the reel is overcome by fire.

Figure 4.17: Time to set up RUI defense hose lines flow chart. Adapted from AFAC (2004, Charts 7&10)

Table 4.19: Time to set up RUI defense hose lines flow chart explanation.

Box / diamond	Description	Value
15	Time taken for individual crews to set up hose lines in preparation for RUI defense.	n/a
16	The Office in Charge must first complete a size up of the RUI and determine which properties the taskforce will focus on. This is considered to be equivalent to complex wayfinding in a structure fire context (AFAC, 2004, Table K) and the time taken to gather information in an area >10,000m^2 (AFAC, 2004, Table L). Total 135 seconds.	135 seconds Table 4.20
17	If lay flat hoses are used proceed to Box 18. If high pressure hose reels are to be used proceed to Box 19.	n/a
18	Lay flat hose must be removed, connected and charged from the appliance. Guidance is provided in Table 4.20, amended from AFAC (2004, Table V, p110).	Table 4.20
19	Appliance hose reel must be removed from appliance and carried to position. Guidance is provided in Table 4.20, amended from AFAC (2004, Table Q, p109) and is considered equivalent to firefighter horizontal speed in PPC with equipment.	Table 4.20
20	Total time taken to set up RUI = sum of shaded boxes (16 + 18 or 19) along chosen path.	n/a

Table 4.20: RUI defense activities and times. Adapted from AFAC (2004, Tables K, L, Q, V)

Activity	Time (s)	
	μ	σ
Officer in Charge size up	135	-
Remove and position high pressure hose reel*	15.8	23.1
Remove and connect hose from appliance to branch – 65mm diameter hose	39.4**	17.4**
Remove and connect hose from appliance to branch – 38mm diameter hose	33.3**	15.4**
Charge delivery hose from appliance to branch – 65mm diameter hose	20.3**	13.2**
Charge delivery hose from appliance to branch – 38mm diameter hose	18.4**	10.2**

*Movement speed of firefighter in turnout uniform carrying equipment (AFAC, 2004, Table Q)

**Per 30m length of hose

4.4.2.4 Time taken for firefighters to seek shelter

This process is used to calculate the time required for firefighters to seek shelter in an appropriate refuge prior to the arrival of the wildfire front.

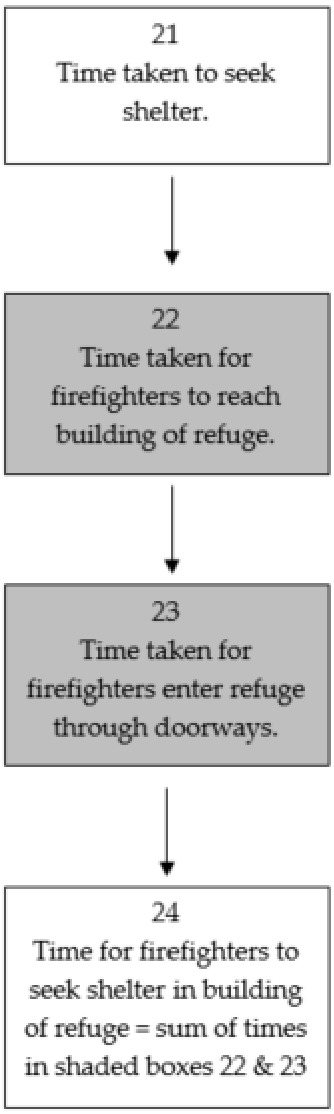


Figure 4.18: Time for firefighters to seek shelter flow chart.

Assuming firefighters are only required to travel horizontally (i.e. no stairs are involved) and firefighters move at $\mu = 2.3ms^{-1}$, $\sigma = 1.3$ (AFAC, 2004, Table Q 'dressed in turnout uniform with equipment') the time taken for firefighters to reach the building of refuge can be estimated by:

$$\frac{R_d\ (m)}{S_F\ (ms^{-1})} \quad (4.8)$$

Where R_d is the distance of the firefighters from the building of refuge; S_F is the speed of the firefighters. In the absence of available data it is suggested that as a worse case credible scenario it is appropriate to consider this distance to be 90m, being three lengths of 30m hose consistent with the tactics of RUI defense (DFES, 2013 & 2014).

The time taken for a group of people (including firefighters) to pass a point in a path of travel (corridor, aisle, ramp, doorway) is expressed as (Gwynne & Rosenbaum in DiNenno, 2008, Eqn 11):

$$t_p = P/[(1 - aD)kDW_e] \quad (4.9)$$

Where t_p is the time for passage in seconds, P is the population size in persons, D is the population density in persons per m^2, k is 1.40, a is 0.266ms^{-1}, and W_e is the effective width in metres of the component being transferred (door, corridor, ramp etc.). In the absence of alternate data, W_e of a door can be assumed to be 0.6m and D assumed to be 1.9 persons per m^2 (Gwynne & Rosenbaum in DiNenno et al., 2008).

Whilst the time available to complete property protection tasks (T_F) is not on the critical path for RUI defense, removal of proximal fuel from houses can increase their resilience to wildfire impacts (Leonard, 2009; Blanchi et al., 2006). T_F is calculated by:

$$T_F = ASRPT - (T_R + T_T + T_{HL} + T_S) \tag{4.10}$$

If ASRPT<RSRPT then Incident Controllers need to consider the high potential for the responding taskforce to be caught by the approaching headfire in the open, either on route or during RUI preparation.

4.4.2.5 RUIM Case Study

In order to provide the pathway between firefighting theory and practice, and demonstrate the practical application of the RUIM to a realistic wildfire scenario, the following case study based on recent and potential wildfire events in Western Australia (illustrated in figures 4.19-4.21) is presented:

A wildfire ignition is reported in the Blackwood State Forest in the south west of Western Australia. Aurora wildfire simulation completed by the IMT predicts the wildfire will impact Nannup, a town approximately 47km to the east in 30-34 hours post ignition. The fire will also impact the road between the taskforce staging point and Nannup in 26-30 hours post ignition. For the first 11 hours suppression is unsuccessfully attempted through aerial firefighting and the construction of containment lines. Community warnings are issued and residents are advised to evacuate north towards the regional city of Bunbury, however a large aged care facility of 80 high dependency residents cannot be evacuated and a critical radio communications tower is also located in Nannup townsite. At the 12 hour mark the IMT determine a defend-in-place strategy is required to protect the aged care facility. A request for a taskforce is issued however it is not known whether the taskforce will arrive too late to protect the town. The taskforce of 30 personnel (including the Officer in Charge) will be coming from the regional city of Bunbury and the state capital city of Perth. Bunbury is approximately 70km to the north, whilst Perth is approximately 220km to the north (both distances measured lineally). Whilst the Bunbury Taskforce is already assembled and ready to depart to the RUI staging area, the Perth Taskforce is to be made up of fire appliances from various metropolitan and regional volunteer fire stations, including Lancelin (114km northwest of Perth) and Northam (90km northeast of Perth). The crew of Northam have advised there will be a four hour delay due to appliance technical issues before they can depart to the Perth staging area where the convoy will depart. The IMT are situation in the town of Busselton, 50km northwest of Nannup. This is also the location of the RUI Taskforce Staging point. To provide the IMT guidance, the RUIM is applied. An overview map is provided in figure 7.

Step One – Determining ASRPT and safety factors

From the Aurora modelling, the town of Nannup wll be impacted by the headfire in 30-34 hours post ignition. It is critical however to acknowledge the request for the taskforce is issued 12 hours post ignition, reducing the Available Safe RUI Preparation Time (*ASRPT*) to 18-22 hours. The Incident Controller takes a precautionary approach and requires the lower 24 hour period to be used.

$$\therefore ASRPT = 22\ hours$$

However, another critical point is also identified for the scenario, being the available time before access road is impacted by fire, being 28-30 hours post ignition. It is equally as critical to acknowledge this event is forecast to occur 16-18 hours after the request for the taskforce is issued. This is termed the Available Safe Time to Critical Point 1 or ASTCP1 = 16 hours = 960 minutes.

The Incident Controller also requires 90th percentile margins and safety factors to be applied where possible, except for the initial travel to the taskforce staging area located well away from the fireground or any smoke impacts etc, and requires a Safety Factor (F_S) of 2 to be applied in all instances.

Step Two – Calculating time taken for RUI taskforce to respond (T_R)

Separate T_R must be calculated for each section of the taskforce, subsequently denoted Bunbury TF and Perth TF. With reference to figures 4.15-4.16, the process for determining T_R for each section is detailed in tables 4.21-4.22 from initial dispatch to arrival at the Busselton staging point to receive their briefing and then table 8 from Busselton to the RUI staging point. The process results in T_R for the Bunbury TF calculated as 58.5 minutes and the T_R for the Perth TF as 637 minutes. When considering the two separate taskforces are to join into a single taskforce to respond to the RUI, the greater value of 637 minutes is applied.

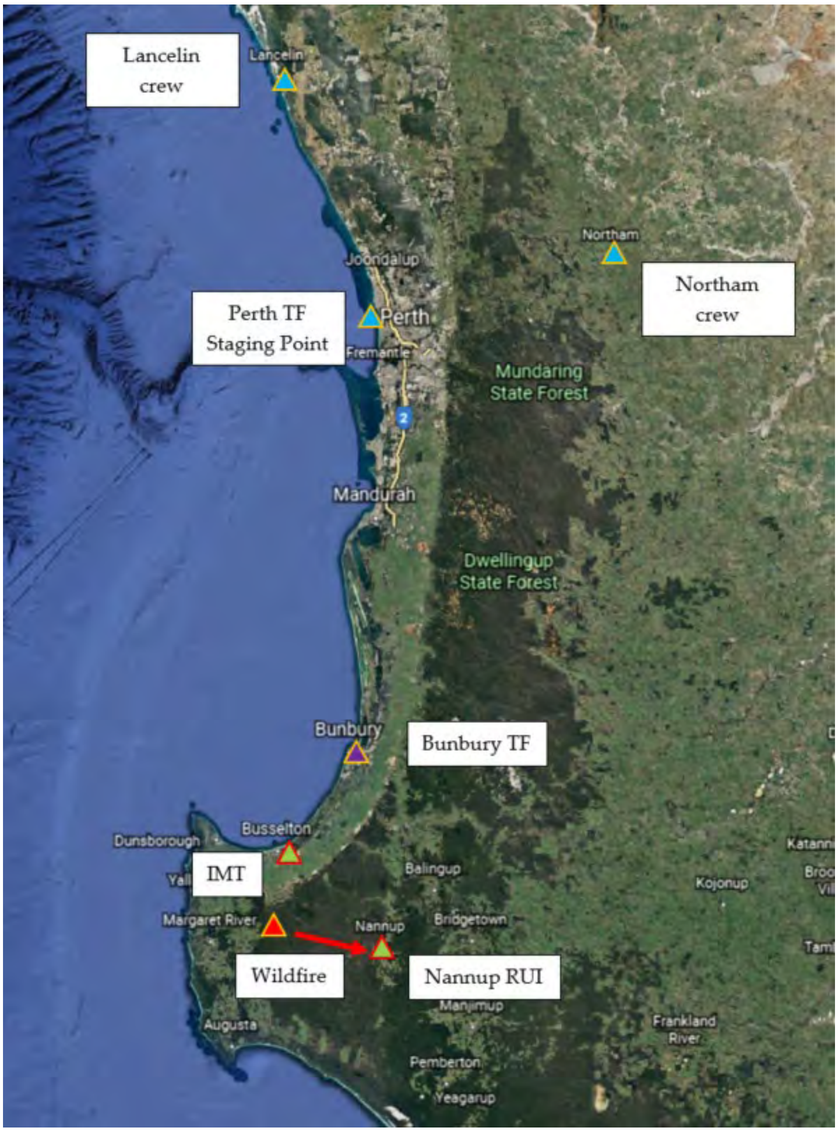


Figure 4.19: Wildfire scenario. Image source: Google AU earth.google.com

Figure 4.20: Wildfire scenario. Image source: Google AU earth.google.com

Figure 4.21: Wildfire scenario. Image source: Google AU earth.google.com

Table 4.21: *T_R* Bunbury TF

Step	Comment	Time
1	Start of RUIM. Proceed to step 2.	n/a
2	Task force is ready to depart Bunbury but is not at the RUI staging area. Proceed to step 4.	n/a
4	Firefighters are at their station. Proceed to step 5.	n/a
5	Firefighters dress, assemble, assimilate information and leave station. Duration 90 seconds. Proceed to Step 7.	1.5 min
7	Calculation of travel time to RUI Staging Point in Busselton starting at step 9.	n/a
9	No action required. Proceed to step 10.	n/a
10	Exact distance by road is known. Proceed to step 11.	n/a
11	Actual distance of 52km is used, 10km through 'major city outer suburb' and 42km through 'rural country'. Proceed to step 13.	n/a
13	Table 3 'Average' values used. Proceed to step 14.	n/a
14	Travel time to taskforce staging area = (10/49.0) + (42/55.7) = (0.2 + 0.75) = 0.95 hours	57 min
End	Total Bunbury TF travel time to taskforce staging area in Busselton equals time to respond plus travel time, being 1.5 + 57 min. Equal to 58.5 minutes.	58.5 minutes

Table 4.22: *T_R* Perth TF

Step	Comment	Time
1	Start of RUIM. Proceed to step 2.	n/a
2	Task force is not assembled. Proceed to step 4.	n/a
4	Firefighters are not at their station. Proceed to step 6.	n/a
6	For all stations except for Northam, time to travel to fire station, dress, assemble, assimilate information and leave station is 1,200 seconds = 20 minutes. For Northam station, the stated delay is 4 hours = 240 minutes. The highest value is used for the purposes of calculation. Proceed to step 7.	240 min
7	Calculation of travel time to Perth base for Perth TF to form starting at step 9.	n/a
9	No action required. Proceed to step 10.	n/a
10	Exact distance by road is not known, travel times calculated for the two stations required to travel the greatest distance, being Lancelin (114km) and Northam (90km). Assumption made that as all other metropolitan appliances are within 20km of the Perth base they will arrive prior to either Lancelin or Northam. Proceed to step 12.	n/a
12	Maximum radial distance from staging area calculated as: Lancelin = 1.5 x 114 = 171km; and Northam = 1.5 x 90 = 135km Both distances assumed to include 10km through 'major city outer suburb' and the remaining distance through 'rural country'. Proceed to step 13.	n/a
13	Table 3 'Average' values used. Proceed to step 14.	n/a
14	Travel time to taskforce staging area is calculated as: Lanceline = (10/49.0) + (161/55.7) = (0.2 + 2.9) = 3.1 hours = 186 minutes Northam = (10/49.0) + (135/55.7) = (0.2 + 2.4) = 2.6 hours = 156 minutes.	156 min

	As the Lancelin crew will arrive at the Perth base prior to the Northam crew leaving their station, the Northam value of 156 minutes is the critical value used for the purposes of calculation. Proceed to step 1 to determine time required for Perth TF to respond to TF staging area in Busselton.	
1	No action required. Proceed to step 2.	n/a
2	Perth TF is assembled at the Perth base and ready to depart to the staging area in Busselton. Proceed to step 4.	
4	Crews are at the Perth base. Proceed to step 5.	
5	Crews receive their briefing and depart. Duration 60 seconds. Proceed to step 7.	1 min
7	Calculation of travel time to RUI Staging Point in Busselton starting at step 9.	n/a
9	No action required. Proceed to step 10.	n/a
10	Exact distance by road is known. Proceed to step 11.	n/a
11	Actual distance of 222km is used, 20km through 'major city outer suburb' and 202km through 'rural country'. Proceed to step 13.	n/a
13	Table 3 'Average' values used. Proceed to step 14.	n/a
14	Travel time to taskforce staging area = (20/49.0) + (202/55.7) = (0.4 + 3.6) = 4 hours	240 min
End	Total Perth TF travel time to taskforce staging area in Busselton equals time to respond plus travel time, being 240 + 156 + 1 + 240 min. Equal to 637 minutes. This is greater than the Bunbury TF travel time and is used for subsequent calculations.	637 min

Step Three – Calculating time taken for joint taskforce to travel to RUI (T_T)

Now the taskforce is united, subsequently referred to as the Joint TF, at the Busselton staging area, a single travel time (T_T) to the RUI staging area can be calculated. With reference to figure 4.15, the process for determining T_T is detailed in table 4.23. Noting that the Joint TF is now proceeding to the fireground, the IC requirement for 90th percentile values and safety factor of 2 to be applied will be in effect. Importantly, the calculations demonstrate *ASTCP1 of 960 minutes > (T_R+T_T) of 925 minutes* and the taskforce can be safely deployed to the RUI with reasonable confidence that they will not be impacted by the headfire during the journey. The total T_T is calculated as 288 minutes.

Table 4.23: T_T Joint TF

Step	Comment	Time
9	No action required. Proceed to step 10.	n/a
10	Exact distance by road is known. Proceed to step 11.	n/a
11	Actual distance of 60km is used, 5km through 'major city outer suburb' and 55km through 'rural country'. Proceed to step 13.	n/a
13	Table 3 'Average' values used and 90th percentile applied. 90th percentile= μ-1.28σ, therefore major city outer suburb speed = (49.0 – (1.28x14.4) = 30.7kph and 'rural country' speed = (55.7 – (1.28 x 23.6) = 25.5kph. Proceed to step 14.	n/a
14	Travel time to RUI staging area = (5/30.7) + (55/25.5) = (0.2 + 2.2) = 2.4 hours.	144 min
F_S	Safety factor of 2 applied.	288 min
ASTCP1	For the taskforce to travel to the RUI without being impacted by the fire front, ASTCP1 > (T_R+T_T). Using the forecast time of impact of the access road and the calculated T_R and T_T: *ASTCP1 = 960 minutes* T_R = 288 minutes and T_T = 637 minutes, therefore T_R+T_T = 925 minutes	

Step Four – Calculating time taken to set up hose lines (T_{HL})

Once the taskforce arrives at the Nannup RUI the time taken to set up hose lines and establish the urban defense must be calculated. With reference to figure 5, the process for determining T_{HL} is detailed in table 4.24. The IC requirement for 90th percentile values and safety factor of 2 to be applied is incorporated into the calculation. The total T_{HL} is calculated as 10 minutes.

Table 4.24: T_{HL} Joint TF

Step	Comment	Time
15	No action required. Proceed to step 16.	n/a
16	Time taken for Officer in Charge (OIC) to complete size up is 135 seconds = 2.3 minutes. Proceed to step 17.	2.3 min
17	The OIC determines that hose lines will consist of 1 length of 65mm hose and 2 lengths of 38mm hose. Proceed to step 18.	n/a
18	Table 5 values used and 90th percentile applied. 90th percentile= μ+1.28σ, therefore time to remove and connect 65mm hose from appliance to branch / other length of hose is = (39.4 + (1.28 x17.4)) = 61.7 seconds and time to remove and connect 38mm hose from appliance to branch / other length of hose is = (33.3 + (1.28 x 15.4) = 53.0 seconds. Time to charge hose is the time to charge the 65mm length and both 38mm lengths of hose. This is calculated by (20.3+(1.28 x 13.2)) + 2(18.4+(1.28 x 10.2) = (37.2+62.9) = 100.1 seconds = 1.7 minutes Proceed to step 14.	1.7 min
20	T_{HL} = 2.3 + 1.7 min = 5 minutes	5 min
F_S	Safety factor of 2 applied.	10 min

Step Five – Calculating Time taken for firefighters to seek shelter (T_S)

With reference to figure 4.18, the process for determining T_S is detailed in table 4.25. The required time for firefighters to seek shelter prior to the arrival of untenable conditions associated with the head fire are calculated in accordance with equations 4.8 and 4.9, where R_d is the distance of the firefighters from the building of refuge = 90m; S_F is the speed of the firefighters μ = 2.3ms^{-1}, σ = 1.3, therefore S_F = 2.3 – (1.28 x 1.3) = 0.6 ms^{-1}; P is 30, W_e is 0.6m; and D is 1.9 persons per m^2. The F_S of 2 is again applied. The total T_S is calculated as 12.6 minutes.

Table 4.25: T_S Joint TF

Step	Comment	Time
21	No action required. Proceed to step 22.	n/a
16	Time taken for firefighters to reach shelter, applying equation 6. $\therefore Time\ required\ to\ reach\ shelter\ \frac{90\ (m)}{0.6\ (ms^{-1})} = 150\ seconds = 2.5min$ Apply Safety factor.	2.5 min
F_S	Safety factor of 2 applied. Proceed to step 23.	5 min
18	Time taken for firefighters to enter shelter, applying equation 7.	0.65 min

	$t_p = {}^{30}/_{[(1-0.266\times 1.9)1.4\times 1.9\times 0.6]} = 38\ seconds.$ Apply Safety factor	
F_S	Safety factor of 2 applied. Proceed to step 24.	1.3 min
24	T_S = 5 + 1.3 min = 6.3 minutes	6.3 min

Step Six – Deterministic analysis and calculating T_F

Equation 4.4 is now applied to determine whether there is sufficient RSRPT for the taskforce to be deployed. ASRPT was previously determined to be 22 hours.

$$RSRPT = (T_R + T_T + T_{HL} + T_S)$$

$$\therefore RSRPT = (637 + 288 + 10 + 6.3)$$

$$\therefore RSRPT = 941.3\ minutes = 15.7\ hours$$

$$\therefore ASRPT > RSRPT$$

In this scenario, the deterministic analysis provides guidance to the IMT that there is sufficient time for the taskforce to safely reach the Nannup RUI and ready the defense of the nursing home. The calculation of RSRPT also enables evidence based trigger points to be set by the IMT. For instance, should spotting result in a new headfire that will impact the access road into Nannup 20 hours post ignition (8 hours after the taskforce request is submitted) and impacting the Nannup RUI 26 hours post ignition (15 hours after the taskforce request is submitted), then the revised ASTCP1 of 480 minutes > (TR+TT) of 925 minutes and the revised ASRPT of 900 minutes < RSRPT of 941.3 minutes. Having completed the RUIM process, the IMT are aware that without waiting for the Perth TF, the Bunbury TF RSRPT is 369.1 minutes (6.2 hours); and only 310 minutes (5.2 hours) if they are already assembled at the Busselton staging area. This analysis supports the IMT to enact the contingency plan of deploying a smaller taskforce to the Nannup RUI as opposed to no taskforce at all. It also supports the establishment of operational 'go/no-go' trigger points to reduce the potential for responding firefighters to be caught in burnover.

4.4.3 *Evacuations*

Evacuations of communities in the path of large wildfires is a growing problem for both land use planners and Incident Management Teams alike (Cova, 2005; Taylor & Freeman, 2010). If left too late or incorrect routes are taken during evacuations, fatalities may result, particularly in the wake of significant wildfires (Haynes et al, 2008; Blanchi et al, 2014; Handmer et al, 2010; Ronchi et al, 2019). When considering whether community evacuations are possible, a hydraulic model which simplifies egress behaviour and enables evacuation to be described by a set of equations can be used (Gwynne & Rosenbaum in DiNenno, 2008; ICC et al, 2005). This subsequently enables deterministic analysis of Available Safe Evacuation Time (ASET) versus Required Safe Evacuation Time (RSET) as described in the wildfire context by Ronchi et al, (2017 & 2019):

$$ASET > RSET = t_d + t_{FDA} + t_{FDI} + t_N + t_{prep} + t_{foot} + t_{veh} + t_{ref} \tag{4.11}$$

where t_d is the time for the incident to be detected after ignition, t_{FDA} is the time spent by the fire department assessing the situation on site, t_{FDI} is the time spent by the fire department intervening and attempting to control the incident, t_N is the time for the population to be notified once intervention has been deemed unsuccessful, t_{prep} is the time for a resident to complete preparations after they have initially been notified, t_{foot} is the time for the population to move on foot (e.g. walk to a place of safety or to a vehicle), t_{veh} is the time for the population to move into a vehicle, and finally t_{ref} is the time for the individual to be on-boarded at a place of safety. An additional consideration not inherently contained within the model is the requirement for assisted evacuations from schools, aged care facilities, hospitals etc. When considering evacuations from such places it may be more suitable to adopt a shelter-in-place strategy with dedicated urban firefighting appliances. As illustrated in Figure 4.22, the timing and adequacy of decisions made by Incident Controllers can have significant impact on the ability of the community to safely evacuate. Whilst t_d, and t_{prep} are often beyond the control of responding fire services, rapid and accurate assessment of the incident and subsequent selection of appropriate strategies and tactics (t_{FDI}), including evacuation as a tactic, coupled with detailed and timely community warnings t_N can increase the available time for evacuees to find safe refuge. It is important to note that this approach implies various assumptions about human behaviour and has several limitations including (Gwynne & Rosenbaum in DiNenno, 2008, p3-376):

1. Behaviours that detract from movement are not explicitly considered;
2. People are considered as a group as opposed to their own personal identity and attributes;
3. Movement between egress components is considered, rather than within them; and
4. The results are deterministic and will therefore remain the same unless changes are made to the scenario or the assumptions employed.

As a result it is important to include a safety factor when considering the suitability of an evacuation strategy. For example, depending on the size of the population to be evacuated, the complexity of the situation and the Incident Controller's own risk tolerance they may require ASET > 2.7RSET prior to approving and evacuation plan. As a point of reference, whilst AFAC (2004) identifies that the safety factor for a well-established discipline supported by robust evidence may be quite small and as low as 1.2, for structural firefighting efforts a factor of 2 is appropriate. Given the relative infancy of wildfire engineering as a discipline, the lack of robust data and the potential for mass fatalities associated with evacuating people being caught in a burnover (Haynes et al., 2008; Handmer, O'Neil & Killalea, 2010; Blanchi et al., 2014) the authors suggest a minimum safety factor of 2.5 is utilised for community evacuation purposes in the landscape wildfire context. In sub-landscape scale wildfire scenarios within the urban environment, where head fire suppression is possible and smaller community movements need to be considered, a safety factor of 1.5 may be suitable.

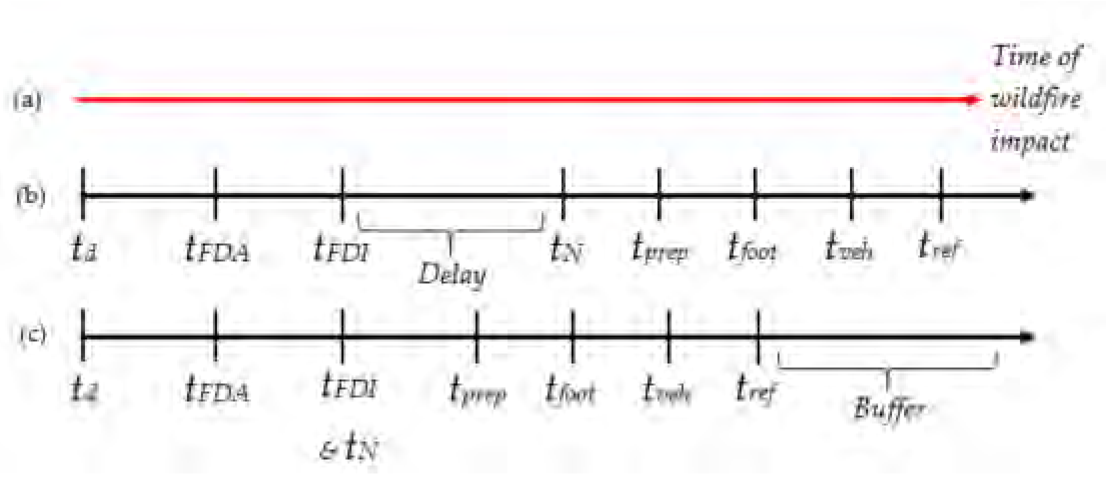


Figure 4.22: (a) ASET; (b) RSET with delayed community notification; (c) RSET with rapid community notification and early evacuation decision.

t_{foot} and t_{ref} include movement and queuing times for all evacuees and can become complicated where large numbers of evacuees are moving to different refuges. In such instances guidance can be found in Gwynne & Rosenbaum (in DiNenno, 2008), however in simple cases flow of persons through a certain point (such as the doors of buildings) can be calculated by:

$$F_c = SDW_e \tag{4.12}$$

where F_c is calculated flow (m/s), S is speed of movement(m/s), D is population density (persons/m^2), and W_e is effective width of component being traversed such as a door or stairwell (m).

$$S = k - akD \tag{4.13}$$

where k and a are both constants, obtained from sources including Gwynne & Rosenbaum (in DiNenno, 2008, Table 3-13.2) or Vaughan and Bain (2001).

The complexity of mass evacuations during natural disasters and emergencies requires dynamic modelling software to be used (Shiwakoti et al., 2013). Dynamic traffic simulation enables the comparison of different evacuation plans under a variety of situations (Yuan et al., 2006), however there is often a trade-off between accuracy, cost, data requirements and the time required for simulations to be completed (Shiwakoti et al., 2013). In addition to recommending minimum traffic means of egress standards for urban design in wildfire prone areas, Cova (2005) also identifies the major factors that can impede community evacuation.

Whilst accurately calculating t_{veh} remains problematic (Cova et al, 2011; Intini et al, 2019; Ronchi et al, 2017), in an urban design and planning assessment context when a shelter in place strategy is adopted, calculation of t_{veh} is not required as occupants are not leaving the site. To improve the design of wildfire prone communities (including visiting tourists) in regards to large scale evacuation and egress, Cova (2005) recommends a number of safety aspects. These recommendations are summarised in Tables 4.26-4.29.

Table 4.26: Wildfire prone road design safety aspects. Adapted from Cova (2005)

Component	Standard
Occupant load factor (density)	The density of homes along the roads in any fire-prone community or portion thereof should not exceed: that specified in Table 4.16 (reproduced with permission from ASCE)
Number of exits	The number of means-of-egress from any fire-prone community or portion thereof shall meet the minimum specified in Table 4.28 (reproduced with permission from ASCE)
Exit capacity	The total egress capacity from a fire-prone community or portion thereof shall meet the factors specified in Table 4.29 (reproduced with permission from ASCE)
Exit arrangement	The closest distance between any two points along any of the n exits from a fire-prone community must be at least 1/n the maximum diagonal distance across the community. The maximum diagonal of a community is defined as the greatest Euclidean distance between any two households that rely on the same exit set, and the minimum distance between exits is defined as the shortest Euclidean distance between any two points along two exiting roads.
Maximum exist distance	No household in a fire-prone community shall be further than 3 km by road from its closest exit. The maximum exit distance for a community is defined as the household with the greatest shortest-path distance on the

	road network to an exit discharge in the most constraining bottleneck set i.e., the end of one of the exiting roads from the community.
Exit vulnerability (distance to fuel)	Exits in a fire-prone community shall have a 10m buffer on each side that is clear of fuel.

Table 4.27: Occupant load factor (density). Cova (2005), reproduced with permission from ASCE

Use	Hazard	Road length per household (m)	Road length per vehicle (m)
Residential	Low	12.5	6.3
	Moderate	16.7	8.3
	High	20.0	10.0
Residential & Tourism	Low	12.5	4.2
	Moderate	16.7	5.6
	High	20.0	6.7

Table 4.28: Minimum exits. Cova (2005), reproduced with permission from ASCE

Number of households	Minimum number of exiting roads	Maximum households per exit.
1-50	1	50
51-300	2	150
301-600	3	200
600+	4	200

Table 4.29: Exit capacity. Cova (2005), reproduced with permission from ASCE

Use	**Hazard**	**Minimum total exit capacity (vehicles per hour per household)**	**Minimum evacuation time (hours)**
Residential	Low	1	2
	Moderate	2	1
	High	4	0.5
Residential & Tourism	Low	1.5	2
	Moderate	3	1
	High	6	0.5

4.5 Implications for frontline firefighters, fire behaviour specialists and IMT's

Wildfires, particularly mega wildfires such as those experienced in late 2019 and early 2020 throughout Australia are dynamic and complex disasters that require significant interstate and international resourcing over prolonged durations. When such events occur they will inevitably impact life and property as well as overwhelming firefighting efforts. This chapter discussed the strategies available to firefighters, their limitations, and where the evidence suggests they may be successful. Detailed and accurate planning is required to be completed by IMT's and fire behaviour specialists to ensure firefighting operations are suitable and to minimise the potential for firefighter injury. When applied correctly and in the right context, the findings of new research including Table 4.15 and the RUIM may assist IMT's to achieve this.

As will be the case in many landscape scale wildfires and mega wildfires, detailed predictions and analysis of wildfire behaviour in itself is insufficient. Care must be taken to bridge the theory – practice gap and ensure planning is operationally relevant. The research presented in this chapter demonstrates that even in mild conditions, the head fire will often be unstoppable where it occurs in continuous vegetation fuel bed geometry. This is further supported by the findings presented in Chapters 5 and 6. The use of existing wildfire scars and prescribed burns for wildfire suppression can only be considered opportunistic and with marginal chance of success unless the burn scar is both recent (within 2-3 years) and significant in area. As climate change continues to result in worsening fire conditions, frontline firefighters, IMT's and fire behaviour specialists need to apply increased scrutiny to fuel bed structure and geometry, focusing suppression efforts where fuels are discontinuous and broken.

4.6 Implications for urban planners

By understanding wildfire behaviour and wildfire suppression strategies, urban planners can significantly influence the defendability and resilience of communities to wildfire impacts through appropriate design of development at the RUI. The research and increased analysis presented in this chapter enables wildfire impacts and potential suppression to be considered at the design stage of RUI development. Evidence based design that incorporates minimum measures for evacuations and eliminates the unrealistic expectation that firefighters will be able to defend every property will lead to more appropriate passive[3] wildfire resilient design

The use of design wildfires, Wildfire Engineering Briefs and Wildfire Engineering Reports, similar to the standard fire engineering processes within the urban fire engineering profession will only further increase the standard of safety in bushfire prone areas. These are detailed and complex technical documents however that required a high degree of technical knowledge and proficiency from both the engineer and the agencies involved.

[3] Passive systems do not require action or maintenance. For instance, ensuring road design allows sufficient evacuation opportunity without additional control measures is a passive measure that can be supported by appropriate and timely community evacuation messages. Firefighters being required to suppress a wildfire is an active intervention.

5. Firefighter tenability in the wildfire context

5.1 Introduction

Whilst the wildfire suppression thresholds discussed in Chapter 4 are utilised internationally by fire services, they fail to sufficiently consider firefighter tenability. The International Fire Engineering Guidelines (ICC, 2005) defines untenable conditions as "environmental conditions associated with fire in which human life is not sustainable." This should not be confused with the conditions required to facilitate effective firefighting suppression which are significantly milder than those able to be withstood for short periods of time. Therefore, improving firefighter safety during wildfire suppression by clearly defining fire ground environmental conditions that are considered tenable, or safe for firefighters is paramount. Both the Society of Fire Safety (2014) and Poh (2010) identify four primary hazards associated with fires within the built environment that affect tenability being convected heat, radiant heat, toxic gases and smoke obscuration. However, as Poh (2010) reports, there is no single set of related values for tenability criteria which is universally accepted. This chapter defines and discusses firefighter tenability in the wildfire context to assist Incident Controllers to make critical incident decisions during chaotic and large wildfire incidents.

5.2 Defining Tenability

Smoke obscuration is excluded as a factor affecting firefighter tenability in the wildfire context due to the lack of injuries and incidents associated with visual obscurity during wildfire events (Hayes et al, 2008; Penney, 2019 – risk). Knight, Brown and Leonard (2001) identify the toxic gases produced during the thermal degradation of vehicle componentry, particularly the interior vehicle componentry, will be subsequent to the loss of tenability due to radiant heat and other factors. The same authors do note that hydrogen chloride (HCl), a severe irritant released when vinyl interiors thermally degrade even without combustion, formaldehyde (HCHO), hydrogen cyanide (HCN) and carbon monoxide (CO) may cause significant irritation to occupants in the vehicle cabin, however not to the extent of affecting tenability. The concentration for each of these gases that are immediately dangerous to life or health (IDLH) are detailed in Table 5.1. Brown et al. (2003) reports fire truck cabins will generally remain tenable in regards to toxic gases unless there is catastrophic window failure with glass falling from the frame.

Table 5.1: IDLH concentrations

Material	IDLH (ppm)	Source & Comments
CO	1000-8000	(Brown et al., 2003; NIOSH, 2014)
HCHO	20-100	(Brown et al., 2003; Kent, 1998; NIOSH, 2014a) @20ppm – severe respiratory irritation @50ppm – pulmonary oedema @100ppm – immediate death
HCl	50-1000	(Brown et al., 2003; Hull et al., 2008; NIOSH, 2014b) @50ppm – barely tolerable @1000ppm pulmonary oedema
HCN	50-280	(Brown et al., 2003; NIOSH, 2016) @ 100 death after 1 hour @181 fatal after 10 minutes @280 immediately fatal

Radiant heat transfer is primarily responsible for the propagation of landscape scale bushfire and subsequent impacts on firefighters (Penney & Stevenson, 2019; SAI Global, 2018; Butler, 2014; Frankman et al., 2012; Leonard, 2010) therefore it is proposed any impacts of convective heat transfer, or noxious gases on firefighters would first occur from radiant heat transfer. Direct flame contact from the passing fire front or adjacent involved fuels (including burning fuels underneath the vehicle) have the potential to result in rapid vehicle fire involvement and untenable conditions in as little as 90 seconds (DFES, 2012a & 2016; Pearce et al, 2004). Post burnover investigations support the conclusion radiant heat remains the greatest threat to firefighters (Sullivan et al., 2003) and conditions within the vehicle cabin may become untenable in a much shorter timeframe than this (Linton, 2016; Johnstone, 2002; Pearce et al., 2004; WFA, 2013). Calculated potential peak radiant heat flux from large wildfires can exceed 76 kWm^{-2}, even at greater than 10 m separation from the head fire under mild fuel loads and weather conditions (Penney et al., 2019a). By comparison experiential forest fire field data reported by Frankman et al. (2013) identified peak heat fluxes of 179 kWm^{-2} and 263 kWm^{-2}, whilst an analysis of 216 homes post the Springwood wildfire in New South Wales, Australia in 2013 by Newnham et al. (2014) estimated peak radiant heat fluxes experienced by houses to be as much as 52.5kWm^{-2}.

Purser (2008) cites three methods of incapacitation from exposure to fire are possible, being heat stroke, body surface burns and respiratory tract burns. The sensation of pain occurs prior to burns, incapacitation and ultimately death, however in the case of significant bushfire such events may be almost simultaneous as opposed to the more prolonged onset of hyperthermia.

In considering pain and burns two assumptions detailed in both Poe (2010) and Purser (2008) are retained:

1. Thermal burns to the respiratory tract will not occur unless the air temperature / or humidity are sufficient to cause (unprotected) facial skin burns; and
2. Heat flux and temperature tenability limits designed to protect victims from incapacitation by skin burns should be adequate to protect them from burns to the respiratory tract.

Whilst the protective effects of Personal Protective Clothing (PPC) and Equipment (PPE) are acknowledged, this report includes a third assumption that unprotected skin thresholds are suitable for modelling purposes (and as a result incorporate an inherent safety factor where structural firefighting PPC and PPE are worn). Limited experimental data involving human test subjects is available to support tenability thresholds and variance between the literature exists. Although Raj (2008) suggests exposure to as much as 5 kWm^{-2} may occur without pain or injury in clothed subjects, Poe (2010) identifies 2.5 kWm^{-2} is sufficient to result in both skin and respiratory burns. The Australasian Fire Authorities Council (2004) provides further guidance for firefighters in structural firefighting PPC (including Self Contained Breathing Apparatus) as detailed in Table 5.2, however the Society of Fire Safety (2014) suggest the 'Routine' exposure threshold may be inappropriate considering radiant heat flux received whilst sunbaking may be as high as 1.1 kWm^{-2}. For firefighters sheltering inside a fire appliance cabin Knight et al. (2001) utilise a 60 second radiation limit of 2 kWm^{-2} and air blast temperature limit of 200°C however the lower temperature of 150°C for exposed personnel is adopted in Europe (2010). Further guidance regarding human tolerance to thermal radiation is provided by Purser (2008, Table 2-6.19] as summarised in Table 5.3.

Table 5.2: Firefighter exposure limits

	Routine Condition	Hazardous Condition	Extreme Condition	Critical Condition
Maximum Time	25 minutes	10 minutes	1 minute	< 1 minute
Maximum Air Temperature	100°C	120°C	160°C	>235°C
Maximum Radiation	1kWm^{-2}	3kWm^{-2}	4-4.5kWm^{-2}	>10kWm^{-2}

Table 5.3: Radiant heat flux effects

Heat Flux kWm^{-2}	Time to Effect (seconds)		
	Pain	Burn	Full Burn
2.5	40	-	-
4.2	-	30 (blisters)	-
10.5	5	-	-
23.5	1.6	-	-
30	6	10	>15
35	5	9.5	>15
40	4.5	9	>15
50	4	7	>15
100	2	4	6
150	1	2.5	4

The time taken for various effects as a result of exposure to thermal radiation can also be calculated by Purser's (2008) equation:

$$t_{rad} = \frac{r^{4/3}}{{q_r}^{4/3}} \tag{5.1}$$

where t_{rad} is the time to reach end effect for the identified thermal radiation (minutes), q_r is the given radiant heat flux, and r is the radiant heat exposure [$(kWm^{-2})min^{-1}$] for the identified endpoint detailed in Table 5.4:

Table 5.4: Radiant heat exposures

Thermal radiation [$(kWm^{-2})min^{-1}$]	Endpoint
1.33	tolerance limit / pain / first-degree burns
10	severe incapacitation and second-degree burns
16.7	fatal exposure with third-degree burns

Applying Purser's equation, Penney et al. (2019a) provided comparison of the various times to reach the identified endpoint as a function of radiant heat flux. This is shown in Figure 5.1 and illustrates that incapacitating burns can occur within relatively small timeframes at the lower end of possible wildfire induced radiant heat flux. The results demonstrate fatal exposure occurs within 1 minute once radiant heat flux exceeds 20 kWm^{-2}, whilst incapacitating injuries occur within 1 minute once radiant heat flux exceeds 20 kWm^{-2}.

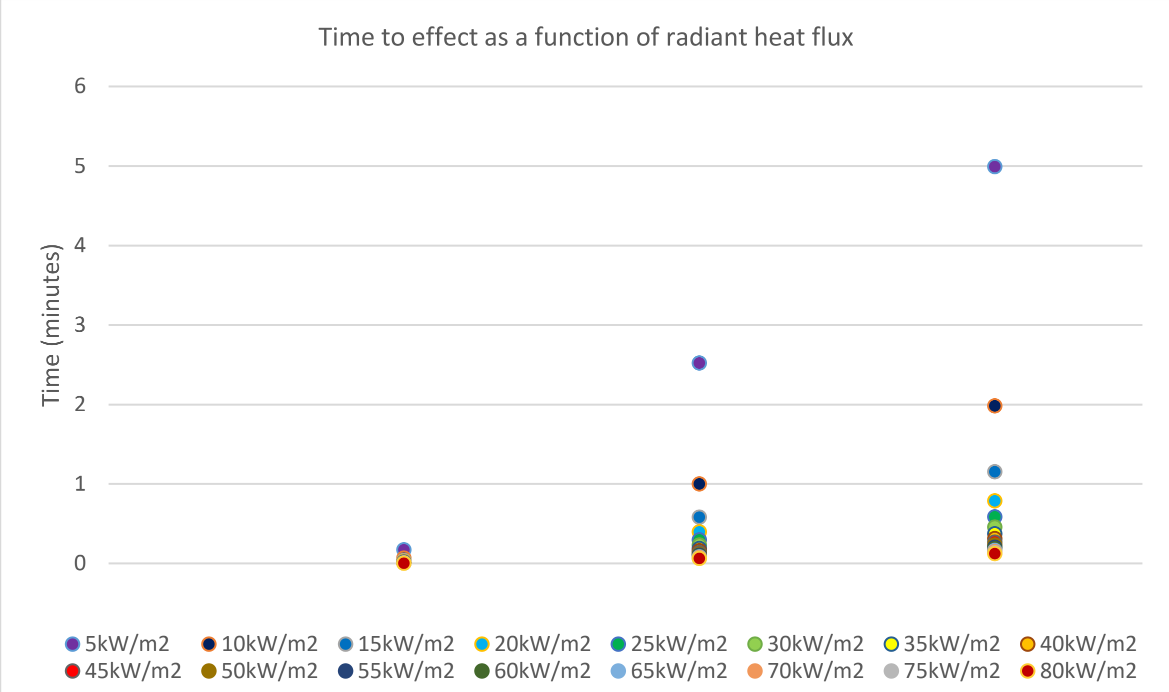


Figure 5.1: Time to effect as a function of thermal radiation

5.3 Radiant heat flux suppression and tenability thresholds

Penney et al. (2019) reported that when setting firefighter tenability thresholds, the worse cast credible scenario should be adopted. This is defined as firefighters in personal protective clothing (PPC) suitable for wildland fire suppression are exposed to radiant heat effects of a rapidly advancing flame edge that is part of a continuous landscape scale wildfire flank or head. This is a deliberate measure to account for burnover situations in appliances are disabled and firefighters attempt to flee by foot. In these situations sheltering behind appliances and other small structures will provide little if any shielding from radiant heat flux (Penney & Stevenson, 2019). Whilst the literature identifies several potential tenable limits as previously discussed, it is recommended the AFAC (2004) "Hazardous Condition" limit of 3 kWm^{-2} is adopted as the threshold for suppression operations involving personnel (the "Suppression Threshold"). This is less than both the "Extreme" limit of 4 kWm^{-2} (AFAC, 2004) and the acceptable 5 kWm^{-2} exposure in normal clothing reported by Raj (2008) which were considered to provide an insufficient margin for error to firefighters to retreat to a safe area as incapacitating injury may occur within 30 seconds depending on the individual, but greater than the limit adopted by Knight et al. (2001). As illustrated in Figure 5.1, the "Critical" limit of 10 kWm^{-2} [58] can result in incapacitating burns in less than one minute and is subsequently identified as the "Tenability Threshold". The "Suppression Threshold", being the radiant heat flux the firefighters in PPC can withstand whilst being able to undertake suppression activities is inherently lower than the "Tenability Threshold", being the radiant heat flux those same firefighters could physically survive. Whilst different PPC affords firefighters various levels of protection however exposed skin and respiratory tracts (in the absence of closed circuit breathing apparatus) remain vulnerable. As a result the thresholds reported by Penney et al. (2019) incorporate an inherent safety factor where structural firefighting PPE is worn.

Illustrated in Table 5.5, even in the mildest of fuel loads and fire weather conditions, when attempting to suppress a fully developed forest head fire in continuous fuel structures, firefighters will need to remain at least 20 m from the head fire (Penney et al., 2019). At understory fuel loads of 5 t/ha and assuming no shielding, the Suppression Threshold is exceeded even at an FDI of 10 until 20 m separation from the head fire is achieved, whilst tenability limits are exceeded for the first 6 m from the head fire. The required separation for the Suppression Threshold increases with FDI, with 28 m separation necessary to reach suitable conditions once an FDI of 40 is reached. Conditions supportive of suppression efforts are not experienced within 30 m of the head fire at or above an FDI of 50. As illustrated in Figures 5.2 and 5.3, representative of typical Woodland and Forest fuel loads [28], conditions worsen as fuel load increases. For typical Woodlands fuel loads, depending on FDI, radiant heat flux falls below the Tenability Threshold at 15 m-35 m whilst 35 m-80 m separation is required for conditions to be conducive to safe suppression efforts. These distances increase to 20 m to 50 m and 45 m to >100 m respectively for typical Forest fuel loads. None of the scenarios analysed resulted in conditions that would facilitate suppression efforts on the head fire within 10 m of the flame edge, being the typical maximum separation from the flaming zone for firefighters to effectively apply suppressants from hand held attack lines or machine monitors.

Table 5.5: Separation (distance between firefighters and flaming zone) required for suppression and tenability thresholds

Separation (m) required for suppression and tenability thresholds (based on 5 m increment data)											
Surface Fuel (t/ha)		**FDI 10**	**FDI 20**	**FDI 30**	**FDI 40**	**FDI 50**	**FDI 60**	**FDI 70**	**FDI 80**	**FDI 90**	**FDI 100**
w5	Tenability	10	10	10	10	15	15	15	15	15	20
	Suppression	20	25	25	30	35	35	35	40	40	45
w10	Tenability	10	15	15	15	20	20	25	25	25	30
	Suppression	30	35	40	45	45	50	55	60	60	65
w15	Tenability	15	15	20	20	25	30	30	30	35	35
	Suppression	35	40	50	55	60	65	70	70	75	80
w20	Tenability	15	20	25	25	30	35	35	40	40	45
	Suppression	40	50	55	65	70	75	80	85	90	90
w25	Tenability	20	25	30	30	35	40	45	45	50	50
	Suppression	45	55	65	70	75	85	90	95	100	>100
w30	Tenability	20	25	30	35	40	45	50	50	55	60
	Suppression	50	60	70	80	85	90	95	>100	>100	>100

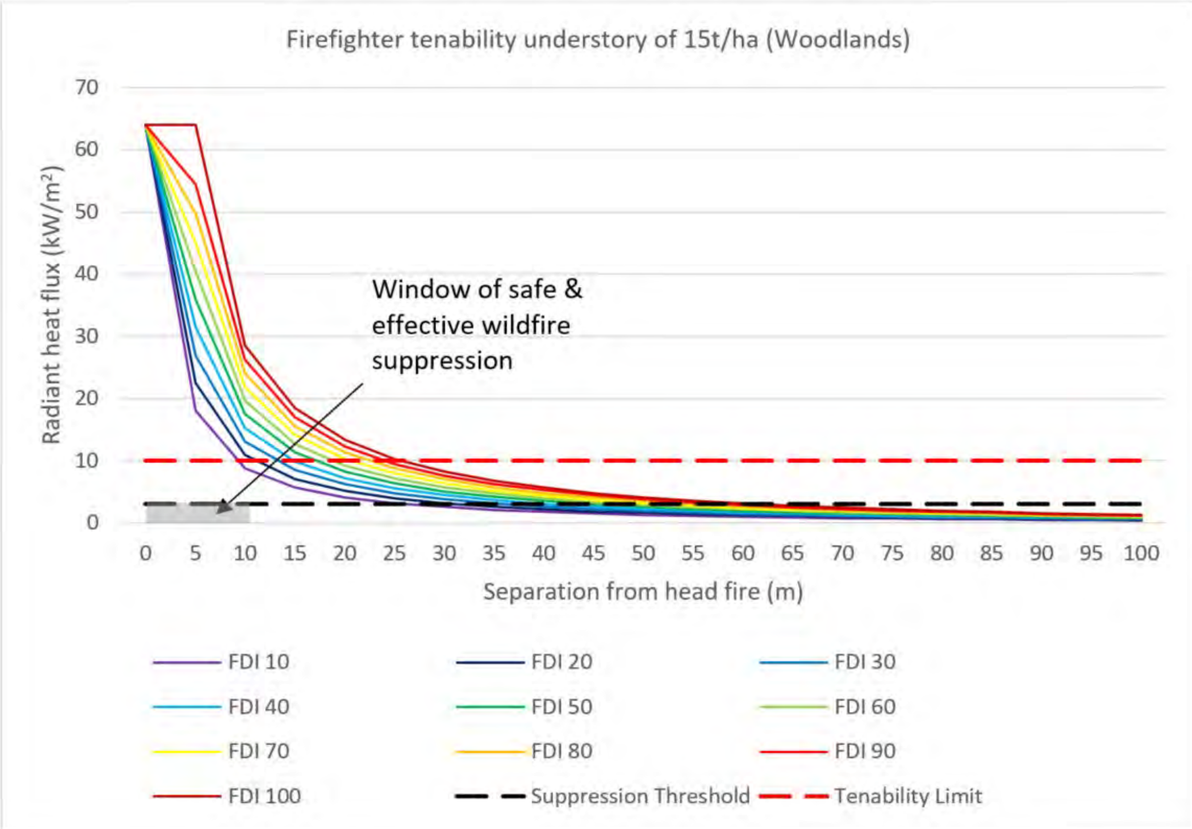


Figure 5.2: Firefighter tenability and suppression thresholds – the relationship between radiant heat flux, separation distance from the head fire and FDI in Woodlands fuel structures

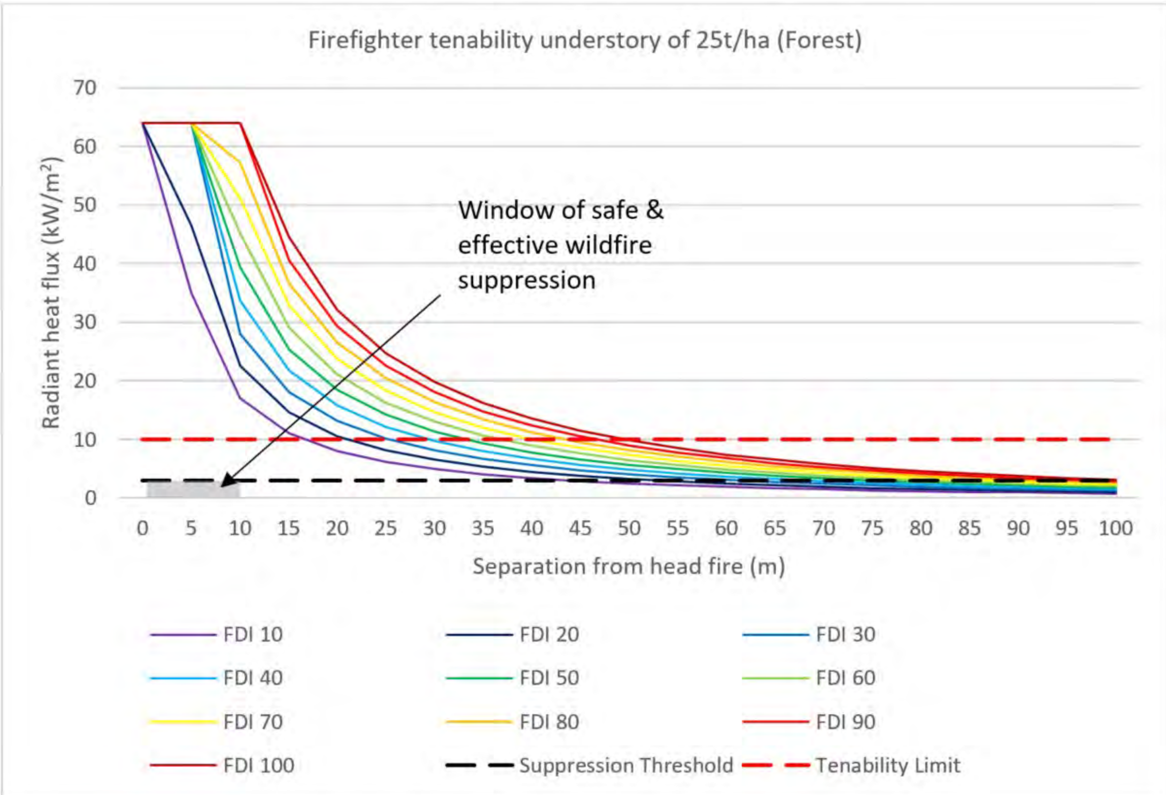


Figure 5.3: Firefighter tenability and suppression thresholds – the relationship between radiant heat flux, separation distance from the head fire and FDI in Forest fuel structures

Applying Purser' equation [56] and assuming 10 m separation from the head fire, the reality of the environmental conditions faced by firefighters becomes evident across understory fuel loads and FDI (Table 5.6). In the mildest of conditions, the time taken for pain tolerance thresholds to be reached and for first degree burns to occur is 8 seconds. In foreseeable circumstances, such as an FDI of 60 and understory fuel loads of 25 t/ha, this time is reduced to less than a second. In comparison, the time taken for severe incapacitation to occur in the mildest conditions at 10 m separation from the head fire is approximately 120 seconds, whilst at an FDI of 60 and understory fuel load of 25 t/ha this drops to approximately 10 seconds. At 10 m separation and at the lowest FDI and fuel load, fatal exposure limits are also rapidly reached, occurring in under 233 seconds. At understory fuel loads of 25t/ha and an FDI 60 fatal exposure will occur in less than 17 seconds (Table 5.6).

The time frame for incapacitating burns to occur is a critical factor when identifying safe zones for firefighter retreat and for assessing the appropriate wildfire suppression strategies and tactics. When interpreting the results of this study, it is suggested that once incapacitation occurs a firefighter will likely be imminently exposed to fatal levels of radiant heat and the shorter time frame should be applied. It is also important to consider the shielding effects of intervening unburnt vegetation may provide firefighters a false sense of fire intensity until the flames engulf the vegetation in front of them. Firefighters surprised by the rapid emergence of landscape scale wildfire from behind thick vegetation could be rapidly incapacitated and may have insufficient time to retreat to vehicles and activate protective systems such as sprinklers and radiation shields fitted to the vehicles. Even if protective systems are activated, the flow rates required to extinguish or substantially lessen fire impact is likely to exceed the capacity of the protective systems (Penney et al., 2019b; Penney et al. 2020b) which suggests fatal burnovers may still occur.

Table 5.6: Time to pain, incapacitation and fatal exposure from radiation at 10m separation from the head fire

Time (seconds) taken to tolerance limit / pain / first degree burn at 10m separation										
w/FDI	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
w5	8.0	6.4	5.3	4.5	3.9	3.4	3.0	2.7	2.4	2.2
w10	4.8	3.6	2.8	2.3	1.9	1.7	1.4	1.3	1.1	1.0
w15	3.4	2.4	1.9	1.5	1.2	1.0	0.9	0.8	0.7	0.6
w20	2.5	1.8	1.3	1.1	0.9	0.7	0.6	0.5	0.5	0.4
w25	2.0	1.4	1.0	0.8	0.7	0.5	0.5	0.4	0.3	0.3
w30	1.6	1.1	0.8	0.6	0.5	0.4	0.3	0.3	0.3	0.3
Time (seconds) taken to severe incapacitation and second degree burns at 10m separation										
w/FDI	10	20	30	40	50	60	70	80	90	100
w5	117.5	94.4	78.2	66.3	57.3	50.2	44.5	39.8	35.9	32.7
w10	71.4	53.2	41.8	34.1	28.5	24.4	21.2	18.6	16.6	14.9
w15	49.7	35.7	27.3	21.9	18.0	15.2	13.1	11.4	10.1	9.0
w20	37.3	26.2	19.7	15.6	12.8	10.7	9.1	7.9	6.9	6.1
w25	29.5	20.3	15.2	11.9	9.6	8.0	6.8	5.9	5.0	5.0
w30	24.1	16.4	12.1	9.4	7.6	6.3	5.0	5.0	5.0	5.0
Time (seconds) taken to fatal exposure with third degree burns at 10m separation										
w/FDI	10	20	30	40	50	60	70	80	90	100
w5	232.8	187.0	155.0	131.4	113.4	99.4	88.1	78.9	71.2	64.7
w10	141.4	105.5	82.9	67.6	56.6	48.3	42.0	36.9	32.8	29.4
w15	98.4	70.6	54.1	43.3	35.7	30.2	25.9	22.6	19.9	17.8
w20	74.0	51.8	39.1	30.9	25.3	21.2	18.1	15.6	13.7	12.1

w25	58.4	40.3	30.0	23.5	19.1	15.9	13.5	11.6	10.0	10.0
w30	47.8	32.5	24.0	18.7	15.1	12.5	10.0	10.0	10.0	10.0

As discussed in Chapter 3, emissivity will vary depending on the depth of the active fire front. Table 5.7 illustrates the effect of emissivity on the Tenability and Suppression thresholds. For Woodlands fuels, the Tenability Threshold is not achieved until a minimum 25 m separation from the head fire flames is reached whilst the Suppression Threshold is not achieved until a minimum 60 m separation is reached. For Forest structures, these distances increase to 40 m and 80 m respectively. These results suggest suppression efforts will be ineffective against siege head fires where the flame emissivity exceeds 0.6, representative of optically thick flames in head fires with an active flame depth of more than 1 m to 1.5 m (Boulet et al., 2009; SAI Global, 2019; Poon, 2003; Rossi et al., 2011).

Table 5.7: Separation required from head fire line for suppression and tenability thresholds – sensitivity to emissivity

Separation (m) required for suppression and tenability thresholds (5m increment data)									
Surface Fuel (t/ha)		**ε 0.6**	**ε 0.65**	**ε 0.7**	**ε 0.75**	**ε 0.8**	**ε 0.85**	**ε 0.9**	**ε 0.95**
w15	Tenability	25	30	30	30	35	35	35	35
	Suppression	60	65	65	70	70	75	75	80
w25	Tenability	40	40	40	45	45	50	50	50
	Suppression	80	85	85	90	95	95	100	>100

As illustrated in Table 5.8, as the FDI and understory fuel loads increase, slope has a greater effect on the separation distance required to achieve tenable and operational conditions. In all scenarios presented, increased positive slope and associated increase in fire behaviour decreases tenability and suppression potential compared to equivalent siege wildfire burning over flat terrain.

Table 5.8: Separation required from head fire line for suppression and tenability thresholds – sensitivity to slope

Separation (m) required for suppression and tenability thresholds (5m increment data)						
FDI		**0° Slope**	**5° Slope**	**10° Slope**	**15° Slope**	**20° Slope**
10	Tenability	20	20	25	25	30
	Suppression	45	50	55	60	65
20	Tenability	25	25	30	35	45
	Suppression	55	60	70	80	85
30	Tenability	30	30	40	45	55
	Suppression	65	70	80	95	>100
40	Tenability	35	40	50	60	70
	Suppression	75	80	90	>100	>100
50	Tenability	35	40	50	60	70
	Suppression	75	90	100	>100	>100
60	Tenability	40	45	55	65	80
	Suppression	85	95	>100	>100	>100
70	Tenability	45	50	60	70	85
	Suppression	90	100	>100	>100	>100

80	Tenability	45	55	65	75	90
	Suppression	95	>100	>100	>100	>100
90	Tenability	50	60	70	80	100
	Suppression	100	>100	>100	>100	>100
100	Tenability	50	60	75	85	>100
	Suppression	>100	>100	>100	>100	>100

5.4 Implications for frontline firefighters, fire behaviour specialists and IMT's

It is concerning that existing operational wildfire suppression thresholds do not systematically or quantifiably take account of wildfire behaviour (*RoS, I* and L_F) combined with the associated potential radiant heat flux received by firefighters attempting suppression activities in a landscape scale wildfire scenario. Current fire behaviour-linked suppression guidelines do not specifically address the tenability of environmental conditions in the proximity of the flaming zone where firefighters are often working to suppress the fire. Once tenability thresholds are considered it is evident that offensive, direct attack on the head of large wildfires is extremely hazardous to firefighters under all but the mildest of conditions.

Consideration of radiant heat flux also reveals how truly dangerous defensive rural urban interface firefighting is. Firefighters exposed to head fire fronts will potentially be subjected to levels of radiant heat that are capable of causing severe incapacitating burns in as little as five seconds in elevated fire weather conditions and higher fuel loads. Incident Controllers and fire crew leaders must therefore carefully consider whether properties and the occupants that shelter insider them are defendable or whether the credible risk to their own crews is too high. As discussed in Chapter 7, firefighters have a personal risk tolerance higher than that of their commanding officers, this means that frontline firefighters are more likely than their ranking officers to commit themselves to defending occupants from insuppressible wildfire fronts. This is potentially due to firefighters' own personal expectations that they should put themselves in personal danger to protect and rescue civilians, whist officers also consider the responsibility of keeping their crews safe and potential greater reaching consequences on the firefighter's family should they be severely injured or killed during wildfire suppression operations (Penney, 2019).

As opposed to being part of a RUI strategy, sheltering inside or behind firefighting appliances during the passage of a wildfire front should be considered an absolute last resort only. Instead, firefighters should seek refuge in suitable structures well before the expected impact of the wildfire front and emerge to salvage property where they are able to do so. Committing to a RUI defense by positioning firefighters in between a landscape scale forest wildfire front and private property or critical infrastructure with the expectation that suppression efforts will be either safe or successful is at best, reckless. Even the intervention of aerial firefighting suppression is unlikely to be sufficient to make this approach safe or effective. Given the extreme danger associated with RUI firefighting, it should be considered only as a contingency plan except in extreme circumstances where large populations of vulnerable communities including school, nursing homes and hospitals cannot be safely evacuated prior to the arrival of the wildfire front.

5.5 Implications for urban planners

Current wildfire planning guidelines and policy in Australia typically set deemed to satisfy 'acceptable'[4] threshold for development at $10kW^{-2}$ (NSWRFS, 2019; WAPC, 2015, 2017) for

[4] Planning approval will typically be provided.

vulnerable, critical or hazardous land use[5] and between 19kWm^{-2} to 29kWm^{-2} (NSWRFS, 2019; WAPC, 2015, 2017) for standard development such as subdivision. As detailed in this chapter, 10kWm^{-2} is considered critical conditions for firefighters in structural PPC and breathing apparatus, with retreat required in less than 60 seconds. At the same level, for a healthy person without protective equipment, incapacitating burns are predicted in approximately 60 seconds, with severe pain and first degree burns expected to occur after substantially less exposure. By adopting these thresholds, communities are effectively being designed to be undefendable by firefighters. At 29kWm^{-2}, firefighters in structural PPC and breathing apparatus are likely to face incapacitating burns in less than 30 seconds. This realisation is also significant for firefighters and IMT's who are considering firefighting defense of threatened communities who must consider whether they are expected to, or are indeed themselves expecting to do the impossible and un-survivable.

The solution from an urban planning perspective may rest in several approaches that require consideration on a case by case basis:

1. If development is required to be actively defendable by firefighters during the passage of a wildfire front, the maximum radiant heat impact at any point within the development needs to be within the window of safe and effective wildfire suppression. In turn, this arguably either requires extensive and permanent vegetation modification and fuel reduction around the development, or appropriate landscaping that forms part of a passive wildfire engineered design;
2. If development does not require active firefighter defense then the actual level of wildfire radiant heat impact can, in theory, be addressed by the application of enhanced wildfire resilient engineering construction such as that detailed in AS3959. In turn, this may also allow the fire truck related road access standards to such as those described in existing guidelines (NSWRFS, 2019; WAPC, 2015, 2017; GSA, 2012) to be revisited;
3. Development of an evidence based performance based wildfire urban planning code, similar to that of the Building Code of Australia and that adopted by Tasmania (2017). This would need to go beyond the existing and largely subjective planning guidelines and carry throughout the planning and building legislation and process, as is the case in Victoria (VSG, 2019);
4. Professionalisation and regulation of the wildfire engineering industry. Whilst the existing Bushfire Planning and Design (BPAD) accreditation scheme is the first step in this process, the technical knowledge and expertise required of wildfire engineers arguably requires greater accreditation and regulation.

[5] Vulnerable land use includes schools, nursing homes, tourism etc.

6. Critical water flow rates

6.1 Introduction

Globally various retardants are applied during wildfire suppression efforts, yet water remains the primary extinguishing agent (Hansen, 2012). Whilst prediction of water suppression requirements and its impacts on firefighting strategies and logistics within the urban environment has been the subject of many previous publications (Grimwood, 2017; Barnett, 2004), the same level of research has yet to be applied in the field of wildfire suppression (Hansen, 2012; Simpson et al., 2019). With fire services around the globe advocating offensive wildfire fighting strategies (DFES, 2012, 2014a; DBCA, 2014; Hirsch et al., 1996; Eurofire, 2012) heavily reliant the application of both water and other suppressants, it is suggested this knowledge gap and a lack of suitable data may be impeding firefighting efforts of significant wildfires, known as siege or campaign wildfires amongst fire services internationally.

Existing water extinguishment models reported by Hansen (2012) have been validated against field data from low intensity experimental burns with fire line intensities of less than 1 MWm^{-1} and flame lengths of less than 2.5 m. These experimental conditions are far from the conditions faced during siege wildfire events which can include fire line intensities of 88 MWm^{-1} and flame heights extending 10–20 m above the crowns of trees (Cruz et al, 2012). Further limiting the application of existing research to dynamic emergency conditions is the lack of consideration for the capabilities of firefighting vehicles and aircraft that have limited water capacities and may be away from the active fire front for considerable durations whilst they refill.

To work towards addressing the identified knowledge gap, this chapter applies a fire engineering analysis of water flow rates required for head fire suppression during wildfires. Guidance is provided in relation to critical water flow rates required to extinguish large wildfire across a wide range of forest fuel loads, fire weather and active fire front depths. The impacts of the results on current suppression strategies and logistics are discussed in order to facilitate enhanced effectiveness and safety of operational response to siege wildfire incidents.

6.2 Calculating critical flow rates

The prevention or extinguishment of fire through the application of water occurs by three methods (Hansen, 2012; Grimwood, 2017):

1. Water is applied to fuel surfaces not yet involved in fire, preventing pyrolysis and the production of combustion gases;
2. Water is applied directly into the flames, cooling the flame below the critical temperature; or
3. Water is applied directly to the burning fuel surface, cooling the fuel and resulting in a reduced pyrolysis rate and quenching of the flames.

When considering active suppression efforts during high intensity bushfires only surface cooling should be considered as evaporating water vapour is rapidly dispersed and will not noticeably affect the flame temperature (Hansen, 2012). As a result, by applying Fire Point Theory and accounting for external radiant and convective heat flux, the critical flow rate (*CF*) in $Lm^{-2}s^{-1}$ can be calculated for the wildfire scenarios using Equation (6.1). *CF* is the flow rate of water required to extinguish a burning surface, with an infinite period of time available (Särdqvist, 2002). As the wildfire length and depth of the active flame front changes over time and is influenced by many factors including but not limited to terrain, wind, fuel structure and fuel geometry (Cruz et al., 2015, Penney & Stevenson, 2019), the *CF* can only be calculated at a specific point in time. The limitations of fire ground suppression, including appliance or aircraft capacity and available must be considered and are addressed later in the chapter.

$$CF = \dot{m}''_{water,cr,0} + \frac{\dot{q}''_E}{\eta_{water} \times L_{v,water}} \quad (6.1)$$

where:

$\dot{m}''_{water,cr,0}$ is the critical water application rate assuming no external heat flux, identified as ≈0.0129 $Lm^{-2}s^{-1}$ (Hansen, 2012), η_{water} is the efficiency of water application, representing the portion of water leaving the firefighting branch which actually contributes to fire extinguishment, conservatively assumed to be 0.7 (Hansen, 2012), $L_{v,water}$ is the enthalpy change of water, identified as 2640 $kJkg^{-1}$, $\dot{q}''_E$ is external heat flux, calculated using Equation (6.2),

$$\dot{q}''_E = \left(\frac{0.27 \times I}{(2 \times L_f + D)} \times \tau\phi\right) + \left(h \times (T_g - T_{fuel})\right) \quad (6.2)$$

Where I is fire line intensity in kWm^{-1}, L_f is flame length in m, D is depth of the active flame in m, τ is atmospheric transmissivity, assumed to be 1 due to the proximity of the unburned fuel in respect to the flames, ϕ is view factor, assumed to be 1 due to the proximity of the unburned fuel in respect to the flames, h is the convective heat transfer coefficient set at 0.077 kW/m^2K assuming a forced convection and air velocity at 10 ms^{-1} (Hansen, 2012), T_g is gas temperature of the flame, assumed to be 1090 K, representative of siege wildfire conditions (Penney & Stevenson, 2019; SAI Global, 2018; Poon, 2003; Rossi et al., 2011; Wotton et al., 2011), T_{fuel} is the fuel temperature of the fuel, assumed to be 588 K, being the ignition surface temperature for pine-needle fuel beds (Hansen, 2012).

Penney et al., (2019b) completed analysis of *CF* using Equation (6.1) across variations of fuel load, *FDI* and active flame depth to simulate a large range of wildfire conditions and scenarios. Six variations of forest understory fuel loads at 5 tha^{-1} increments between 5–30 tha^{-1} with corresponding total fuel loads between 15–40 tha^{-1} (Note: the assumption that the canopy contributes 10 tha^{-1} reported in SAI Global (2018) is retained) were simulated, representing a broad spectrum of forest fuel loads (Penney et al., 2019a). Ten variations of *FDI* at increments of 10 between 10–100, identified as the 99.9th percentile of fire weather conditions across Australia (Dowdy et al., 2012) were incorporated into the simulations. Nine variants of active flame depth (*D*) were also modelled at 1m increments between 2–10 m, representative of the optically thick head fire flame experienced during severe wildfire events (Penney & Stevenson, 2019; SAI Global, 2018; Poon, 2003; Rossi et al., 2011). In total, 540 wildfire scenarios were analysed. Appliance and aircraft water suppression capabilities were derived from technical literature (DFES 2013, 2014c, 2014d, 2016c, 2017) and discussions with technical experts (Parks, 2018). These capabilities are summarised in Table 6.1, with maximum potential flow rates, representing best case scenario, selected for the study. Deterministic analysis of calculated required *CF* to available flow rates was completed. For the purposes of deterministic analysis, it was assumed that appliances and aircraft can apply a uniform pattern of water to a 10 m length of active head fire front. These values can be easily converted should different active head fire lengths be required.

Table 6.1. Appliance and aircraft water suppression capabilities.

Type	Name	Water Capacity (L)	Flow Rate (Ls^{-1})
Aircraft-Rotary [1]	Dauphin Type 2	1000–1200	~333–400
Aircraft-Rotary [2]	Erikson S64E Aircrane	7560	~1512
Aircraft-Fixed wing [3]	AirTractor AT802F	3150	~1050
Appliance 4WD [4]	Light Tanker	~500	2.5
Appliance 4WD [4,5]	Heavy Tanker	~3000	3.8–7.9

[1] Drop width ~6 m, drop length ~15 m, full deployment in 3 s; [2] Drop width >8 m, drop length ~30 m, full deployment in 5 s; [3] Drop width ~6 m, drop length ~30 m, full deployment in 3 s; [4] Branch jet spray width ~1 m; [5] 700 L water required for appliance sprinkler protection which activates at 3 Ls^{-1} from each head.

6.3 Implications for wildfire suppression

As reported in Penney et al. (2019b), figure 6.1a–f illustrate critical flow (*CF*) rates per 10 m section of active head fire range from 0.94 Ls^{-1} in a 2 m deep active flame front through understorey fuels of 5 tha^{-1} at a *FDI* of 10 through to 21.10 Ls^{-1} in a 10 m deep active flame front through understorey fuels of 30 tha^{-1} at an *FDI* of 100. As previously described, this study assumes appliances and aircraft can apply a uniform pattern of water to a 10 m length of active head fire front and the results are presented on this basis.

Deterministic analysis of required *CF* to available *CF* identifies that a single Light Tanker cannot apply the required flow rate to 10 m section of wildfire front once an active flame depth of 6 m is attained, irrespective of fuel loads and *FDI*. Prior to the active head fire attaining a 6 m depth, in limited Light Tankers can engage in head fire suppression for a duration of 200 s in limited circumstances. Larger appliances such as the Heavy Tanker have a maximum flow rate of 7.9 Ls^{-1} and can supply enough water to extinguish at 10 m section of active wildfire front at all *FDI*'s in understorey fuel loads of 5 tha^{-1}. As conditions worsen, the capacity of a single Heavy Tanker to extinguish a 10 m section of active head fire rapidly diminishes. With significantly higher capabilities, all aircraft assessed are found to provide enough flow rates to extinguish a 10 m section of active head fire, regardless of flame depth, *FDI* or understorey fuel load.

The results demonstrate small firefighting appliances such as light tankers cannot deliver sufficient water flow rates to extinguish wildfire, regardless of *FDI*, once the active flame depth reaches 2.5 m in typical Woodland fuels of w = 15 tha^{-1} or 3 m in typical Forest fuels of w = 25 tha^{-1} [22,26]. In larger appliances with higher delivery capacities, the required *CF* cannot be achieved once the active flame depth reaches approximately 5 m with an *FDI* of 40. All aircraft reviewed are capable of achieving the required *CF*. However, they remain restricted by the inherent limitations of availability, turn around, restricted ability to operate at night where they may be most effective due to reduced fire behaviour, and the increasing presence of privately operated drones over fire grounds which requires the cessation of aerial suppression on safety grounds (Parks, 2018).

In translating the theory to practical application during a wildfire emergency, Figure 6.1a–f may assist Incident Controllers quickly determine the suitability of appliance-based suppression strategies where fuel load, *FDI* and active flame depth are known. In jurisdictions that do not rely on *FDI* or surface fuel loads, it is suggested Table 6.2 (with an appropriate safety factor) may be suitable to provide a deterministic assessment required *CF* to available *CF*, and therefore determine whether ground suppression efforts are potentially suitable. Used in conjunction with existing suppression thresholds and newer thresholds that consider radiant heat flux and firefighter tenability (Penney et al. 2019 – tenability), these results will assist provide greater justification for the selection of appropriate wildfire suppression strategies.

The results also demonstrate the importance of active flame depth when analysing wildfire severity and the suitability of suppression strategies. In addition to having a significant impact on *CF* as shown in this study, the depth of the active flame front has significant effects on emissivity and subsequently, radiant heat flux. It is therefore proposed that active flame depth may be a better measure of wildfire intensity than the traditional measures of *RoS*, intensity or L_f utilised internationally. Where active flame depths remain less than 3 m, traditional suppression strategies may remain suitable as long as firefighter tenability is considered and due care is exercised.

In order to meet the required *CF* to extinguish a wildfire in accordance with the assumptions applied in this research, firefighters must be able to have appliances consistently attacking each 10m section of wildfire. Whilst it is not in any way suggested incident logistics is as simplistic as providing a single suitable ground appliance for every 10 m section of fire front, it may be applied for determining initial resourcing turnout to developing wildfires that have the potential to grow into siege wildfire dimensions.

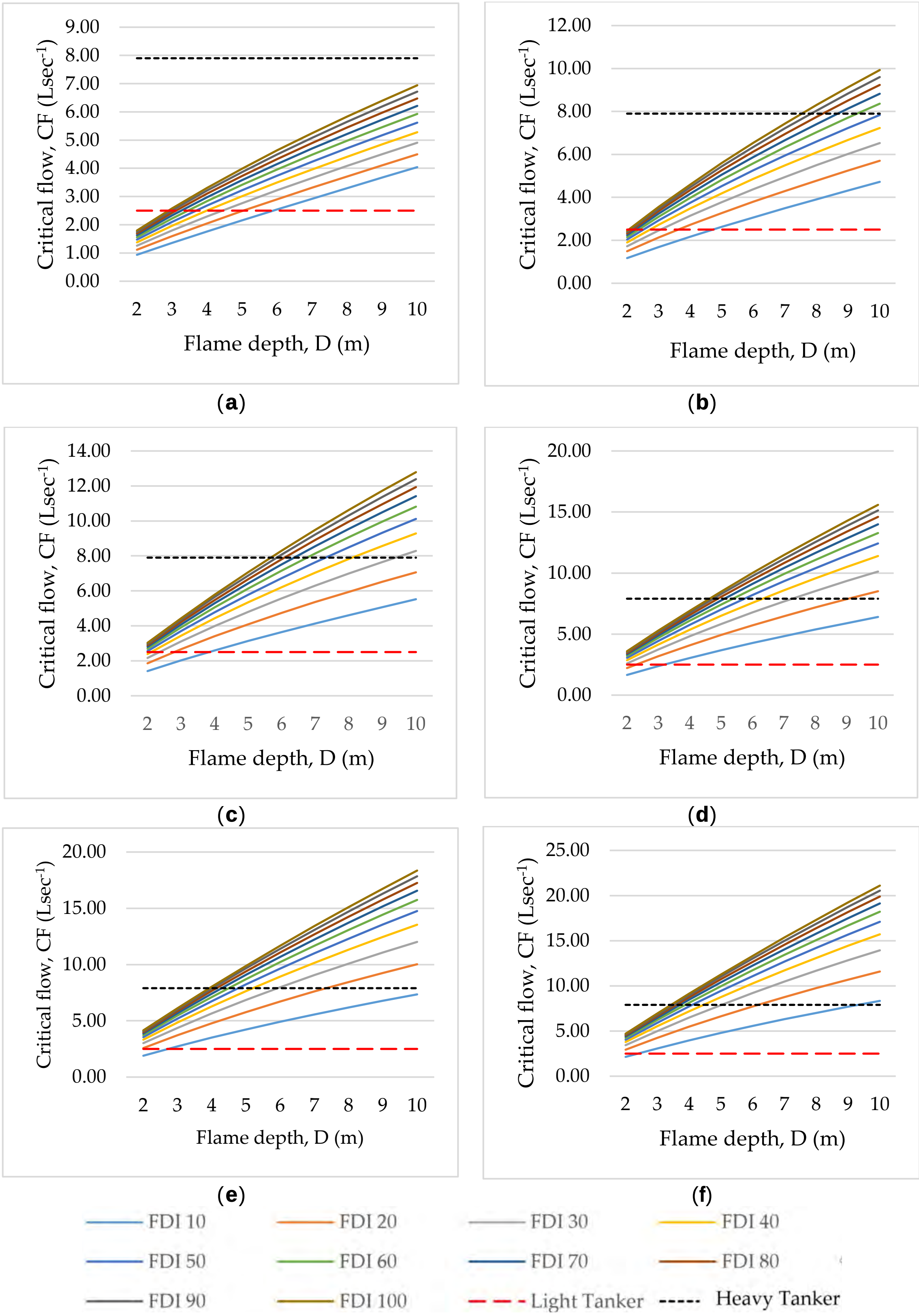


Figure 6.1. Critical flow, (*CF*) per 10 m length of head fire across the selected range of *FDI*'s for Forest with surface fuel loads (*w*) of: (**a**) 5 tha^{-1}; (**b**) 10 tha^{-1}; (**c**) 15 tha^{-1}; (**d**) 20 tha^{-1}; (**e**) 25 tha^{-1}; (**f**) 30 tha^{-1}.

CF as functions of (*RoS*), intensity (*I*) and flame length (L_f) are illustrated in Figures 6.2–6.4. This also enabled *CF* as a function of active flame depth (CF_D) to be expressed as equations of the corresponding the fire behaviour, summarised in Table 6.2. The advantages of this approach are:

(1) The analysis incorporates the full spectrum of fire weather conditions and understorey fuel loads. Therefore the *CF* can be rapidly estimated by Incident Controllers without requiring current or predicted fire weather conditions (an essential component for calculating *FDI*) or understorey fuel loads (*w*) which may vary across the landscape.; and
(2) It provides Incident Controllers both visual and mathematical tools to assess the potential suitability of suppression strategies.

The limitation of this approach is that as wildfire behaviour intensifies the power functions appeared to under-predict *CF* at active flame depths greater than 6m compared to using Fire Point Theory and Equation (6.1) directly. This may be explained however as the equations are trend lines of the data, which are influenced by the somewhat clustered data at lower levels of wildfire behaviour.

Table 6.2. CF_d as functions of Rate of Spread, intensity and flame length.

Rate of Spread, *RoS* (kmh^{-1})	
Active Flame Depth (m)	**Function**
2	$CF_2 = 2.72\ RoS^{0.42}$
3	$CF_3 = 3.97\ RoS^{0.43}$
4	$CF_4 = 5.12\ RoS^{0.44}$
5	$CF_5 = 6.24\ RoS^{0.44}$
6	$CF_6 = 7.23\ RoS^{0.45}$
7	$CF_7 = 8.30\ RoS^{0.45}$
8	$CF_8 = 9.23\ RoS^{0.45}$
9	$CF_9 = 10.20\ RoS^{0.45}$
10	$CF_{10} = 11.11\ RoS^{0.46}$
Intensity, *I* (kWm^{-1})	
Active Flame Depth (m)	**Function**
2	$CF_2 = 0.11(I)^{0.33}$
3	$CF_3 = 0.15(I)^{0.34}$
4	$CF_4 = 0.12(I)^{0.35}$
5	$CF_5 = 0.22(I)^{0.35}$
6	$CF_6 = 0.24(I)^{0.36}$
7	$CF_7 = 0.27(I)^{0.36}$
8	$CF_8 = 0.30(I)^{0.36}$
9	$CF_9 = 0.32(I)^{0.36}$
10	$CF_{10} = 0.35(I)^{0.36}$
Flame Length, L_f (m)	
Active Flame Depth (m)	**Function**
2	$CF_2 = 0.64\ L_f^{0.62}$
3	$CF_3 = 0.90\ L_f^{0.63}$
4	$CF_4 = 1.14\ L_f^{0.65}$
5	$CF_5 = 1.35\ L_f^{0.65}$
6	$CF_6 = 1.56\ L_f^{0.66}$
7	$CF_7 = 1.74\ L_f^{0.67}$
8	$CF_8 = 1.93\ L_f^{0.67}$
9	$CF_9 = 2.11\ L_f^{0.68}$
10	$CF_{10} = 2.28\ L_f^{0.68}$

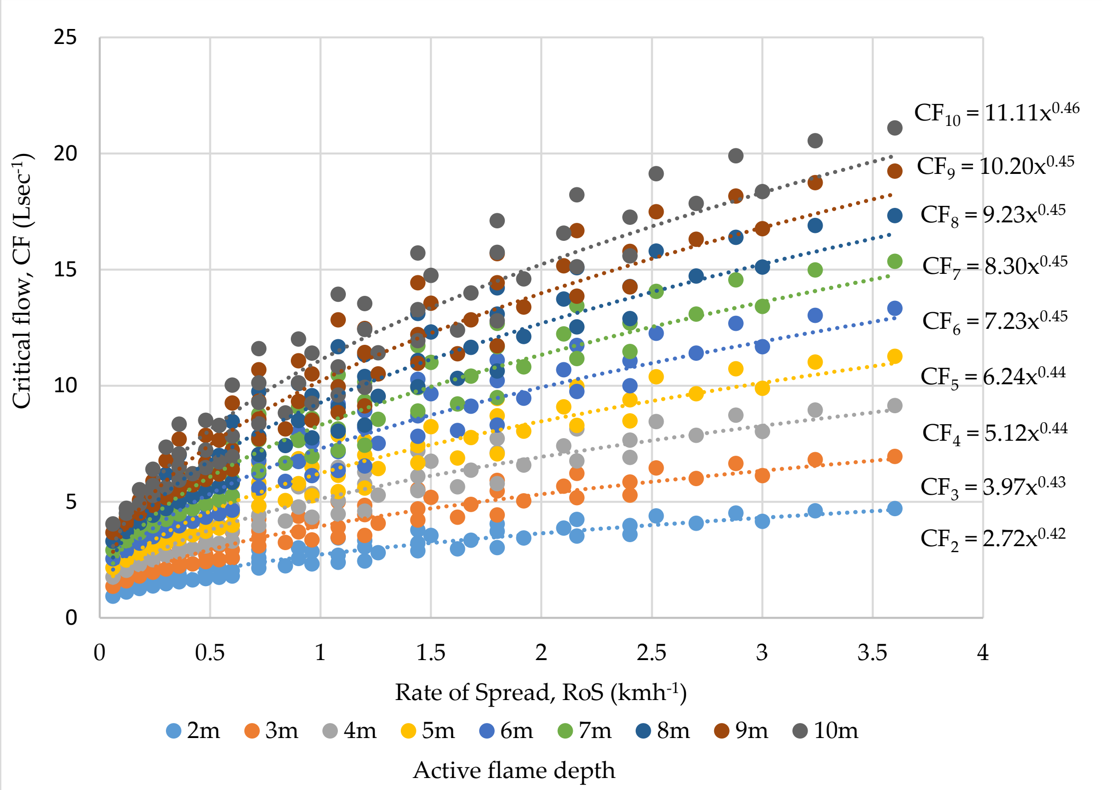


Figure 6.2. Critical flow rates at various active flame depths, *CF*D (Ls⁻¹), as a function of head fire Rate of Spread, *RoS* (kmh⁻¹).

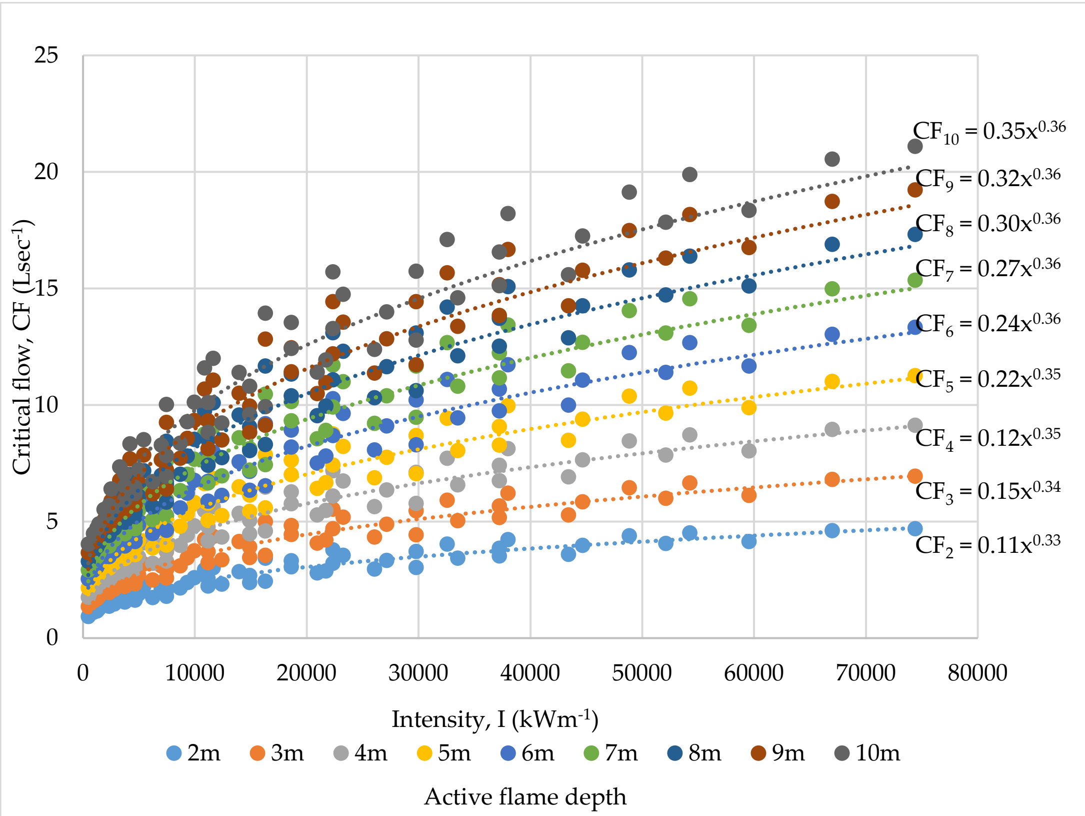


Figure 6.3. Critical flow rates at various active flame depths, *CF*D (Ls⁻¹), as a function of intensity, *I* (kWm⁻¹).

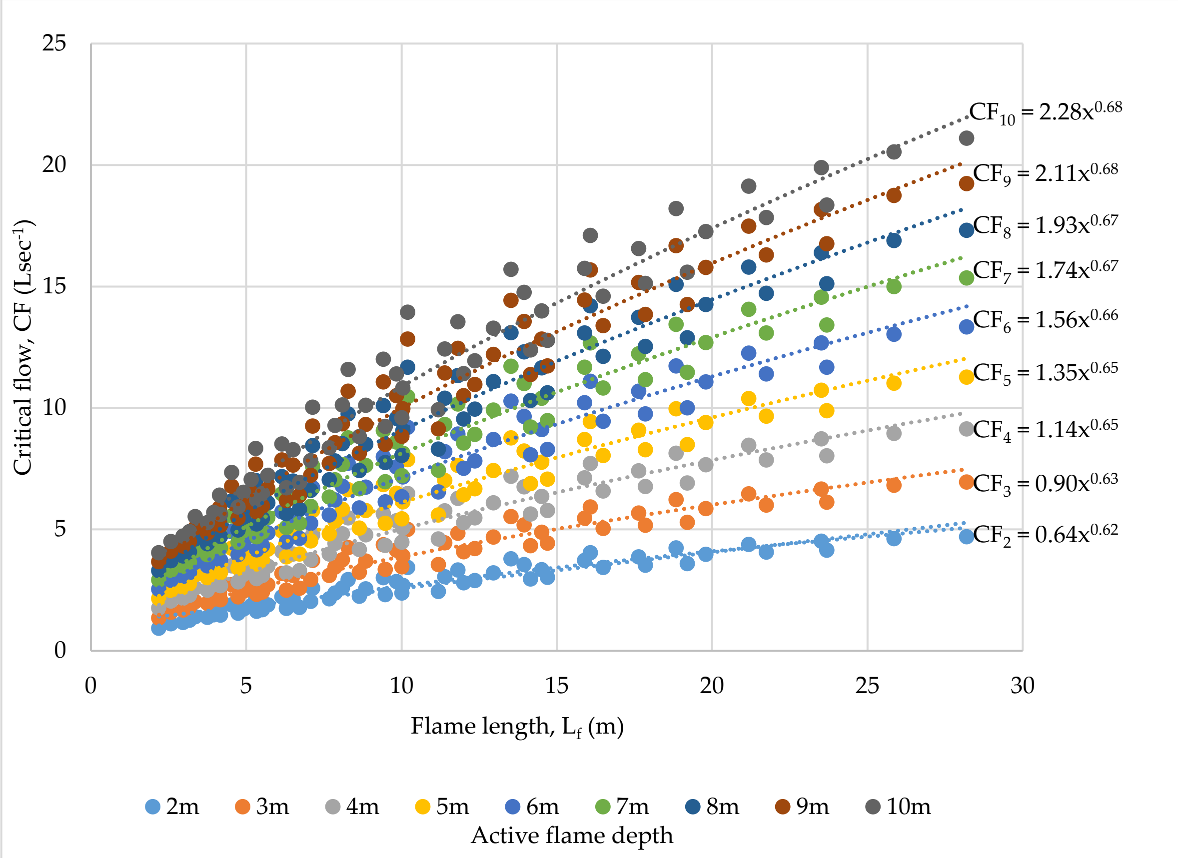


Figure 6.4. Critical flow rates at various active flame depths, CF_D (Ls⁻¹), as a function of flame length, L_f (m)

Sensitivity to variations in the base inputs was conducted to evaluate how they influence *CF*. To complete the sensitivity analysis the following inputs were assumed: *FDI* = 80, *w* = 25 tha⁻¹, *W* = 35 tha⁻¹, *D* = 4 m, L_f = 19.8 m, *I* = 43,000 kWm⁻¹, *h* = 0.077 kW/m²K, T_g = 1090 K, T_{fuel} = 588 K, η_{water} = 0.7, $L_{v,water}$ = 2640 kJkg⁻¹, $\dot{m}''_{water,cr,0} \approx$ 0.0129 Lgm⁻²s⁻¹, τ = 0.8, ϕ = 0.8. As the effects of *FDI*, fuel load (and thereby L_f and *I* due to the mathematical relationships identified in Chapter 2) and flame depth are investigated throughout the study, sensitivity to the remaining inputs was assessed by decreasing and increasing the subject base input by 20%, all other inputs as assumed. The results are summarised in Table 6.3. With the exception of τ and ϕ, there was little if any change to *CF* as a result of a 20% to the base input. It is worth noting that in the context of wildfire where the fuel and the flame are in close proximity, both τ and ϕ should be set at 1 (Hansen, 2012).

Table 6.3. Sensitivity analysis.

Input	% Change to Base Input	% Change to Critical Flow (*CF*)
h	±20%	±1%
T_g	±20%	±2%
T_{fuel}	±20%	±1%
η_{water}	±20%	±1%
$L_{v,water}$	±20%	±1%
$\dot{m}''_{water,cr,0}$	±20%	±0%
τ	±20%	±24%
ϕ	±20%	±24%

6.4 Implications for frontline firefighters, fire behaviour specialists and IMT's

Put simply, the effectiveness of suppression by applying water to landscape scale forest and woodlands fires drops significantly as the active flame depth of the head fire increases. By understanding this concept, as well as how vegetation structure influences fire behaviour and fire front geometry, IMT's and firefighters can more realistically assess the potential for suppression success. At the same time, if fire behaviour specialists understand these relationships, they are better prepared to describe the fire behaviour in terms that are meaningful for the IMT and frontline firefighters. The use of guiding analysis such as that presented in this and other chapters may assist IMT's determine that suppression strategies are unlikely to succeed and resources would be better spent in evacuations or allowing crews more time to prepare to defend vulnerable assets.

This chapter provides guidance for Incident Controllers in relation to CF required to extinguish large wildfire across a wide range of forest fuel loads, fire weather and active fire front depths. Perhaps the greatest ramification of the results is the need to reexamine the use of aerial and appliance suppression in high fire intensity conditions. The use of ground based appliances remains vital in suppression of wildfires. However, in both forest and woodland fuel structures, and when faced with siege wildfire behavior with active flame depths across the head fire greater than 3 m, increased reliance on aerial suppression may be required to deliver the CF necessary to impact the head fire and have any effect on the forward Rate of Spread. In reality this will require greater investment to ensure that fuel loads adjacent or near congregations of high value assets are prevented from reaching the thresholds that support this level of fire intensity. Fire services investment in improved technologies that supports night time aerial suppression operations during periods of reduced fire behaviour is also suggested. Where aerial resourcing is limited, strategies such as guiding head fire direction and pre-emptive line building adjacent to existing fuel breaks such as major roads, supported by appliance based suppression may provide enhanced outcomes compared to reliance on head fire suppression alone.

7. Vehicle protection systems during entrapment and burnover

7.1 Introduction

During wildfire operations the use of inappropriate suppression tactics [Penney et al, 2019a] or sudden changes in wind direction (Lahaye et al., 2018) can result in firefighters being directly caught by wildfire smoke and fire, a situation known as entrapment. The occurrence of wildfire flame directly impacting firefighters is known as burnover. The threat posed from entrapment and burnover is significant and has resulted in 411 firefighter deaths in the USA from 1910 to 2006 (Mangan, 2007), 92 Australian firefighter deaths from 1901 to 2011 (Blanchi et al., 2014) and 165 Canadian firefighter deaths between 1941 and 2010 (Alexander & Buxton-Carr, 2011). In many cases multiple fatalities resulted from a single entrapment and burnover. The causes entrapment and burnover are well known (Wilson,1977), although more recent studies have increased this understanding by defining human factors and fire behaviour leading up to these events (Blanchi et al. 2012; Butler et al. 1998; Diakakis et al. 2016; Page & Butler, 2017; Lahaye et al., 2016, 2018; Viegas et al. 2009).

7.2 Vehicle Protection Systems

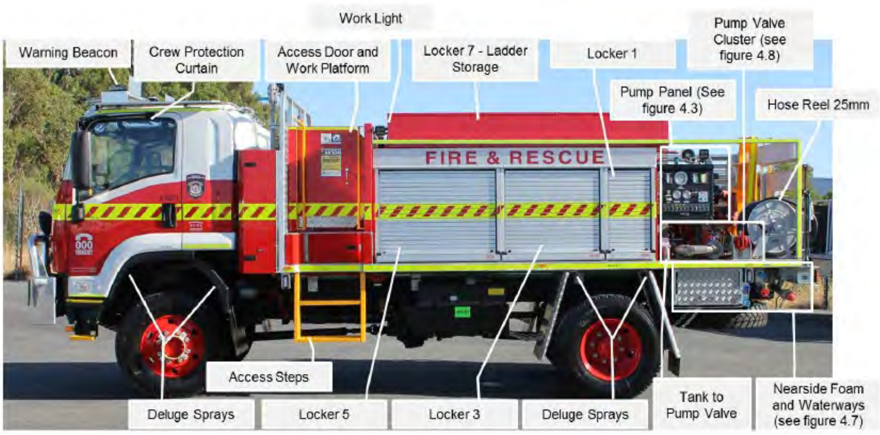
In an effort to improve firefighter safety and aiming to protect the integrity of firefighting vehicles, enabling escape and improving the tenability for entrapped occupants, Australian fire services have invested in vehicle protection systems (VPS).

Vehicle protection systems include (DFES, 2016a; IDES, 2014) (figure 2):

1. Installation of deluge sprinklers, drop down thermal shielding blankets and personal fire blankets;
2. Protect components essential to vehicle mobility against thermal damage, through shielding, relocation and lagging;
3. Protect components critical to firefighting against thermal damage, through shielding, relocation and lagging;
4. Ensuring the cabin is a suitable refuge and provides a continuous enclosure of non-combustible materials through:
    i. removal of wheel arches, mudguards, step shrouds, cabin body aesthetic panels, side mirror mounts, door handles, backing plates and underbody panels; or
    ii. Where this is not possible, making these products fire resistant;
5. Protection of windows that are not essential for vision including the replacement of rear and side rear windows with solid panels;
6. Adding infill panels between the cabin and the vehicle tray; and
7. Modifying the air-conditioning system to prevent smoke and heated gases entering the cabin.

(a)

(b)



(c)

Figure 7.1. Burnover protection systems (**a**) Drop down shielding blanket deployed (DFES, 2013c); (**b**) Firefighter under a personal fire blanket (DFES, 2013f); (**c**) Typical wildfire fighting appliance showing position of side deluge sprays (DFES, 2013a).

The vehicle protection system deluge sprays designed to (DFES, 2016b):

1. Prevent glass failure, i.e. to ensure integrity of the cabin;
2. Cool the cabin to reduce occupant heat exposure; and
3. Cool the tyres to reduce risk of ignition.

The deluge system is required to be activated from the cabin, operate for a minimum of 5 minutes from the time the 'crew protection water alert' sounds which occurs once water tank reserves reach 600L, and to have a nominal flow rate of 120Lmin^{-1} with a flow pressure of 3 bar (DFES, 2016a). An audible and visual warning device alerts crews once they have reached the deluge system reserve capacity, however the crew can continue to utilise this reserve without restriction. Not all appliances can be fitted with deluge systems. For instance Light Tankers, a small four wheel drive appliance with a 500L water tank, cannot be fitted with deluge systems due to insufficient water capacity to generate the required protection duration and existing vehicle weight restrictions (IDES, 2014; Knight et al, 2003). Note that existing design specifications do not consider water droplet size or their effect on thermal attenuation.

Limited field experimentation has been completed (Cruz et al., 2016) and the inherent danger of wildfire suppression during elevated fire weather conditions has prevented the potential effectiveness of vehicle protection systems being suitably quantified in full scale field experimentation. Addressing this gap is vital and forms a critical component of thorough fire engineering safety analysis [ICC et al., 2005; SFPE, 2007]. Current external vehicle protection systems utilised in Australian fire service vehicles incorporate drop down thermal shielding blankets and sprinkler deluge systems have been tested against fire line intensities of between 2500-10000kWm^{-1} and designed to withstand 7500kWm^{-1} (Nichols, Gould, Knight, Leonard, & Brown, 2005). In similar tests, Nichols et al. (2003) reported that cabin tenability was maintained when simulated fire line intensities of up to 12000kWm^{-1} were maintained for up to 14 seconds when water spray protection systems were used in conjunction with window radiation shields, whilst Sargeant et al. (2003, p7) reported that

"In general vehicle orientated front on remained tenable at radiation levels up to 30kWm^{-2}. while side on and rear facing vehicles lost integrity at around 10 to 15 kWm^{-2}"

By comparison forensic wildfire analysis(Cruz et al., 2012) and field experimentation (Cruz et al., 2011; Frankman et al., 2012) identified fire line intensities of up to 88MWm^{-1} and radiant heat fluxes in excess of 100kWm^{-2} can be experienced for longer durations during landscape scale wildfires, far exceeding the limits of crew protection systems (Nicholas et al., 2003).

The potential effectiveness of vehicle protection systems in providing an adequate level of fireifghter protection during burnover remains unquantified. Without validation firefighters may overestimate their personal safety during wildfire suppression based on the belief they will be adequately protected. To address this knowledge gap and provide further guidance the potential effectiveness of VPS in improving firefighter tenability during entrapment and burnover, Penney et al. (2020b) completed:

1. Systematic analysis of historical entrapments and burnover; and
2. Simulated wildfires encompassing the 99th percentile of weather conditions and fuel structures.

In order to verify the effectiveness of fire safety systems clear objectives and performance criteria must be defined (ICC et al., 2005; SFPE, 2007; Yung, 2008). Effectiveness is defined as the product of fire safety system efficacy and reliability (Thomas, 2002). The objective of vehicle protection systems is to increase the tenability of firefighters during vehicle entrapment and burnover. For the purposes of the study the performance criteria (PC) required to meet this objective were subsequently defined as:

PC1. VPS is determined to have worked effectively where fire line intensity (*I*) is less than 7500kWm^{-1} (the current rating of VPS);

PC2. VPS is determined to have worked effectively where fire line intensity (*I*) is less than 10000kWm^{-1} (the maximum intensity VPS have been tested to);

PC3. VPS is determined to have worked effectively where fire line intensity (*I*) is less than 12000kWm^{-1} (maximum short duration intensity VPS can withstand);

PC4. VPS is determined to have worked effectively where fire line intensity (*I*) is less than the mean historical upper reported / calculated intensity for all entrapments resulting in fatality or injury;

PC5. VPS is determined to have worked effectively where radiant heat flux (RHF) is less than 15kWm^{-2}, assuming vehicles are orientated side on or with the rear to the advancing headfire; and

PC6. VPS is determined to have worked effectively where radiant heat flux (RHF) is less than 30kWm^{-2}, assuming vehicles orientated front on to the advancing headfire.

7.3 Historical entrapment analysis

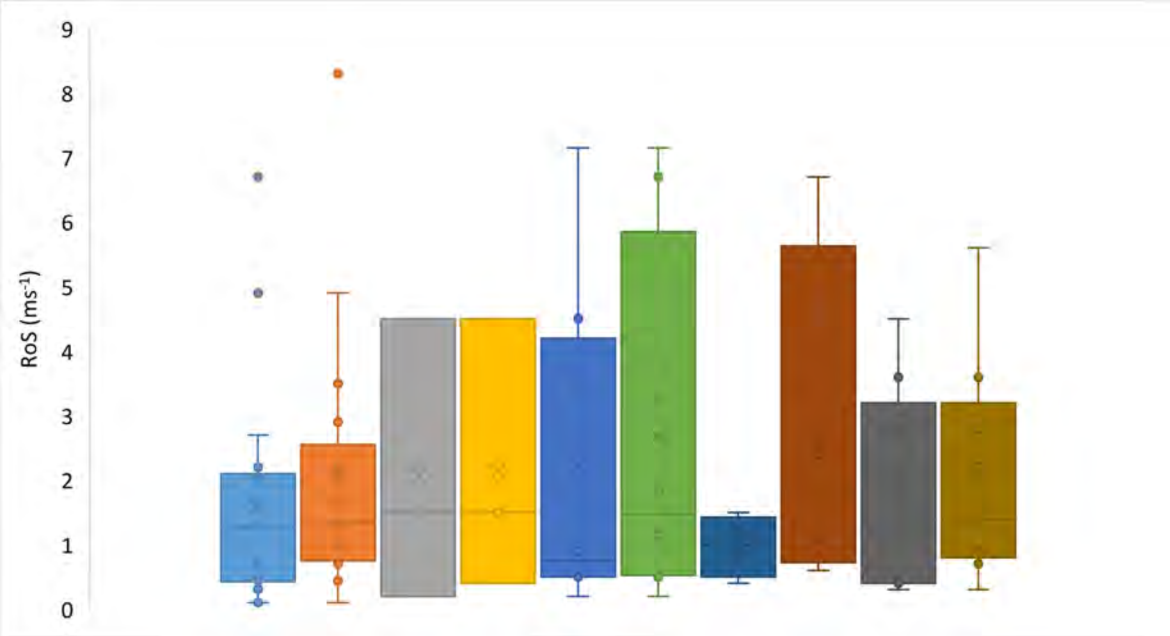
Of the 4856 reports initially reviewed in the study (Penney et al., 2020b), 4336 were excluded as they did not meet the initial inclusion criteria. Of the remaining 520 reports, 56 reports were excluded because they did not involve a fatality or injury; two reports were excluded because they detailed accidents unrelated to entrapment (one structure fire propane tank explosion and one ATV rollover); eight reports were excluded as they related to controlled burns; and 392 reports were excluded because they contained insufficient information to extract or calculate fire line intensity. A total of 62 reports were included in the final study, 42% (n=26) containing firefighter fatalities and 58% (n=36) reports containing firefighter injuries only.

By vegetation, forest fuel structures accounted for approximately 62% (n=16) of fatal entrapments, scrub 23% (n=6), shrub 7.5% (n=2) and grassland 7.5% (n=2). For entrapments involving injury only, forest accounted for approximately 25% (n=9) of incidents, woodlands 14% (n=5), scrub 11% (n=4), shrub 17% (n=6) and grassland 33% (n=12).

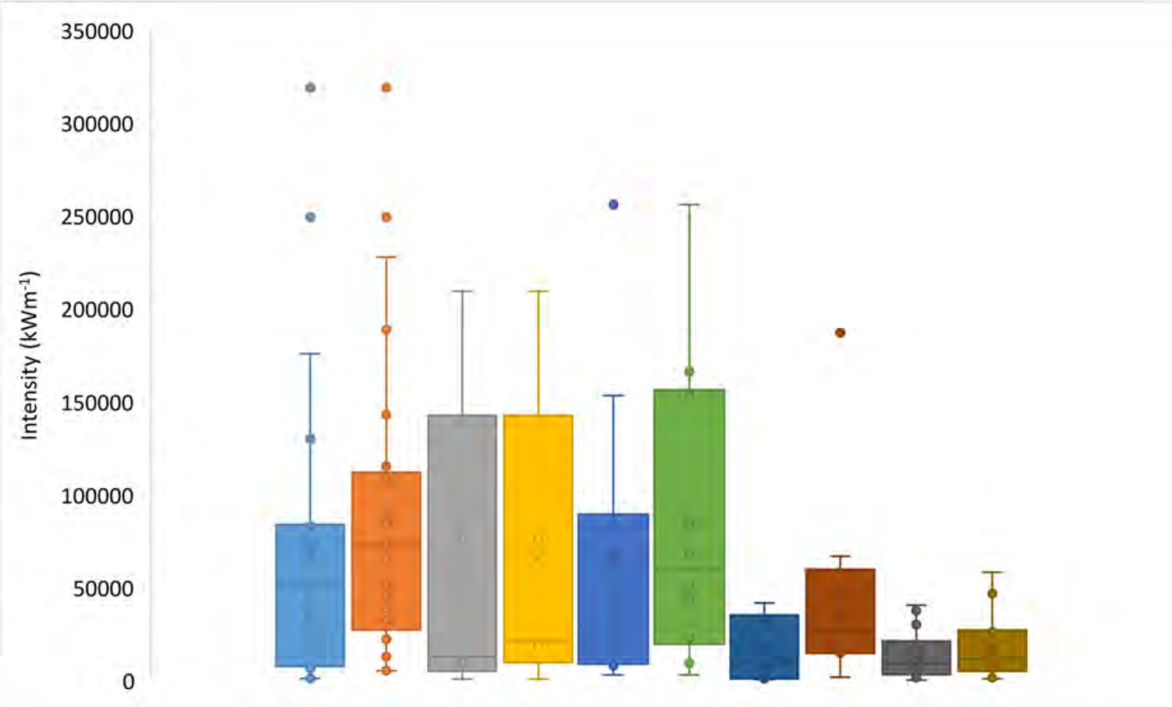
For all entrapments resulting in either fatality or injury, forest accounted for approximately 40% (n=25) of incidents, woodlands 9% (n=5), scrub 16% (n=10), shrub 13% (n=8) and grassland 22% (n=14). Wildfire behaviour (lower and upper reported / calculated values) during entrapments and burnover at the time of fatality, injury and all incidents is detailed in Table 7.1, with distribution across all incidents illustrated in Figure 7.2. The highest RoS by vegetation type was Forest 8.3ms^{-1}, Woodland 4.53ms^{-1}, Scrub 7.23ms^{-1}, Shrub 6.73ms^{-1}, and Grass 5.63ms^{-1}. The highest intensity and flame length occurred in planation Forest fires during fatal entrapments, with the highest reported intensity being 249226kWm^{-1}, the highest calculated intensity being 318990kWm^{-1} and the largest flame length being reported as between 45.7 to 61m. The mean (μ) upper reported / calculated intensity across all entrapments was 64453kWm^{-1} and was subsequently adopted as the intensity threshold for Performance Criteria 4. Acknowledging the limitations and assumptions of the wildfire models used in the study, these figures are consistent with explosive wildfire behaviour over short runs (Alexander & Cruz, 2016; Tedim et al., 2018; Penney et al., 2019a).

Table 7.1. Wildfire behaviour at point of impact during entrapments resulting in injury or fatality, showing minimum and maximum reported or calculated values, mean (μ) and standard deviation (σ)

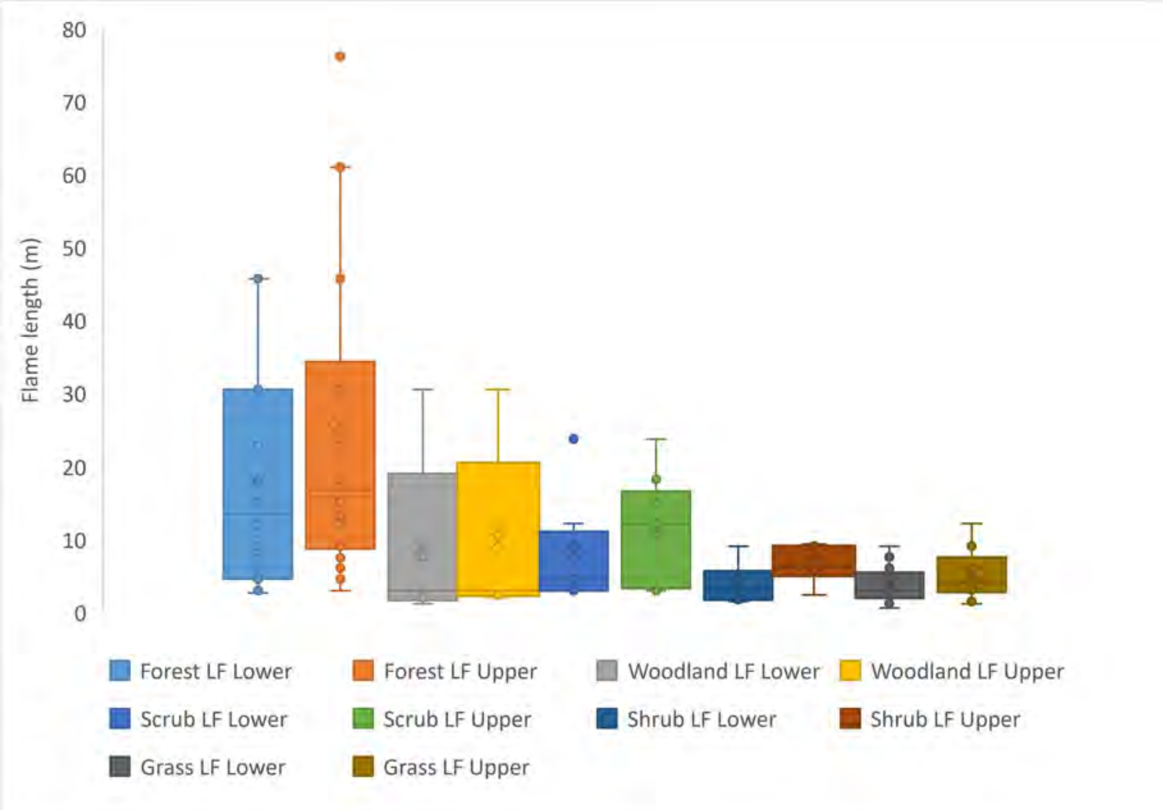
Fatality only incidents				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.1	7.2	2.0	2.1
RoS upper reported value (ms^{-1})	0.1	8.3	2.3	2.4
I lower reported / calculated value (kWm^{-1})	1012	318990	68523	87142
I upper reported / calculated value (kWm^{-1})	3113	318990	83545	85912
L_F lower reported value (m)	1.8	45.7	13.7	13.0
L_F upper reported value (m)	3.0	61	19.8	18.5
Injury only incidents				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.2	4.5	1.5	1.4
RoS upper reported value (ms^{-1})	0.2	6.7	2.2	1.8
I lower reported / calculated value (kWm^{-1})	253	209250	32937	7481
I upper reported / calculated value (kWm^{-1})	850	227850	50664	60349
L_F lower reported value (m)	0.6	45.7	8.5	10.9
L_F upper reported value (m)	1.2	76.2	11.8	15.5
All incidents considered				
Wildfire behaviour	**min**	**max**	**μ**	**σ**
RoS lower reported value (ms^{-1})	0.1	7.2	1.8	1.8
RoS upper reported value (ms^{-1})	0.1	8.3	2.2	2.1
I lower reported / calculated value (kWm^{-1})	253	318990	47860	67687
I upper reported / calculated value (kWm^{-1})	850	318990	64453	73373
L_F lower reported value (m)	0.6	45.7	10.6	11.9
L_F upper reported value (m)	1.2	76.2	15.0	17.1



(a) RoS all incidents by vegetation



(b) Intensity all incidents by vegetation



(c) L_F all incidents by vegetation

Figure 7.2. Wildfire behaviour all incidents by vegetation type **(a)** RoS; **(b)** Intensity; **(c)** L_F

Efficacy is the ability of a fire safety system to successfully achieve its required objective, assuming it functions as intended (SFPE, 2008; Thomas, 2002, Yung, 2008). Table 7.2 details the efficacy of vehicle protection systems against Performance Criteria 1 to 4 using the results from the historical entrapments analysed. Vehicle protection systems designed to operate up to an intensity 7500kWm^{-1} (i.e. Performance Criteria 1) have an efficacy between 0.12 to a maximum of 0.36. An increase in efficacy from 0.12 to 0.42 is observed when vehicle protection systems performing to Performance Criteria 2, i.e. 10000kWm^{-1}, are considered. Vehicle protection systems designed to operate up to an intensity of 12000kWm^{-1} (i.e. Performance Criteria 3) demonstrate an efficacy between 0.12 to 0.47. Applying Performance Criteria 4 (i.e. performance threshold equal to the mean historical upper recorded / calculated intensity of 64453kWm^{-1}), efficacy of vehicle protection systems increases to between 0.62 to 0.81. By comparison, Yung (2008) reports the efficacy of sprinklers in suppressing a 'large' fire in buildings as between 0.89 to 1.00, with an overall effectiveness (efficacy multiplied by reliability) of 0.77 to 0.96. In conjunction with the analysis of historical entrapments, this suggests that existing vehicle protection systems may be unreliable in protecting vehicle occupants from entrapment and burnover. Improvements in vehicle protection system efficacy could be achieved by increasing the performance standard they are required to meet, whilst further research into the reliability of vehicle protection systems will facilitate greater understanding of overall effectiveness.

Table 7.2. Vehicle protection system efficacy based on historical entrapments considering lower and upper recorded / calculated intensity

Fatality only incidents (n=26)		
Performance Criteria	**lower intensity**	**upper intensity**
PC 1 (intensity <7500kWm^{-1})	0.19 (n=5)	0.12 (n=3)
PC 2 (intensity <10000kWm^{-1})	0.31 (n=8)	0.12 (n=3)
PC 3 (intensity <12000kWm^{-1})	0.31 (n=8)	0.12 (n=3)
PC 4 (intensity <64453kWm^{-1})	0.69 (n=18)	0.62 (n=16)
Injury only incidents (n=36)		
Performance Criteria	**lower intensity**	**upper intensity**
PC 1 (intensity <7500kWm^{-1})	0.36 (n=13)	0.22 (n=8)
PC 2 (intensity <10000kWm^{-1})	0.42 (n=15)	0.28 (n=10)
PC 3 (intensity <12000kWm^{-1})	0.47 (n=17)	0.33 (n=12)
PC 4 (intensity <64453kWm^{-1})	0.81 (n=29)	0.67 (n=24)
All incidents (n=62)		
Performance Criteria	**lower intensity**	**upper intensity**
PC 1 (intensity <7500kWm^{-1})	0.29 (n=18)	0.18 (n=11)
PC 2 (intensity <10000kWm^{-1})	0.37 (n=23)	0.21 (n=13)
PC 3 (intensity <12000kWm^{-1})	0.42 (n=26)	0.24 (n=15)
PC 4 (intensity <64453kWm^{-1})	0.76 (n=47)	0.66 (n=41)

7.4 Design wildfire analysis

Where full scale systems testing is prohibitive, fire safety systems analysis using simulations and modelling (International Code Council et al., 2005; SFPE, 2007, 2008) is required. Assessing the effectiveness of existing VPS against the full scale of wildfires experienced in Australia using field testing is not achievable due to the inherent dangers associated with catastrophic wildfire events and the costs associated with the burnover of firefighting appliances. To in part address this and provide some guidance to firefighters, Incident Management Teams and fire safety engineers, simulated design fires are used for the study. Yung (2008, p80) defines define fires as "*prescribed fires that can be used by fire protection engineers for performance-based fire safety designs*".

The approach adopted by Penney et al. (2020b) enabled vehicle protection systems designed to Performance Criteria 1 to 6 (intensities of 7500kWm^{-1}, 10000kWm^{-1}, 12000kWm^{-1}, 64453kWm^{-1}; and radiant heat flux of 15kWm^{-2} and 30kWm^{-2}) to be assessed across Forest, Woodland, Scrub, Shrub and Grassland fuel structures, fuel loads, forest and grassland fire danger indices, windspeeds, slope and fuel age.

7.4.1 *Fire line intensity analysis*

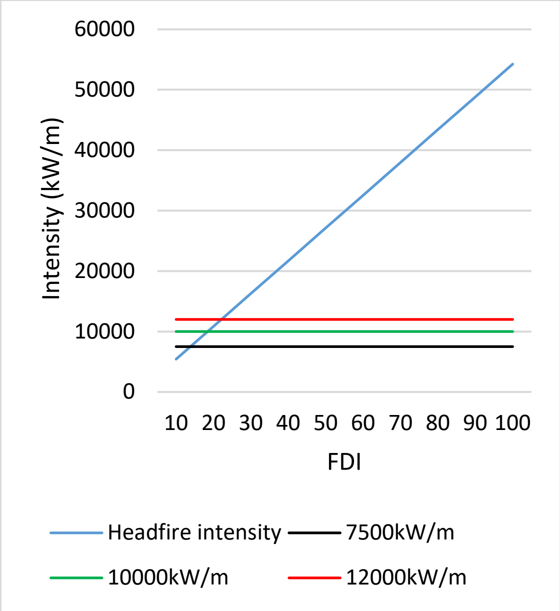
A total of 90 simulations were completed during the first phase of the study. As expected wildfire intensity increased with slope, windspeed (*V*) and Forest / Grassland Fire Danger Indices (Figure 7.3a-j), which is consistent with the principles of established wildfire behaviour. Forest simulations on flat ground resulted in intensity exceeding Performance Criteria 1 (7500kWm^{-1}) and Performance Criteria 2 (10000 kWm^{-1}) between a Fire Danger Index of 10 to 20, and Performance Criteria 3 (12000 kWm^{-1}) being exceeded between a Fire Danger Index of 20 to 30. Performance Criteria 4 (i.e. performance threshold equal to the mean historical upper recorded / calculated intensity of 64453kWm^{-1}) was not exceeded regardless of the Fire Danger Index. By comparison Woodland simulations on flat ground resulted in intensity exceeding Performance Criteria 1 (7500kWm^{-1}) between a Fire Danger Index of 30 to 40, intensity exceeding Performance Criteria 2 (10000 kWm^{-1}) between a FDI of 40 to 50, and Performance Criteria 3 (12000 kWm^{-1}) being exceeded between a Fire Danger Index of 50 to 60. Echoing the results of Forest simulations, Performance Criteria 4 (64453kWm^{-1}) was not exceeded in Woodland regardless of the Fire Danger Index. In Grassland under equivalent conditions, intensity exceeded Performance Criteria 1-3 prior to a Grassland Fire Danger Index of 50 while Performance Criteria 4 was not exceeded at any Fire Danger Index.

To put these figures into context, Blanchi et al. (2010) report virtually all house loss from wildfire in Australia occurs on days when the FDI exceeds the 99.5th percentile in the distribution of daily Fire Danger Index for each of the regions considered, with the majority of house loss occurring on days of Fire Danger Index greater than 100. Further, they report there is little house loss on days where the Fire Danger Index did not exceed 50. This indicates that vehicle protection systems designed to current performance criteria are unlikely to be effective on days that firefighters are most likely to be actively involved in the protection of houses during significant wildfire events.

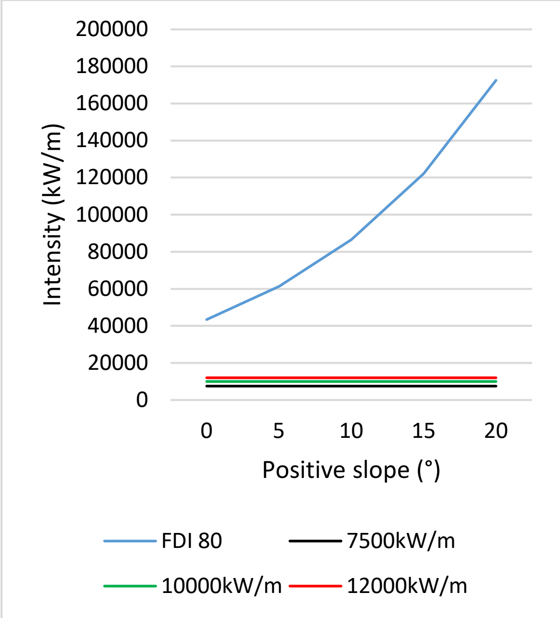
The influence of windspeed on fire line intensity in Scrub and Shrub wildfires is illustrated in Figures 7.3g and 7.3i. Scrub simulations on flat ground resulted in intensity exceeding Performance Criteria 1 to 3 between windspeeds (*V)* of 5 to 15kmh^{-1}. Unlike all other simulations, intensity exceeded Performance Criteria 4 in simulated Scrub wildfire, but only once windspeed exceeded approximately 55kmh^{-1}. By comparison, Shrub simulations in equivalent conditions resulted in intensity exceeding Performance Criteria 1 and 2 between windspeeds of 5 to 15kmh^{-1}, and Performance Criteria 3 being exceeded between windspeeds of 25 to 35kmh^{-1}. Intensity did not exceed Performance Criteria 4 regardless of windspeed in Shrub simulations.

Sensitivity analysis was completed to determine the effect of changing slope across all vegetation structures. Simulations in each fuel structure were completed at 0° to 20°. When simulating the effect of increase in slope (Figures 7.3b,d,f,h,j), a positive relationship was confirmed between slope and wildfire intensity (Table 7.3). This subsequently resulted in Performance Criteria 1-3 thresholds being exceeded more rapidly as slope increased. Increased slope may also result in Performance Criteria 4 being exceeded where it previously provided adequate protection. These outcomes were expected given the mathematical relationship between slope, rate of spread and intensity detailed in Penney et al (2020b).

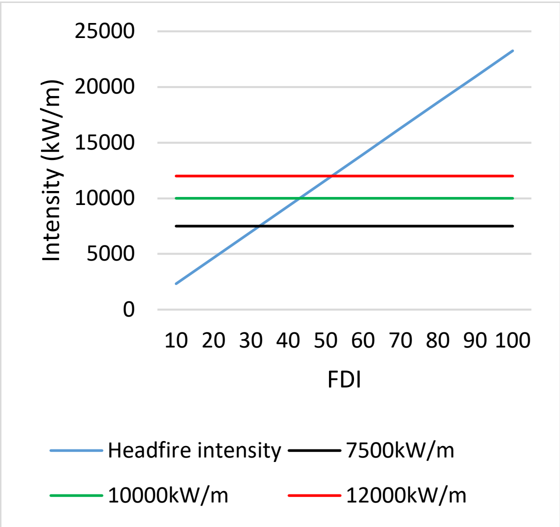
Sensitivity analysis of intensity to fuel load in Forest and Woodland also confirmed consistent increase of intensity as understory (*w*) and total fuel (*W*) load increased (Figure 7.4). At a Fire Danger Index of 80 and assuming flat ground, fire line intensities exceeded Performance Criteria 1 and 2 when Forest fuels reached 40-50% of their default design wildfire values (*w*= 10-12.5tha^{-1} and *W*= 14-17.5tha^{-1}) and Performance Criteria 3 was exceeded once Forest fuels reached 50-60% (w= 15-17.5tha^{-1} and W= 21-24.5tha^{-1}) of default design wildfire values. Under the same conditions, Performance Criteria 1 was exceeded when Woodland fuels reached 60-70% (*w*= 7.4-9tha^{-1} and *W*= 12.5-15tha^{-1}) of default design wildfire values and both Performance Criteria 2 and 3 were exceeded once Woodland fuels reached 70-80% (*w*= 10.5-12tha^{-1} and *W*= 17.5-20tha^{-1}) of their default design wildfire values (the fuel loads assigned in AS3959). Performance Criteria 4 was not exceeded in Forest or Woodland simulations at any fuel load up to 100% of default values detailed in AS3959. These results indicate that whilst sparser fuels result in reduced intensity, vehicle protection systems designed to existing performance criteria may still be exceeded, however vehicle protection systems designed to Performance Criteria 4 would provide a significantly higher level of firefighter protection.



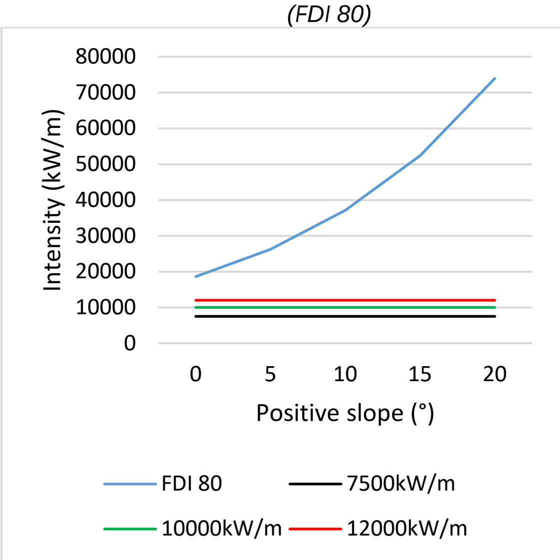
(a) *Forest headfire intensity FDI sensitivity*



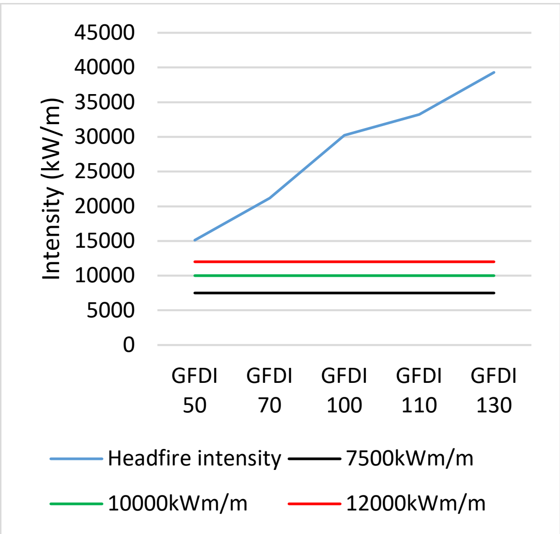
(b) *Forest headfire intensity slope sensitivity (FDI 80)*

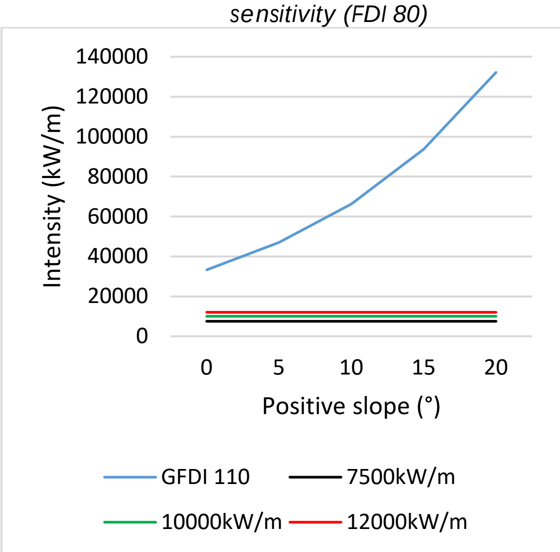


(c) *Woodlands headfire FDI sensitivity*



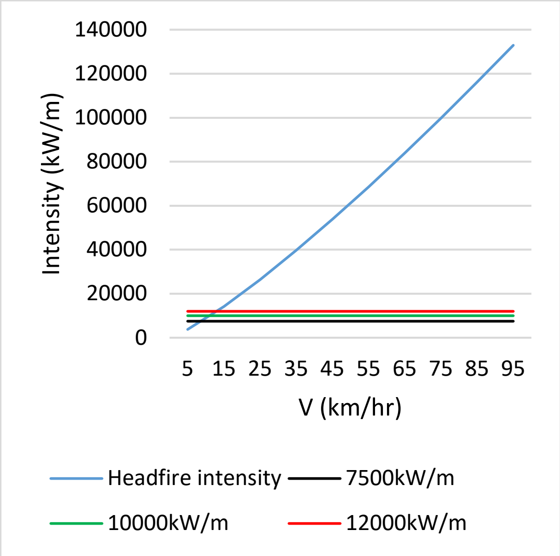
(d) *Woodland headfire intensity slope sensitivity (FDI 80)*

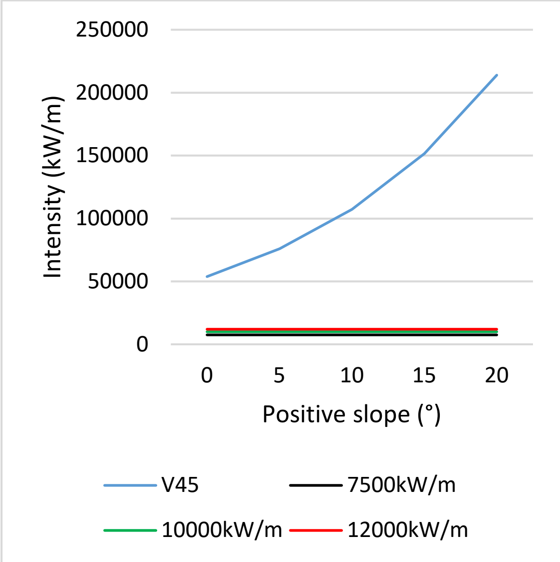




(e) *Grass headfire FDI sensitivity*

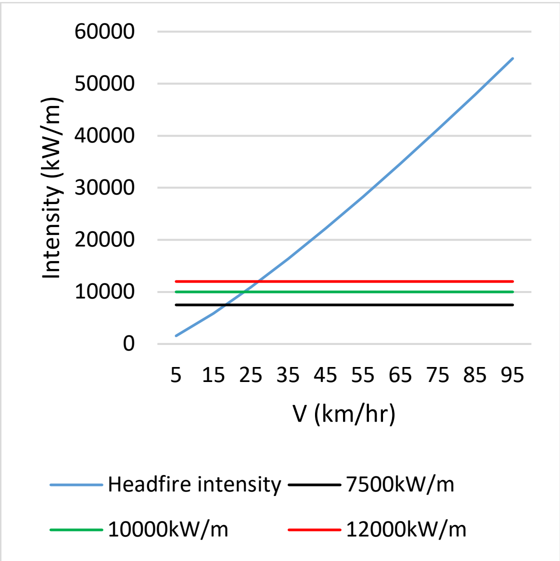
(f) *Grass headfire intensity slope sensitivity (GFDI 110)*

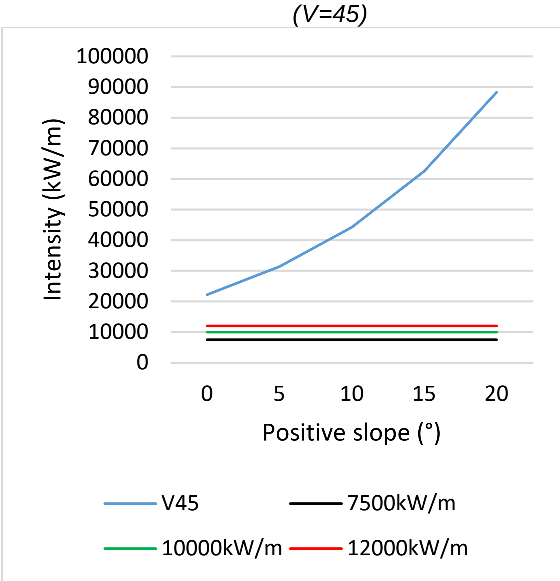




(g) *Scrub headfire V sensitivity*

(h) *Scrub headfire intensity slope sensitivity (V=45)*





(i) *Shrub headfire V sensitivity*

(j) *Shrub headfire intensity slope sensitivity (V=45)*

Figure 7.3. Wildfire intensity by vegetation type

Table 7.3. Relationship between slope and intensity, all vegetation types

Slope	Intensity factor compared to flat ground
Flat	1
5°	1.4
10°	2.0
15°	2.8
20°	4

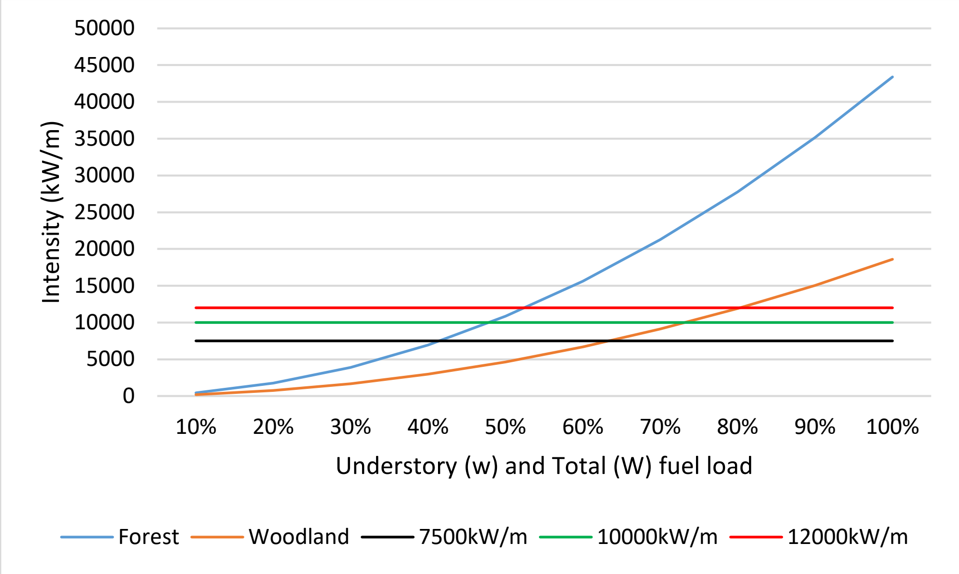


Figure 7.4. Sensitivity to fuel load - Forest & Woodland

7.4.2 *Radiant heat flux analysis*

Wildfire simulations (n=45) enabled radiant heat flux (RHF) to be calculated at 5m increments for 0 to 100m of separation from the headfire for Forest, Woodland, Scrub, Shrub and Grassland vegetation structures (Figure 7.5). As expected, radiant heat flux at each unit of separation increases with slope, Fire Danger Index (FDI), Grassland Fire Danger Index (GFDI) and windspeed (*V*).

In all simulations, regardless of FDI, GFDI, *V*, slope or fuel load, Performance Criteria 5 (15kWm^{-2}) and Performance Criteria 6 (30kWm^{-2}) were exceeded for 0 to 5m separation from the wildfire front. Historical analysis (Table 3) identifies the mean flame length during entrapments and burnover resulting in either injury or fatality is 10.6 to 15m, with a maximum flame length of 45.7 to 76.2m. This indicates vehicle protection systems would likely fail in the event of protracted flame immersion associated with engulfment and burnover during the passage of the headfire.

In Forest simulations (Figure 7.5a), radiant heat flux exceeded Performance Criteria 5 (15kWm^{-2}) for approximately 14m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 44m at a Fire Danger Index of 100. Radiant heat flux exceeded Performance Criteria 6 (30kWm^{-2}) for approximately 8m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 25m at a Fire Danger Index of 100.

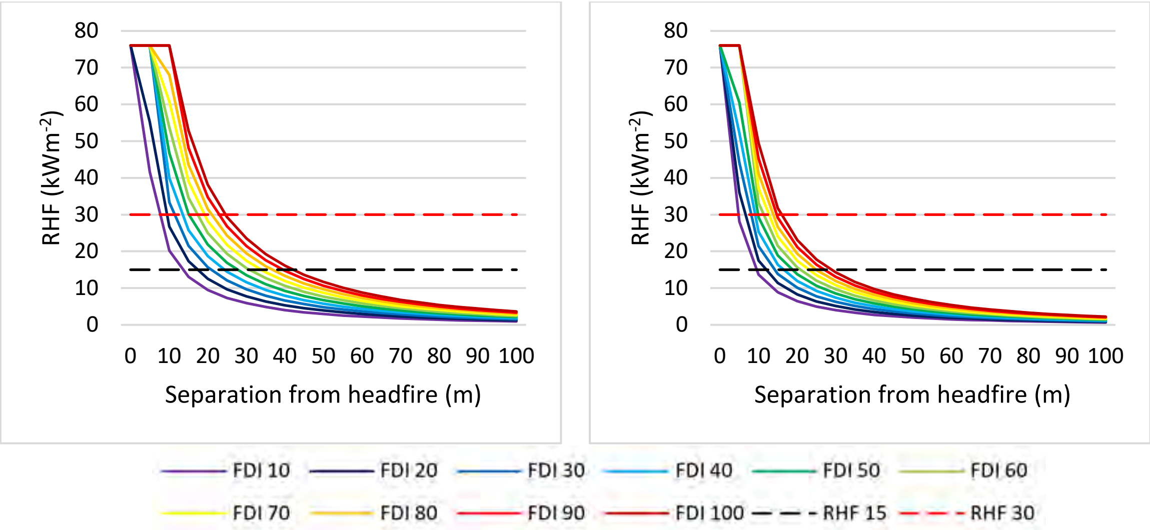
As expected, the efficacy of vehicle suppression systems in Woodlands fuels was slightly higher by comparison, Woodlands having less understory fuel (15tha^{-1}) compared to Forest (25tha^{-1}). Radiant heat flux exceeded Performance Criteria 5 (15kWm^{-2}) for approximately 10m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 30m at a Fire Danger Index of 100 (Figure 7.5b). Radiant heat flux exceeded Performance Criteria 6 (30kWm^{-2}) for approximately 5m separation from the headfire at a Fire Danger Index of 10, increasing to approximately 17m at a Fire Danger Index of 100.

In Scrub simulations (Figure 7.5c), radiant heat flux exceeded Performance Criteria 5 (15kWm^{-2}) for approximately 8m from the headfire at a windspeed of 5kmh^{-1}, increasing to approximately 35m at a windspeed of 95kmh^{-1}. Radiant heat flux exceeded Performance Criteria 6 (30kWm^{-2}) for approximately 5m from the headfire at a windspeed of 5kmh^{-1}, increasing to approximately 20m at a windspeed of 95kmh^{-1}. By comparison, in Shrub simulations (Figure 7.5d), radiant heat flux exceeded Performance Criteria 5 (15kWm^{-2}) for approximately 5m from the headfire at a windspeed of 5kmh^{-1}, increasing to approximately 25m at a windspeed of 95kmh^{-1}. Radiant heat flux exceeded Performance Criteria 6 (30kWm-

^{2})for approximately 4m from the headfire at a windspeed of 5kmh^{-1}, increasing to approximately 13m at a windspeed of 95kmh^{-1}.

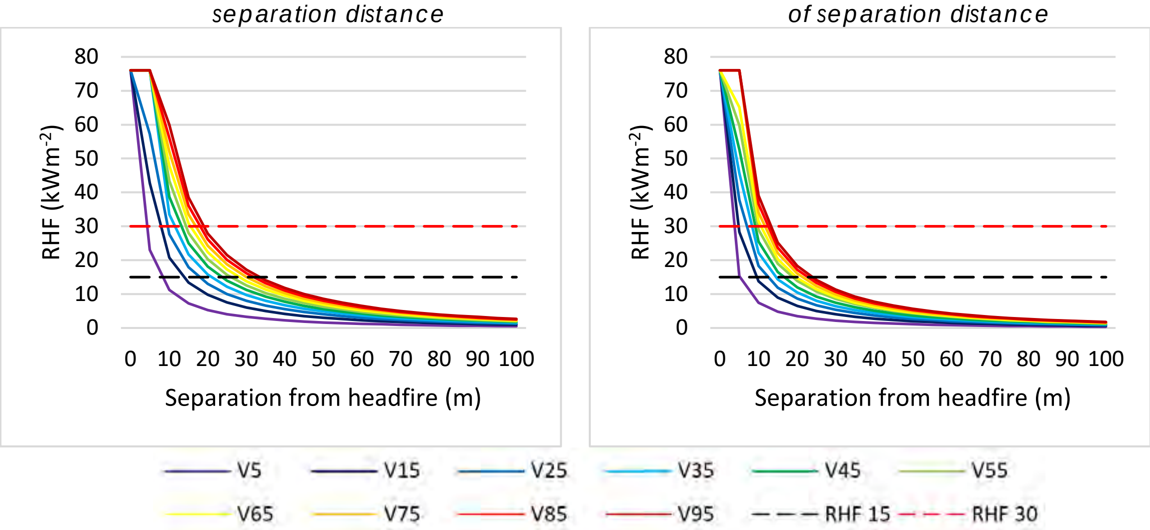
In Grassland simulations (Figure 7.5e) radiant heat flux exceeded Performance Criteria 5 (15kWm^{-2}) for approximately 10m from the headfire at a Grassland Fire Danger Index of 50, increasing to approximately 17m at a Grassland Fire Danger Index of 130. Radiant heat flux exceeded Performance Criteria 6 (30kWm^{-2}) for approximately 5m from the headfire at a Grassland Fire Danger Index of 50, increasing to approximately 10m at a Grassland Fire Danger Index of 130.

These results again demonstrate that the operating parameters of existing vehicle protection systems are likely to be exceeded well below the conditions Blanchi et al (2006) report are most likely to be involved in the defense of life and property.



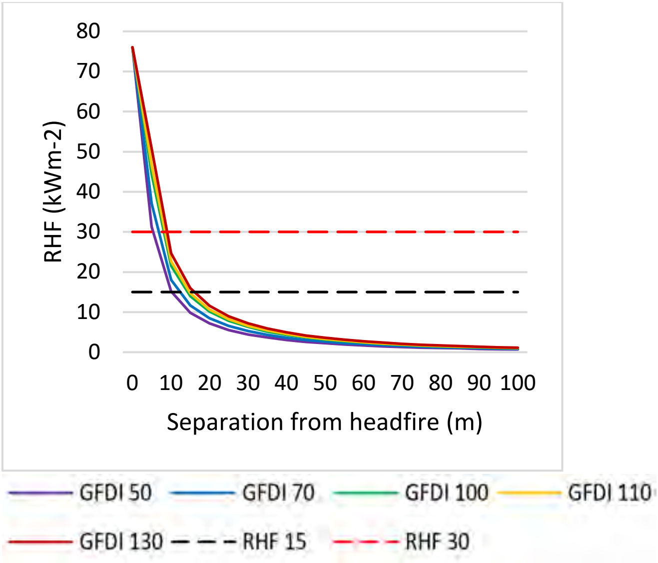
(a) *Forest headfire RHF as a function of separation distance*

(b) *Woodland headfire RHF as a function of separation distance*



(c) *Scrub headfire RHF as a function of separation distance*

(d) *Shrub headfire RHF as a function of separation distance*



(e) *Grass headfire RHF as a function of separation distance*

Figure 7.5. Radiant heat flux (RHF) as a function of separation from headfire: (**a**) Forest; (**b**) Woodland; (**c**) Scrub; (**d**) Shrub; (**e**) Grassland

Sensitivity analysis (table 7.4) demonstrates the separation required from the headfire (all vegetation structures) in order for radiant heat flux to fall below Performance Criteria 5 and 6 increases with slope. Similarly, sensitivity analysis of understory fuel loads (*w)* in Forest/Woodland design wildfires (Figure 7.6a-f) demonstrates a positive relationship between the separation required from the headfire in order for radiant heat flux to fall below Performance Criteria 5 and 6, and understory fuel loads (*w*). At surface fuel loads (*w*) of $30tha^{-1}$, and a Fire Danger Index of 100, radiant heat flux exceeds Performance Criteria 5 ($15kWm^{-2}$) until approximately 45m separation from the forest head fire is achieved. Under the same conditions radiant heat flux exceeds Performance Criteria 6 ($30kWm^{-2}$) until separation of approximately 25m is achieved. The required separation from the head fire for RHF decreases with FDI and *w*, with only approximately 6m separation required for RHF to fall below $30kWm^{-2}$ at a FDI of 100 when w is $5tha^{-1}$; and 10m separation required for RHF to fall below $15kWm^{-2}$ under the same conditions.

Table 7.4. Effect of slope on reparation from headfire required before Performance Criteria 5 & 6 are achieved.

Vegetation	Slope				
	0°	**5°**	**10°**	**15°**	**20°**
Performance Criteria 5 (*Radiant heat flux of* $15kWm^{-2}$) exceeded					
Forest (*FDI*=80)	35-40m	45m	55m	65m	75-80m
Woodland (*FDI*=80)	25m	30m	35-40m	45-50m	55-60m
Scrub (*V*=$45kmh^{-1}$)	20-25m	25-30m	30m	30-35m	35-40m
Shrub (*V*=$45kmh^{-1}$)	15-20m	15-20m	20-25m	20-25m	25-30m
Grassland (*GFDI*=110)	15m	15-20m	20m	15-20m	25-30m
Performance Criteria 6 (*Radiant heat flux of* $30kWm^{-2}$) exceeded					
Forest (*FDI*=80)	20-25m	25-30m	30-35m	40-45m	50-55m
Woodland (*FDI*=80)	10-15m	15-20m	20-25m	25-30m	30-35m
Scrub (*V*=$45kmh^{-1}$)	10-15m	10-15m	15-20m	15-20m	20-25m
Shrub (*V*=$45kmh^{-1}$)	5-10m	5-10m	10-15m	10-15m	10-15m
Grassland (*GFDI*=110)	5-10m	5-10m	10m	10-15m	10-15m

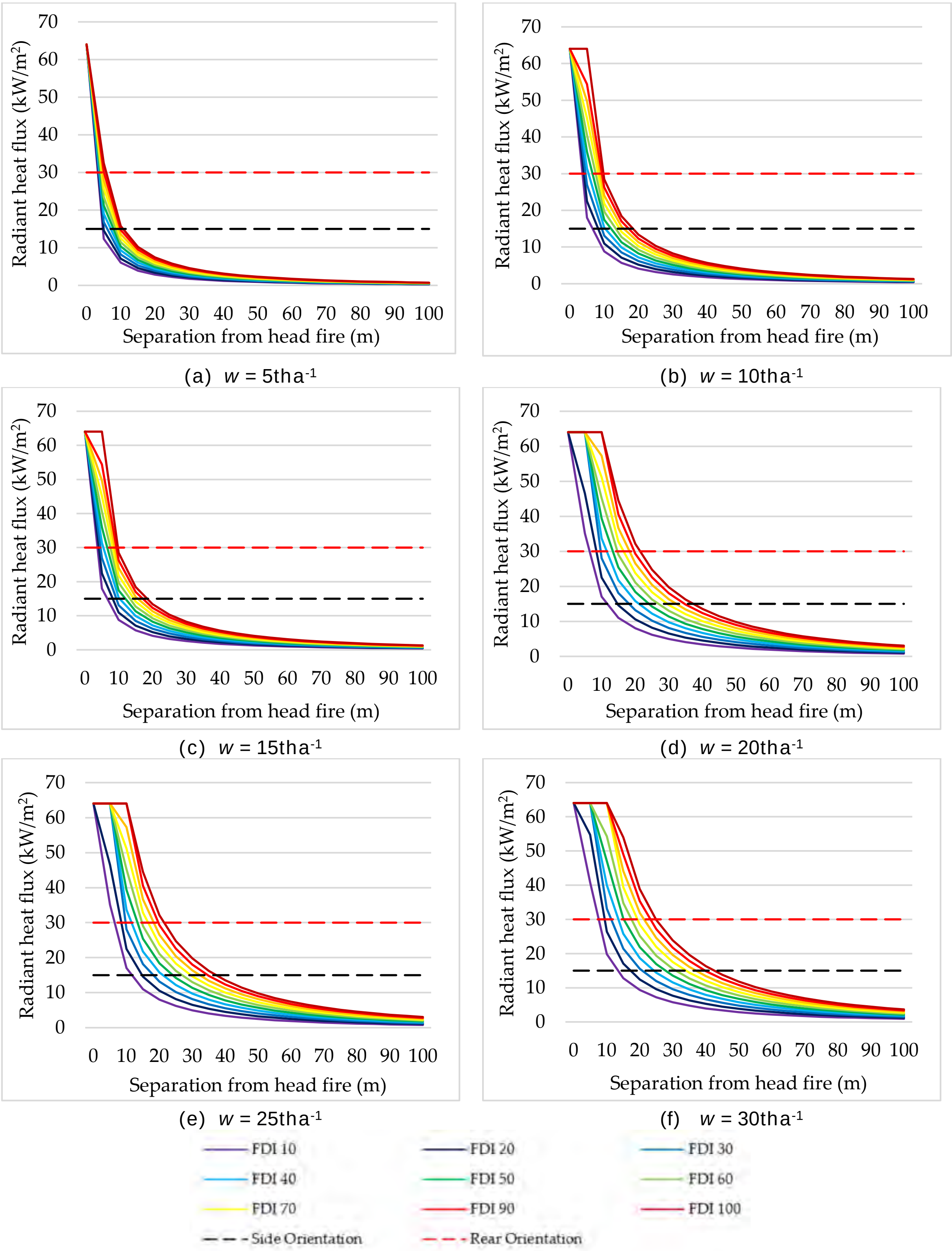


Figure 7.6. Effect of understory fuel load on RHF as a function of separation from the headfire: (**a**) w = 5tha^{-1}; (**b**) w = 10tha^{-1}; (**c**) w = 15tha^{-1}; (**d**) w = 20tha^{-1}; (**e**) w = 25tha^{-1}; (**f**) w = 30tha^{-1}

7.5 Discussion

The results identify that vehicle protection systems designed to operate in fire line intensities of 7500kWm^{-1} (i.e. Performance Criteria 1) could reasonably expected to have been successful in 0.12 to 0.36 of historical entrapments and burnovers, assuming they operate without fault 100% of the time (i.e. a reliability factor of 1.00). An increase in efficacy from 0.12 to 0.42 was observed when vehicle protection systems performing to Performance Criteria 2, i.e. 10000kWm^{-1}, were considered. Vehicle protection systems designed to operate up to an intensity of 12000kWm^{-1} (i.e. Performance Criteria 3) demonstrate an efficacy between 0.12 to 0.47. This is well below the expected efficacy of commercial fire safety systems (Yung, 2008; SFPE, 2008). Increasing the operational performance standard of vehicle protection systems to the mean historical upper recorded / calculated intensity of 64453kWm^{-1} (i.e. Performance Criteria 4) would result in an increase in efficacy of vehicle protection systems increases to between 0.62 to 0.81. To improve firefighter safety during entrapment and burnover it is recommended that significantly higher fire line intensity performance criteria are adopted across fire services for vehicle protection systems. Further research into the reliability of vehicle protection systems is also recommended to enable the effectiveness of each system to be determined as part of a detailed fire safety system validation and fire engineering analysis. Until this is completed the potential of unrealistic expectations of the safety afforded to firefighters during entrapment and burnover may contribute to increased injuries or fatalities during wildfire suppression.

Radiant heat flux analysis further highlights the performance limitations of existing vehicle protection systems. Whilst the 95th and 99th percentiles of Fire Danger Indices across Australia from 2000 to 2007 as reported by Dowdy et al. (2009) are illustrated in figure 2.2 (refer to Chapter 2), fire weather in Australia is increasingly worsening as a result of climate change Lucas et al. (2007). As Blanchi et al. (2010) report, virtually all house loss from wildfire in Australia occurs on days when the Fire Danger Index exceeds the 99.5th percentile in the distribution of daily Fire Danger Index for each of the regions considered, with the majority of house loss occurring on days of Fire Danger Index greater than 100. Further, they report there is little house loss on days where the Fire Danger Index did not exceed 50. Fire line intensity simulations identified Performance Criteria 1-3 (i.e. intensity of 7500kWm^{-1}, 10000kWm^{-1} and 12000kWm^{-1} respectively) were exceeded on flat terrain in Forest below a Fire Danger Index of 30; in Woodlands at Fire Danger Indices between 30 to 60; in Grassland at a Grassland Fire Danger Index of less than 50 (equivalent to a Fire Danger Index of 40); and in Scrub and Scrub at windspeeds of less than 15kmh^{-1}. By comparison, the mean historical upper recorded / calculated intensity of 64453kWm^{-1} (i.e. Performance Criteria 4) was not exceeded in any simulation, regardless of Fire Danger Index or windspeed except for Scrub fuels once windspeed reached approximately 55kmh^{-1}.

Radiant heat flux modelling completed in Penney et al. (2020b) demonstrated vehicle protection system Performance Criteria 5 and 6 (i.e. 15 kWm^{-2} and 30kWm^{-2}) are likely to be exceeded in all cases of entrapment where flame immersion occurs, and, remains a distinct possibility for significant distances of separation from the headfire. To increase firefighter safety it is recommended further research and development into vehicle protection systems satisfying Australian Standard 1530.8.2 *Methods for fire tests on building materials, components and structures – Part 8.2 Tests on elements of construction for buildings exposed to simulated bushfire attack – large flaming sources,* which specifically identifies performance criteria for prolonged radiant heat flux exceeding 40kWm^{-2}.

7.6 Implications for frontline firefighters, fire behaviour specialists, IMT's and fire services

This chapter identifies that vehicle protection systems designed to the existing intensity standard of 7500kWm^{-1} may have been successful in 0.12 to 0.36 of historical entrapments and burnovers, assuming they operate without fault. An efficacy this low is highly unlikely to be tolerated in any traditional fire safety system. In conjunction with research into wildfire weather in Australia, the results of design wildfire analysis indicate existing vehicle protection systems are unlikely to be effective on days that firefighters are most likely to be actively involved in the protection of houses during significant wildfire events. In order to maximise firefighter safety during wildfire suppression, and to avoid providing firefighters unrealistic expectations regarding vehicle protection systems and other fire safety systems which may contribute to firefighters taking unacceptable risks, it is recommended fire services should include training on the limitations of their respective systems.

Significant improvements in firefighter safety during entrapment and burnover may be made by increasing the required intensity threshold of VPS. Increasing the operational performance standard of vehicle protection systems to the mean historical upper recorded / calculated intensity of 64453kWm^{-1} (i.e. Performance Criteria 4) would result in an increase in efficacy of vehicle protection systems increases to between 0.62 to 0.81. Adopting this intensity threshold would also result in vehicle protection systems being theoretically effective in all design wildfires modelled, with the exception of Scrub where VPS may potentially remain effective until windspeeds reach 45 to 55kmh^{-1}.

When considering radiant heat flux, this chapter identifies that both 15 and 30kWm^{-2} is likely to be exceeded in all cases of entrapment where flame immersion occurs, and, remains a distinct possibility for significant distances of separation from the headfire. To increase firefighter safety it is recommended fire services not only ensure wildfire suppression training includes analysis of the magnitude and effects of wildfire radiant heat flux, but include credible worse case radiant heat flux thresholds of 30kWm^{-2} as one of the mandatory performance criteria of VPS and any other wildfire vehicle fire safety system.

The results of this study should not be considered in isolation, but rather alongside the findings of other recent research (Penney et al., 2019a, 2019b, 2020a, 2020b) into wildfire suppression strategies and the limitations of firefighters and the equipment they rely on. A recurring theme within the conclusions of this research is that when attempting to suppress landscape scale wildfire, it may be more appropriate for fire services to consider early instigation of indirect attack or defensive strategies including safeguarding, evacuations and clear communication to the community and other stakeholders that conditions at the head fire are not defendable. It is suggested offensive strategies involving personnel and appliances should be employed with caution after detailed analysis of fuel structure and continuity, secondary to the increased use of aerial firefighting suppression. Early adoption of this approach will assist prevent crews being inappropriately tasked to potential dangerous 'dead man zones' where they will not only be at great risk, but will have little if any impact on the fire. Further, it will clearly articulate the severity of the approaching head fire and will assist to prevent unrealistic community expectations of fire services intervention during catastrophic wildfire events.

8. Risk management during dynamic firefighting contexts

8.1 Introduction

Succinctly described by (Kunadharaju et al., 2011), "there is little protective redundancy in firefighting." Accordingly, effective risk management is an essential component of dynamic firefighting operations throughout the world. International Standard 31000 *Risk management guidelines* (ISO, 2018) subsequently referred to as ISO31000, is the standard of risk management within the Australian emergency services context.

Previous studies (Ash & Smallman, 2012; Sadler et al. 2007) reported decisions made on the incident ground to be reactionary rather than considered, or to be adapted from previous experience at similar situations or incidents potentially without thorough analysis (Tissington & Flin, 2007). Dynamic risk management in the emergency rescue context is often restricted to a qualitative selection of tactics guided by tacit professional craft knowledge as opposed to quantified risk assessment and evidence based practice as part of the entire risk management process (Jacobs, 2010; Loflin & Kipp, 1997). Buoyed by disasters of significant scale including, the devastating Grenfell Tower fire of June 14, 2017 (GTI, 2018) and more frequent siege and mega wildfires such as those experienced in California (CA Gov, 2018; USFS & CDFFP, 2004), Greece (CBS, 2018) and Australia (Bushfire CRC, 2009), fire services are facing increased public scrutiny and both firefighters Incident Management Teams (IMT's) are being held to a higher standard of performance than ever before.

In response to the changing external environment, fire services throughout the world are embracing new technologies and turning to research to support evidence based practice. At the same time, fire services are collecting significant amounts of specific and information rich data. Probabilistic analysis of this data can subsequently facilitate improvements in operational risk management during emergencies and in pre-incident planning (Penney, 2017, 2019) ultimately resulting in a safer workplace and providing Incident Commanders evidence that can be used to support operational decisions. This chapter not only defines risk management within the dynamic emergency fire service context, but explores firefighters risk attitudes and how these may influence Incident Controllers (IC's).

8.2 Defining risk in dynamic fire and emergency situations

Whilst the term 'risk' is often used incorrectly instead of, or interchangeably with the term 'hazard' within the majority of fire services literature (Penney, 2017, 2019), risk is specifically defined as the "effect of uncertainty on objectives" (ISO, 2018). Risk is not an event (SAI Global, 2013a) such as an explosion, fire or other emergency. Instead, risk is expressed as the likelihood of a consequence, positive or negative, occurring. When applied to emergency response it is essential to appreciate that incidents are dynamic, occurring within an environment subject to constant change and therefore the level of uncertainty and therefore risk, must be constantly reassessed. Often inappropriately described, three elements must be defined in order to articulate risk:

1. The objective(s) being referred to;
2. The particular source of uncertainty; and
3. How the source of uncertainty may lead to consequences.

In the emergency response setting an example of a statement of risk may include:

There is the potential that firefighters will have to rescue casualties involved in a high speed vehicle crash, which in turn will cause injury or harm to the firefighters from mechanical, thermal and chemical hazards preventing all firefighters completing the rescue unharmed. In this statement:

1. The objective is firefighters completing the rescue do so unharmed;
2. The source of uncertainty (risk source) is the vehicle rescue; and

3. Exposure to mechanical, thermal and chemical hazards may lead to the consequences, i.e., firefighters getting injured.

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2. The source of uncertainty (risk source) is the vehicle rescue; and
3. Exposure to mechanical, thermal and chemical hazards may lead to the consequences, i.e., firefighters getting injured.

8.3 Risk management in the dynamic emergency context

The term 'risk management' refers to the structure (principles, framework and process) for managing risk effectively whilst 'managing risk' refers to the application of that structure to the decision making process (SAI Global, 2013a). The risk management process provides the architecture for decision making and must be applied in every situation, including emergency response, for risk to be deemed to have been considered sufficiently (Penney, 2016). Further, SAI Global (2013a,p45) provides the following example of how the process must be applied in even the most dynamic emergency situations:

"*A military special forces section leader might have a split second in which to make a tactical decision on which personal wellbeing and that of subordinates as well as the success of the mission, might depend. In that time the leader must recall the objectives, appreciate the external and internal environment, assess the risks, consider the options, review those against the objectives and take the appropriate action. Despite the very short decision making window, the quality of each of these steps must be of the highest standard*."

Failure to comprehend risk or to apply the entire risk management structure to dynamic decision making in the emergency environment can result in decisions that exacerbate rather than mitigate adverse consequences. Should adverse outcomes eventuate it may also lead to post incident scrutiny of the decisions made by ICs. Existing studies suggest risk assessment in accordance with (ISO, 2018) may not occur during frontline emergency response in most jurisdictions (Ash & Smallman, 2012; Sadler et al., 2007; Penney, 2019). In contrast to these findings however, the risk management methodology for dynamic emergency incidents adopted by United Kingdom Fire Services as published by the Department for Communities and Local Government is comprehensive and requires specific attention.

The first of these publications, the Fire and Rescue Authorities "Health, safety and welfare framework for the operational environment" (DCLG, 2013), details a comprehensive architecture for management of dynamic incident risk that commences with the brigade's senior officers and ends with the individual emergency responder on the incident ground. This publication is unique amongst the literature reviewed in that it not only acknowledges Health and Safety legislation, often viewed as encumbrance to emergency response, but embraces it as a pillar of dynamic emergency risk management. In doing so the United Kingdom Fire Services succinctly define both internal and external organisational risk contexts as they apply to frontline operations. Further, DCLG (2013) not only articulates the dynamic incident risk assessment process through the hierarchy of command but also provides multiple fire service specific examples for ICs and front line personnel of all ranks and operational roles to reference. Perhaps most importantly from an organisational context is the recognition that "standard operational procedures need to be sufficiently flexible to allow the Incident Commander to exercise discretion on the resources and the procedures required to resolve the emergency" (DCLG, 2013, p23). The flexibility for ICs and personnel to use 'operational discretion' is carefully articulated and "should be based on a balance in terms of risk versus benefit, and the Incident Commander knowing the action which they are normally required by the relevant standard operational procedure" (DCLG, 2013 ,p23). In these statements the term Incident Commander and IC are interchangeable.

The second publication is the Fire and Rescue Manual 2nd Volume "Fire Service Operations – Incident Command" (DCLG, 2008). It is the doctrine of fire service dynamic incident management at all levels and embraces incident risk management as one of the three key elements required for effective incident command. Most significantly DCLG (2008, p64) recognises "in order to provide an acceptable level of protection at operational incidents, the organisations health and safety management must operate at three different levels – Strategic, Systematic and Dynamic." At a strategic level, the doctrine defines the fire service's risk attitudes and establishes internal context whilst complying with relevant external contexts. This is achieved through appropriate policy and doctrine that embrace the risk philosophy of the fire service. Systematic risk management is completed by operational subject matter experts in each discipline. The results subsequently guide the development and implementation of operations including but not limited to safe work systems, procedures, equipment, training and supervision. Dynamic risk management occurs during an operational incident and encompasses all risk management carried out by all personnel involved in the incident whilst an emergency situation is present.

In considering the application of 'dynamic risk management' it is essential to distinguish between time critical emergency situations, for instance where lives are endangered and rescue is required, and non-emergency situations such as body recovery. The distinction is critical as risk thresholds will vary accordingly as demonstrated in the "Safe Person Concept" (NZFS, 2008) and the philosophy of the DCLG [2008,p65],

"*In a highly calculated way, firefighters:*

- *Will take some risk to save saveable lives.*
- *May take some risk to save saveable property.*
- *Will not take any risk at all to try and save lives or property that are already lost."*

Whilst NZFS (2008) considers dynamic incident risk management in isolation, DCLG (2008, 2013) acknowledge it as only a part of the greater risk management process applicable to the fire service as a workplace. Through this approach the United Kingdom integrates the internal and external risk contexts into the dynamic incident risk management process. This holistic approach empowers ICs to manage risk in accordance with ISO31000 regardless of the nature of the emergency encountered.

8.3.1 *Risk analysis during dynamic emergency situations*

Klein's (1989) Recognition-Primed Decision and Rasmussen's Decision Ladder (1976, cited in Naikar, 2010) represent two accepted models representing the decision process of experienced personnel in dynamic situations. Both models are dependent on a high level of expertise from the decision maker and the ability to process information in a structured sequence that characterises rational, knowledge-based behaviour (Naikar, 2010). Neither model references the application of risk management into the decision making process or how prior exposure may influence risk tolerance and the cognitive process. Recognition Primed Decision Making (RPDM) requires a level of operational maturity bordering on mastery that can only be achieved through significant and repeated exposures that result in both positive and negative consequences. Basing training solely on RPDM can be problematic as it relies on teaching rookie ICs the "experience" of veterans and expecting them to respond as the veteran would, despite not having the personal library of experience to draw upon. Alternatively, the cognitive processes explained by Kahneman (2012) explain how complex cognitive processes such as risk analysis during dynamic emergency situations can be expedited by the development of advanced and efficient cognitive processes that can be taught, practiced and mastered. Unlike RPDM, Kahneman's approach supports the implementation of ISO31000 risk analysis during dynamic emergencies. This is not to say that RPDM does not have a place in risk management during emergency operations, however to introduce it to inexperienced ICs as the sole means of risk analysis is not appropriate.

Risk analysis (also known as risk assessment) is the process to comprehend the nature of risk and to determine the level of risk (SAI Global, 2013a). The process of comprehension requires the risk manager to be able to adequately interpret risk sources in a structured manner and to subsequently understand the probability and consequences of an event occurring. During even the most rapidly changing emergency situations the risk management framework and structure remains the same. Each risk analysis must be considered a new separate process, even if it builds upon a previously and recently completed analysis of the same emergency situation at an earlier point in time. This realisation is significant as it supports the understanding that dynamic risk management does not involve a changing architecture or process of analysis, but rather the same risk management architecture and analysis process applied multiple times during a rapidly changing (dynamic) emergency situation.

Risk analysis may either be qualitative, quantitative or a combination of both. Qualitative analysis involves descriptive and often subjective appraisal of risk as described by the assessor. It is often useful when risk treatment strategies involve multiple risks at different levels that cannot be accurately measured on the same quantitative scale and may be suitable during preliminary or scoping assessments. Importantly, when qualitative analysis is applied "there should be a clear explanation of all the terms employed and the basis for all criteria should be recorded" (SAI Global, 2013a, p18). Review of fire services literature (ACT, unknown; NZFS, 2008; DFES, 2012; SACFS, 2014) identified that whilst prioritised objectives of the protection of life, property and the environment were common across jurisdictions, explanations of terminology were largely absent from operational material. Yung (2008) asserts that reliance on qualitative assessment alone must be considered fundamentally flawed because subjective judgements cannot be verified and may often differ between operators. Further, the same operator may make different decisions given the same situation at various points in time.

Quantitative assessment requires the analysis of numerical data to calculate probabilities, frequencies and distributions. Considered the epitome of fire risk analysis probabilistic risk analysis requires detailed and time consuming consideration of all possible outcomes as either a function of incidence, Bayesean probability or life/dollar loss per unit time (Yung, 2008). Such analysis requires availability of substantial high quality data as well as the ability to numerically represent variability within defined confidence levels, therefore it cannot be undertaken within the parameters and constraints of a single emergency incident. This is supported in (ACTESA, date unknown, p2] by the Dynamic Risk assessment overview statement that "often, rescues have to be performed, exposures protected and hose lines placed before a complete appreciation of all material facts have been obtained". Whilst typical quantitative analysis, including fault tree or event tree diagrams, may be particularly useful for pre-incident planning and as a supporting assurance process, their complexity and time required for completion render them impractical for incident ground completion. Review of available literature identified that whilst significant international statistical analysis of fire related fatality and injury data were available (DCLG, 2015; FEMA, 2011 & 2012) a total absence of statistical analysis of Australian firefighting injuries and risk management during dynamic operations was noted in both published and internal brigade documentation.

For risk analysis during dynamic incidents to align to ISO31000, both qualitative and quantitative components are arguably required. Reviews of historical injury data may provide quantitative probabilities pertaining to the effectiveness of certain personal protective equipment in reducing firefighter injuries. At the same time, experience may provide an IC with valuable insight into qualitatively assessing the effectiveness of specific tactics in certain situations.

8.3.2 *Risk treatment on the fireground*

Risk treatment involves the application of mitigating processes, systems or other inhibitors to reduce the likelihood or consequence of an event occurring (ISO, 2018; SAI Global, 2013a & 2013b). Consequences of inaccurate identification of risk and subsequent treatment can be catastrophic with Ash & Smallman (2012) identifying 19% of all firefighter deaths in the United States between 2000 and 2005 being a direct result of human error. In the context of firefighting operations, risk treatments (also known as controls) are subsequently presented in the contextualisation of the traditional hierarchy of controls.

At the top of the hierarchy is “elimination” which refers to the removal of the risk source. In the firefighting context this may be viewed as pre-operational actions such as arson prevention or road safety campaigns. During an emergency incident “elimination” may include the decision not to commit crews, but rather to isolate a fuel source and permit it to ‘burn out’ so that lives are not endangered.

Next in the hierarchy is “substitution” which is difficult to translate to the firefighting context because firefighters often respond to emergency situations where time and resourcing restrictions are encountered. It may be considered that a decision to use defensive firefighting strategies, as opposed to offensive internal firefighting strategies, may meet the definition for substitution because even though the risk source is not eliminated, the approach to resolving the incident is specifically varied in a manner that reduces the potential for an adverse event to occur.

“Engineering” controls are those that isolate assets from the risk source. In the firefighting context this may only be partially achieved because there is likely to be a requirement for at least several firefighters to be present within the ‘hot’ zone (DFES 2012, 2015a, 2015b) and this remains essential to resolving many dynamic emergency situations. Isolation occurs through the implementation of controlled access to areas within an emergency incident that are the greatest risk source through Entry Control Officers and physical demarcation (DFES, 2015a, 2015b). Despite the use of isolation controls at emergency incidents, which may reduce the potential for greater numbers of adverse outcomes, ICs are still required to commit sufficient firefighters into hazardous situations in order to resolve the emergency.

“Administrative” controls are the policies, procedures and ‘doctrine’ that provide organisational guidance as to the appropriate manner in which to resolve a dynamic emergency situation. Extensive fire services literature in this area was found, however, an absence of established risk criterion or documented risk thresholds was also noted. No reason for this absence was found.

“Personnel attitudes” are an addition to the traditional hierarchy of controls and may be considered a critical component to the contextualised hierarchy of controls within the firefighting environment. It may be considered that personnel attitudes are significantly influenced by the internal context in which they evolve (Lloyd, 2005, 2008) and the internal context of firefighters is particularly influential. It is therefore surmised that the attitude of individual firefighters under the command of an IC must be considered in the contextualised hierarchy of controls. Whilst good attitudes will afford some benefit for the reduction of the likelihood of an adverse outcome, poor attitudes will inevitably increase the potential for failure to implement or abide by other controls and therefore increase both the probability and severity of adverse outcomes on the incident ground.

“Personal protective equipment” colloquially known as PPE within fire services represents the final line of defence between personnel and an adverse outcome. Whilst some PPE may in fact reduce the potential for realisation of an adverse effect, for instance breathing apparatus theoretically preventing a firefighter inhaling toxic smoke and products of combustion, it must also be considered that the presence of PPE may result in firefighters undertaking greater risk taking behaviour due to a perception that the PPE affords them complete or excessive levels of protection (Penney, 2013).

8.4 Risk attitudes amongst firefighters

Differences in the identification of objectives and the willingness to accept and retain risk (risk tolerance) between strategic and tactical levels within an emergency services organisation, as reported by Ash and Smallman (2012) and Jacobs (2010), may result in risk management decisions being made by ICs that could be later considered to be inappropriate or unjustified. Further, Ash and Smallman (2012) identified the perception by emergency services personnel that strategic (organisational) decisions and guidance may hinder achievement of goals at a tactical level and actually contribute to inappropriate risk management during emergency response. Further, inappropriate or insufficient understanding and consideration of risk may leave emergency services personnel with potentially dangerous familiarity with the hazards they face (Sadler et al., 2007).

Also worth consideration is the intimate culture amongst firefighting crews that can affect management of risk during dynamic emergencies. Firefighters spend a significant amount of time together during both emergency incidents and routine station life (Childs et al., 2004). In this environment, indoctrinated traits established by organisational culture invariably flourish and form a unique environment that has the capacity to directly influence an IC's management of risk during dynamic emergency operations. Reports including NIFC (1996) and Moore-Merrell et al. (2008) identify an established culture of risk taking amongst firefighters in order 'to get the job done' regardless of operational guidelines. This is supported by the findings of Kunadharaju et al. (2011) who reported, in contrast to most high hazard work, firefighting operations are actively based on hazard engagement, typically compounded by acute time pressures. In addition to these findings, Fender (2003) reported multiple firefighter specific traits that directly affected personal risk tolerance. These included:

- The age of a victim - the younger the victim the higher the threshold to personal injury or death;
- Respect for the officer in charge – firefighters were willing to undertake more dangerous tasks if they respected the officer giving a command;
- A sense of pride in taking risks; and
- Expectations of the community.

A previous study into the decontamination practices of firefighters exposed to hazardous and toxic materials (Penney, 2013) found a tendency amongst firefighters to perceive potentially life threatening incidents as routine if they were regularly encountered without acute health effects becoming evident. It is suggested the cultural acceptance of personal risk taking amongst firefighting crews needs to be carefully understood by ICs who are ultimately responsible for crew safety and may well have less risk tolerance during incidents.

Recent research (Penney, 2016, 2019) provides insight into the risk attitudes and perceptions of operational Australian firefighters. The research was conducted in two phases: (1) Semistructured interviews and (2) subsequent in-depth structured surveys. This enabled exploration and documentation of the beliefs, understanding, and attitudes of fire and emergency service ICs. Phase one involved ethnographic qualitative interactive observation of 20 current serving professional fire and emergency service ICs over a three-month period. All participants were experienced ICs with a minimum of seven years operational experience across all fire service hazards, including but not limited to structure fire, bushfire, hazardous materials, road crash, and other rescue response. Semistructured interviews and subsequent in-depth structured surveys designed to identify the individual's risk attitudes and beliefs were completed by all participants. The participation of one candidate was interrupted by an incident call out, resulting in 19 interviews and surveys being available for analysis. These represented 7% of the overall officer population from a Western Australian career fire service background.

The first question asked of participants in the semistructured interview was "How do you define risk?" Whilst all participant responses acknowledged that risk is a consideration of consequences and likelihood, only one participant provided the answer "it is the effect of uncertainty on objectives" as defined in ISO31000. Approximately a quarter of participants

(26%) provided answers that were specific to emergency response without consideration of the greater application of risk, and only one participant provided the restrictive definition “risk is the potential to injure me”. Consistent with the findings of Tissington and Flin (2004) and Reinhardt-Klein (2010), these answers suggest fire and emergency service ICs generally have a perception of risk as the practical consideration of consequence and likelihood as it applies to a reactive emergency environment, rather than as a considered and managed process consistent with ISO31000.

The second question asked of participants was “How do you manage risk in a dynamic emergency environment compared to other situations and contexts?” In response, nearly all participants identified that risk management in dynamic contexts was based on a similar process to risk management in other situations, but with limited information available and with restricted time frames in which to make decisions. Ten percent of participants expressed the opinion that dynamic risk management required more “forward thinking” than risk management in other situations. These responses again suggest the study group has adopted a definition of risk that is reasonably consistent throughout their population and contextualised to their perception of reality but does not consider all elements detailed in ISO31000; especially when consideration is given to the example of the special forces soldier in a hostage situation provided in SAHB436 (SAI Global, 2013a).

More than half of participants (58%) also expressed that they managed risk in dynamic emergency environments according to how they believed their organisation expected them to do so, or that they managed risk in accordance with organisational procedures and protocols. This suggests the majority of fire and emergency service ICs believed they managed risk using the same risk attitudes as their organisation. This was despite a review of the literature identifying an absence of organisational risk thresholds and attitudes specific to dynamic emergency response environments.

Responses from the study group to the third question “How do you decide whether risks are acceptable in a dynamic emergency environment?” were varied. A quarter of participants (26%) reported they relied on organisational procedures and protocols; almost half of participants (47%) reported they relied on personal prior experience to determine whether risks were acceptable; 16% of participants stated they simply relied on whether they believed the risk was acceptable to themselves personally; and 10% of participants responded that in the case of “life involvement” (being the fire services terminology for when potential consequences include the loss of occupant life), all risks are acceptable. The variation in answers provided by fire and emergency service ICs represents significant variance in the risk thresholds between ICs within the same organisation. Conflicts between risk attitudes will foreseeably lead to increased risk at an emergency incident because additional uncertainty is introduced when individuals work together to form incident management teams or when they are responsible for different sectors within the same emergency incident. When the answers provided by participants to question three are considered in conjunction with the answers provided by participants to question two, the variance in risk thresholds between participants suggests an absence of a defined organisational internal risk context that may otherwise guide participants towards similar answers. This notion is consistent with Fender (2003) and reinforces the conclusion that, for risk management to be compliant with ISO31000, it must be ingrained as part of the core culture of the fire service inclusive of explicitly defined risk tolerances.

The final question posed to fire and emergency service ICs was “Does the risk management process differ in the dynamic emergency environment compared to other situations? If yes, then how?” Responses provided by participants were far less varied than the responses to question three. Forty-two percent of participants stated there was no difference in the process; however, half of these participants also stated the time frame available for completing the risk assessment was significantly reduced during dynamic emergency environments. Interestingly, one participant also stated that risk tolerance is significantly higher during dynamic emergency operations compared to other situations, which suggests fluctuating risk thresholds depending on the participant's evolving perception of the severity of an incident. In addition, only one participant identified that the risk management process had to be repeated multiple times throughout an emergency incident, suggesting the remaining participants did not consider repeated risk application of the risk management process necessary.

More than half of participants (53%) stated that the risk management process did differ in the dynamic emergency environment compared to other situations. These participants all identified that the process changed due to a significant reduction in both the available information on which to make decisions, and the available time to gather further information. One participant clarified their response by adding they felt "pushed to do things you wouldn't normally do due to expectations and pressure". This indicated they operated at risk thresholds they personally felt were unacceptable. Only one participant stated the dynamic risk management process was reactive as opposed to being a thought out process.

These findings appear to contradict the previous findings of Ash and Smallman (2012), Fender (2003), and Naikar (2010), all of whom identified decision making during dynamic emergency incidents to be reactive and based on recognition of specific cues. Whilst the finding from the study reported may be interpreted with some caution, due to the moderate sample size, the finding is supported by the answers provided by the fire and emergency service ICs to the second question posed in the interview. One participant stated they were unsure whether the risk management process differed in the dynamic emergency environment compared to other situations.

The first question in the structured survey relating to risk perceptions required participants to identify the severity of potential consequence for 20 outcomes that may occur during fire and emergency incidents. From the answers provided, probability analysis was completed across the entire sample population. Conditional probability was then calculated on the basis that participants had, or had not, been previously injured at an incident. Nine participant fire and emergency service ICs had been injured at an incident and 10 had not been injured at an incident, and these results were compared to the severity assigned to the consequence in fire and emergency services risk literature. Full results are provided in Table 8.1. Analysis of the results revealed there was a conditional probability of 0.00 (zero) for all fire and emergency service ICs assigning the same severity to a consequence given the event being realised. Only in a single instance did a subgroup completely agree on the severity of a consequence. This was the non-injured group agreeing that the death of a rescuer was of catastrophic severity (represented by a conditional probability of 1.00).

Further analysis revealed there was an equal probability between the group that had never been injured, with a conditional probability of 0.2 that the survey groups' perception of consequence severity would align with the severity adopted by fire and emergency services. Whilst some variance may be expected due to potential differences in individuals' perception of the consequence realised, a conditional probability of 0.2 signifies agreement between participants and fire and emergency services in the perception of consequence severity of only a single occurrence each year. It is therefore concluded that the internal context of risk attitudes is not harmonious amongst fire and emergency service ICs and may lead to conflicting risk management during dynamic emergency situations or post-incident analysis. Descriptive analysis of the results identified a mean probability of 0.612 (standard deviation of 0.142) that the entire survey group would agree on the severity of any given consequence. This further supports the findings of the potential for conflicting risk attitudes between ICs and parties conducting post-incident analysis.

Table 8.1. Consequence severity across the entire sample and the injured/never been injured subgroups.

Rating	Insignificant			Minor			Moderate			Major			Catastrophic		
Group / Consequence	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	0.42	0.44	0.40	0.53	0.44	0.60	0.05	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.05	0.00	0.10	0.21	0.22	0.20	0.58	0.56	0.60	0.16	0.22	0.10	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.20	0.42	0.44	0.40	0.47	0.56	0.40
4	0.00	0.00	0.00	0.05	0.00	0.10	0.11	0.00	0.20	0.63	0.78	0.50	0.21	0.22	0.20
5	0.00	0.00	0.00	0.05	0.00	0.10	0.26	0.00	0.50	0.47	0.78	0.20	0.21	0.22	0.20
6	0.26	0.22	0.30	0.68	0.67	0.70	0.05	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.11	0.00	0.20	0.83	0.88	0.80	0.06	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.11	0.00	0.20	0.68	0.67	0.70	0.21	0.33	0.10	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.11	0.00	0.95	0.89	1.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.56	0.70	0.37	0.44	0.30
11	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.20	0.42	0.44	0.40	0.47	0.56	0.40
12	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.10	0.61	0.67	0.50	0.33	0.33	0.40
13	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.11	0.40	0.63	0.78	0.60	0.11	0.11	0.00
14	0.00	0.00	0.00	0.06	0.00	0.11	0.17	0.11	0.22	0.72	0.78	0.67	0.06	0.11	0.00
15	0.05	0.00	0.10	0.79	0.89	0.70	0.16	0.11	0.20	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.42	0.44	0.40	0.42	0.56	0.30	0.16	0.00	0.30	0.00	0.00	0.00
17	0.05	0.00	0.10	0.68	0.44	0.90	0.26	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.05	0.00	0.10	0.42	0.33	0.50	0.37	0.44	0.30	0.16	0.22	0.10
19	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.22	0.50	0.58	0.78	0.40	0.05	0.00	0.10
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.44	0.60	0.47	0.56	0.40

Consequences:

1. Near miss—cut finger
2. Near miss—broken arm
3. Near miss—death of rescuer
4. Near miss—exposure to acutely toxic material
5. Near miss—exposure to hazardous material with health effects that may take 20 years to occur
6. Scratch or dent to a vehicle
7. Cut finger requiring first aid treatment
8. Broken arm requiring hospitalization
9. Death of a rescuer
10. Exposure to acutely toxic hazardous material requiring hospital admission
11. Exposure to hazardous material that results in lung damage only evident 20 years post-exposure
12. Inhaling asbestos particulates and dust as a result of rescue activities
13. Exposure to silica particulates and dust as a result of rescue activities
14. Exposure to glass particulates and dusts as a result of rescue activities
15. Damage to a vehicle resulting in $1000 damage
16. Damage to a vehicle resulting in $20,000 damage
17. Damage to the environment that does not result in long term impact
18. Damage to the environment resulting in long term impact
19. Lung tissue damage without respiratory impairment
20. Lung tissue damage that limits physical activity

Group:

A. Total study population

B. Subgroup: Study population that had been injured during emergency response whilst working under a different IC

C. Subgroup: Study population that had never been injured during emergency response whilst working under a different IC

An individual's beliefs and expectations can significantly affect the internal context of the risk management process (SAI Global, 2013a). To investigate how this may be a factor in risk management during dynamic emergency operations, the second question of the survey required participants to state their agreement to four statements regarding external and personal risk attitudes and expectations using a Likert scale. The statements were:

1. There is an expectation that emergency services personnel will risk their own lives to save others.
2. There is an expectation that emergency services personnel will risk their own lives to save property.
3. There is an expectation that emergency services personnel will risk their own lives to save the environment.
4. Emergency services personnel have a moral obligation to put themselves at a higher level of risk than the general public in the course of their duties.

Full results are provided in Table 8.2. Analysis of these results reveals that the overwhelming majority of the entire study group (74%), as well as the both subgroups (injured 77% and never injured 70%), believed there were external expectations that emergency services personnel would risk their own lives to save others. By comparison, only 52% of the entire study group, 78% of the injured subgroup, and 30% of the never injured subgroup believed there were external expectations that emergency services personnel would risk their own lives to save property. This difference in attitudes between the injured and never injured populations appears to suggest personnel who had a higher personal risk threshold may be more likely to be injured during emergency operations; however, further research is required to confirm this hypothesis.

Analysis of the responses to the statement "There is an expectation that emergency services personnel will risk their own lives to save the environment" was less conclusive but appeared to suggest a less strongly held belief amongst the study group of fire and emergency service ICs that this was the case (37% of the total study group stating they either disagreed or strongly disagreed with the statement).

Table 8.2. Incident controller perceptions and expectations across the entire sample and the injured/never been injured subgroups.

Response	Strongly Disagree			Disagree			Neutral			Agree			Strongly Agree		
Group / Belief	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
1	0.11	0.11	0.1	0.11	0.00	0.2	0.05	0.11	0.00	0.53	0.44	0.60	0.21	0.33	0.10
2	0.16	0.11	0.20	0.11	0.00	0.20	0.21	0.11	0.30	0.47	0.67	0.30	0.05	0.11	0.00
3	0.21	0.11	0.30	0.16	0.11	0.20	0.37	0.56	0.20	0.26	0.22	0.30	0.00	0.00	0.00
4	0.05	0.00	0.10	0.16	0.11	0.20	0.05	0.11	0.00	0.68	0.67	0.70	0.05	0.11	0.00

Beliefs:

1. There is an expectation that emergency services personnel will risk their own lives to save others.
2. There is an expectation that emergency services personnel will risk their own lives to save property.
3. There is an expectation that emergency services personnel will risk their own lives to save the environment.
4. Emergency services personnel have a moral obligation to put themselves at a higher level of risk than the general public in the course of their duties.

Group:

A. Total study population
B. Subgroup: Study population that had been injured during emergency response whilst working under a different IC
C. Subgroup: Study population that had never been injured during emergency response whilst working under a different IC

To further define the risk attitudes and tolerance of the study group, participants were required to identify whether potential scenarios were either acceptable or unacceptable when the probability of realisation of the consequence was low, moderate, and high. Participants were required to answer the question in two contexts: First, that they were personally exposed to the risk source and, second, that they were responsible for other responders and it was these other responders who were exposed to the risk source. The scenarios presented were:

1. Entering a burning building to rescue a person where the consequence is being severely injured or killed.
2. Rescuing a person from a vehicle where the consequence is being exposed to dust that may cause immediate lung damage.
3. Entering a toxic smoke plume to rescue a person where the consequence is developing cancer.
4. Rescuing a person from a vehicle where the consequence is being exposed to dust that may cause long term lung damage.
5. Entering a burning building to rescue a child where the consequence is being severely injured or killed.
6. Entering a burning building to rescue a colleague where the consequence is being severely injured or killed.
7. Entering a burning building to save the property where the consequence is being severely injured or killed.

Full results are provided in Table 8.3. Analysis of results revealed a probability of certainty (where probability equals 1.00) amongst the study group of only 0.143. This means there was a probability of 0.857 that participants did not collectively agree on risk tolerance attitudes or thresholds. Further analysis revealed a probability of only 0.286 that all participants shared the same risk tolerance across the presented scenarios. This probability increased to 0.381 amongst the “injured” population, whilst there was no change in the probability of agreeance amongst the “never injured” population compared to all participants. One potential explanation for the increased consensus of risk acceptance amongst the “injured” population may be that those participants who had been previously injured held a higher risk tolerance and therefore were more likely to undertake hazardous tasks that may result in injury compared to the “never injured” group.

Risk acceptance with limited certainty was also higher for the entire study population and both injured and never injured subpopulations where life involvement was present. Participants would typically put both their own safety and the safety of personnel under their command at increased risk to facilitate occupant rescue (from all risk sources). This risk acceptance with limited certainty increased marginally where rescue was of a colleague, particularly when risk was transferred from the participant to those under the participant’s control. Marginal increase in risk threshold was observed between personal and personnel exposure where rescue involved a child compared to an adult. It is hypothesised that this increase may be a consequence of perceived community expectations and/or due to an innate willingness to permit great risk to save a child. Further investigation is required to explore this hypothesis.

Risk acceptance with limited certainty declined quickly for the protection of property, whilst the level of certainty decreased as the lead time to the realisation of potential consequences increased. For example, the certainty regarding risk acceptance involving immediate impacts, such as trauma, was generally higher compared to those involving delayed impacts, such as cancer or lung disease. This suggest participants were more likely to be concerned with impacts they can witness immediately and is supported by the findings of previous research (Penney, 2013).

Descriptive analysis of the results identified a mean probability of 0.529 (standard deviation of 0.336) that the entire survey group would agree on the acceptability of any given situation where the risk was personal in nature. By comparison, a mean probability of 0.449

(standard deviation of 0.321) was found that the entire survey group would agree on the acceptability of any given situation where the risk was to personnel under the participant's command. This further supports the findings that participants were more likely to accept risk when they believed the consequences were limited to themselves.

Table 8.3. Risk tolerance to the participant themselves compared to those under their command.

	Risk to Participant Themselves						Risk to Personnel Under the Command of the Participant					
Risk Tolerance	**Acceptable**			**Unacceptable**			**Acceptable**			**Unacceptable**		
Context & Risk / Group	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
2	0.63	0.56	0.70	0.37	0.44	0.30	0.47	0.56	0.40	0.53	0.44	0.60
3	0.16	0.00	0.30	0.84	1.00	0.70	0.05	0.00	0.10	0.95	1.00	0.90
4	0.95	1.00	0.90	0.05	0.00	0.10	0.79	0.89	0.70	0.21	0.11	0.30
5	0.47	0.56	0.40	0.53	0.44	0.60	0.32	0.33	0.30	0.68	0.67	0.70
6	0.37	0.33	0.40	0.63	0.67	0.60	0.21	0.22	0.20	0.79	0.78	0.80
7	0.58	0.56	0.60	0.42	0.44	0.40	0.63	0.78	0.50	0.37	0.22	0.50
8	0.26	0.22	0.30	0.74	0.78	0.70	0.26	0.22	0.30	0.74	0.78	0.70
9	0.16	0.11	0.20	0.84	0.89	0.80	0.26	0.22	0.20	0.74	0.78	0.80
10	0.84	0.89	0.90	0.16	0.11	0.10	0.74	1.00	0.60	0.26	0.00	0.40
11	0.32	0.22	0.40	0.68	0.78	0.60	0.26	0.22	0.30	0.74	0.78	0.70
12	0.21	0.22	0.20	0.79	0.78	0.80	0.21	0.22	0.20	0.79	0.78	0.80
13	1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00
14	0.79	0.67	0.90	0.21	0.33	0.10	0.53	0.67	0.40	0.47	0.33	0.60
15	0.21	0.11	0.30	0.79	0.89	0.70	0.11	0.11	0.10	0.89	0.89	0.90
16	1.00	1.00	1.00	0.00	0.00	0.00	0.95	1.00	0.90	0.05	0.00	0.10
17	0.79	0.67	0.90	0.21	0.33	0.10	0.63	0.78	0.50	0.37	0.22	0.50
18	0.37	0.33	0.40	0.63	0.67	0.60	0.16	0.22	0.10	0.84	0.78	0.90
19	0.84	0.78	0.90	0.16	0.22	0.10	0.68	0.67	0.70	0.32	0.33	0.30
20	0.16	0.11	0.20	0.84	0.89	0.80	0.16	0.22	0.10	0.84	0.78	0.90
21	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00

Context and Risk:

1. Entering a burning building to rescue a person where there is a low probability of being severely injured or killed.
2. Entering a burning building to rescue a person where there is a moderate probability of being severely injured or killed.
3. Entering a burning building to rescue a person where there is a high probability of being severely injured or killed
4. Rescuing a person from a vehicle where there is a low probability of being exposed to dust that may cause immediate lung damage.
5. Rescuing a person from a vehicle where there is a moderate probability of being exposed to dust that may cause immediate lung damage.
6. Rescuing a person from a vehicle where there is a high probability of being exposed to dust that may cause immediate lung damage.
7. Entering a toxic smoke plume to rescue a person where there is a low probability of developing cancer.
8. Entering a toxic smoke plume to rescue a person where there is a moderate probability of developing cancer.
9. Entering a toxic smoke plume to rescue a person where there is a high probability of developing cancer.
10. Rescuing a person from a vehicle where there is a low probability of being exposed to dust that may cause long term lung damage.
11. Rescuing a person from a vehicle where there is a moderate probability of being exposed to dust that may cause long term lung damage.

12. Rescuing a person from a vehicle where there is a high probability of being exposed to dust that may cause long term lung damage.
13. Entering a burning building to rescue a child where there is a low probability of being severely injured or killed
14. Entering a burning building to rescue a child where there is a moderate probability of being severely injured or killed.
15. Entering a burning building to rescue a child where there is a high probability of being severely injured or killed.
16. Entering a burning building to rescue a colleague where there is a low probability of being severely injured or killed.
17. Entering a burning building to rescue a colleague where there is a moderate probability of being severely injured or killed.
18. Entering a burning building to rescue a colleague where there is a high probability of being severely injured or killed.
19. Entering a burning building to save the property where there is a low probability of being severely injured or killed.
20. Entering a burning building to save the property where there is a moderate probability of being severely injured or killed.
21. Entering a burning building to save the property where there is a high probability of being severely injured or killed.

Group:

A. Total study population
B. Subgroup: Study population that had been injured during emergency response whilst working under a different IC
C. Subgroup: Study population that had *never* been injured during emergency response whilst working under a different IC

8.5 Probability of firefighter injury during emergency response

To determine the probability of firefighter injury during emergency response, a retrospective analysis of Western Australian fire service safety and incident reports between January 1st 2001 and January 1st 2015 was conducted (Penney, 2019). A retrospective analysis of Western Australian fire service safety and incident reports between January 1st 2001 and January 1st 2015 was conducted. Initial analysis enabled the calculation of conditional probability given a reportable incident occurs, and likelihood on the basis of activity, risk source and nature of injury reported. The results are detailed in Tables 8.4-8.6. Each table is ordered from highest to lowest frequency.

Table 8.4. Analysis by activity.

Activity (A)	Count	P(A|B)	Occurrence per year	Likelihood
Firefighting	327	0.491	21.800	Almost certain
RCR	110	0.165	7.333	Almost certain
Bushfire fighting	99	0.149	6.600	Almost certain
Rescue	36	0.054	2.400	Almost certain
Driving	30	0.045	2.000	Almost certain
Breathing Apparatus	20	0.030	1.333	Almost certain
Suicide Response	15	0.023	1.000	Almost certain
Hazmat	12	0.018	0.800	Moderate
Environmental	8	0.012	0.533	Moderate
DBA	5	0.008	0.333	Moderate
Not reported	2	0.003	0.133	Unlikely
Storm	2	0.003	0.133	Unlikely

Table 8.5. Analysis by risk source.

Risk source (A)	Count	P(A|B)	Occurrence per year	Likelihood
Physical Strain	215	0.323	14.333	Almost certain
Exposure - asbestos	120	0.180	8.000	Almost certain
Exposure - psychological	95	0.143	6.333	Almost certain
Impact	49	0.074	3.267	Almost certain
Exposure - smoke	37	0.056	2.467	Almost certain
Exposure - biohazard	24	0.036	1.600	Almost certain
Exposure - hazmat fire	24	0.036	1.600	Almost certain
Equipment failure	21	0.032	1.400	Almost certain
Exposure - chemical	20	0.030	1.333	Almost certain
Thermal	16	0.024	1.067	Likely
Operator error	11	0.017	0.733	Moderate
Animal	7	0.011	0.467	Moderate
Communications	5	0.008	0.333	Moderate
Environmental	4	0.006	0.267	Moderate
Impaired Vision	4	0.006	0.267	Moderate
Other person	4	0.006	0.267	Moderate
Blast/Explosion	2	0.003	0.133	Unlikely
Entrapment	2	0.003	0.133	Unlikely
Exposure - noise	2	0.003	0.133	Unlikely
Violence	2	0.003	0.133	Unlikely
Electrical	1	0.002	0.067	Rare
Not reported	1	0.002	0.067	Rare

Table 8.6. Analysis by injury.

Nature of injury (A)	Count	P(A|B)	Occurrence per year	Likelihood
Inhalation	163	0.245	10.867	Almost certain
Psychological	96	0.144	6.400	Almost certain
Nil	70	0.105	4.667	Almost certain
Back	56	0.084	3.733	Almost certain
Knee	42	0.063	2.800	Almost certain
Eye	32	0.048	2.133	Almost certain
Heat illness	30	0.045	2.000	Almost certain
Shoulder	26	0.039	1.733	Almost certain
Leg	16	0.024	1.067	Almost certain
General	15	0.023	1.000	Likely
Head / spinal	13	0.020	0.867	Likely
Ankle	11	0.017	0.733	Moderate
Arm	11	0.017	0.733	Moderate
Finger	9	0.014	0.600	Moderate
Face	8	0.012	0.533	Moderate

Foot	8	0.012	0.533	Moderate
Multiple	8	0.012	0.533	Moderate
Neck	8	0.012	0.533	Moderate
Hand	7	0.011	0.467	Moderate
Elbow	6	0.009	0.400	Moderate
Ear	5	0.008	0.333	Moderate
Absorption	4	0.006	0.267	Moderate
Not reported	4	0.006	0.267	Moderate
Wrist	4	0.006	0.267	Moderate
Chest	3	0.005	0.200	Unlikely
Groin	3	0.005	0.200	Unlikely
Hip	3	0.005	0.200	Unlikely
Abdominal	2	0.003	0.133	Unlikely
Ingestion	2	0.003	0.133	Rare
Thermal	1	0.002	0.067	Rare

By frequency, firefighting was almost three times more likely to result in a reportable event compared to any other activity with an occurrence of 21.8 times per year. Road crash rescue (RCR) response resulted in 7.3 reportable events per year whilst bushfire fighting resulted in 6.6 reportable incidents per year. This result suggests additional attention should be provided in training personnel and developing suitable risk mitigation procedures the activities most likely to give rise to a reportable incident, for example, firefighting, RCR and bush firefighting.

In terms of risk source, Physical Strain is almost 1.8 times more likely to result in a reportable event compared to other risk sources. This is consistent with the physically demanding nature of firefighting (DFES, 2013) and is comparable to overexertion/strain injury rates in United States firefighters (FEMA, 2011).

Exposure to various hazards including asbestos, chemicals and biohazards collectively accounts for more reports than any other risk source (total of 225 incidents with a conditional probability of 0.338). Such exposures are impossible to eradicate due to the inherent nature of all hazards emergency response. However, the likelihood of adverse outcomes can be partly mitigated through procedural and tactical measures. Such an approach is best illustrated using a bow tie analysis (Robinson et al., 2010) as shown in Figure 8.1. In this manner both pre-exposure and post exposure controls or barriers can be implemented holistically to reduce the likelihood and severity of adverse consequences. The bow tie analysis also facilitates the illustration of relationships between various barriers. Figure 8.1 provides a simple example of this in the firefighting context. Where a relationship exists between barriers, the influence of the preceding barrier may be either agonistic or antagonistic on the effectiveness of the following barrier. For example, inappropriate or insufficient research and data may lead to inappropriate organisational policy. This, in turn, can result in inappropriate training which will ultimately weaken risk management at all operational and organisational levels. The combined effect of the barriers and intrinsic relationships can ultimately affect the severity of realised consequences.

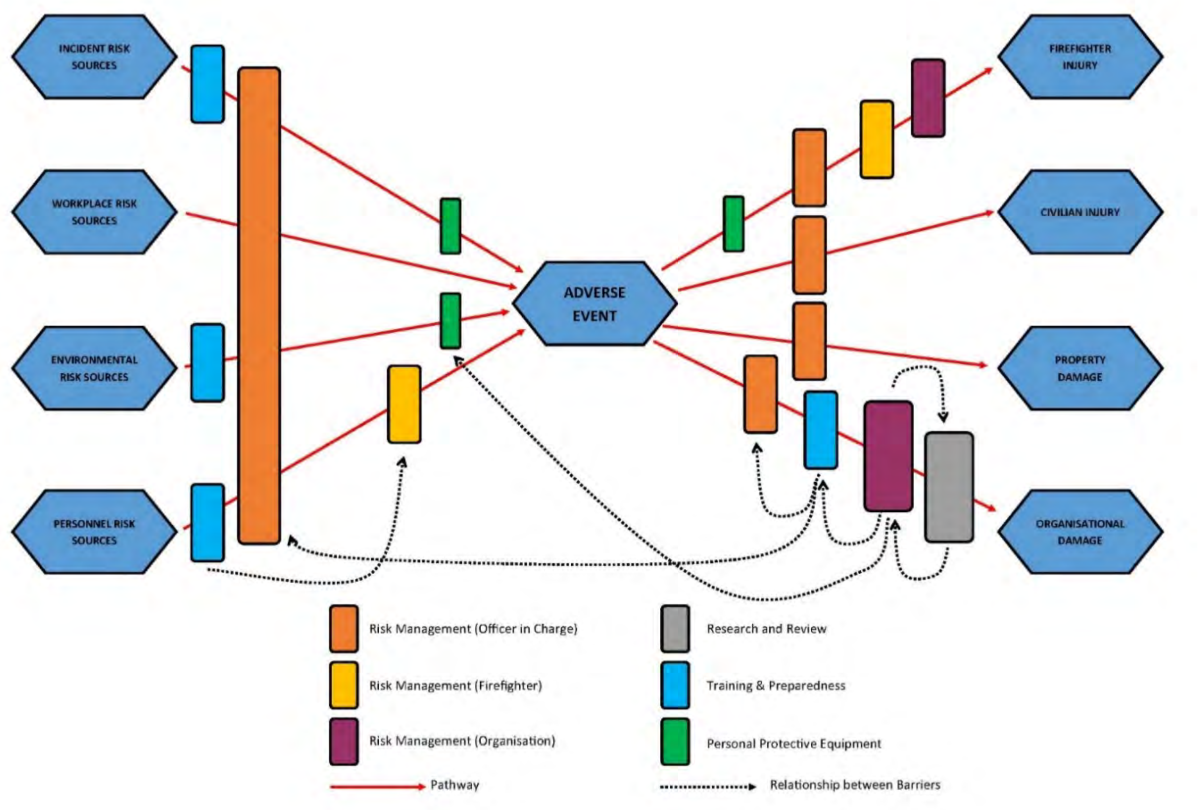

Figure 8.1. Simplified bow tie analysis contextualised to firefighting operations

Just as firefighting is extremely physically demanding, it is also psychologically demanding with exposure to psychological trauma identified as the second most common risk source resulting in reportable events. Other researchers (Carll, 2007; Trappler, 2014) concur that care must be taken in addressing risks arising from exposures of a psychological nature in firefighting which are unique to the emergency service profession. Just as education, awareness and resilience training is important prior to exposure to events of a psychological nature, specific psychological management programs and counselling are required post exposure.

Analysis by injury yields results that, in limited circumstances, appear to conflict with other available data sets. Inhalation ‘injuries’ are the most probable of all classified injuries to occur. However, this may be explained by the fact that all reported incidences of “inhalation” of smoke or other chemicals were captured in this category, regardless of whether acute injury occurred. Psychological ‘injuries’ were the second most common reported injury and this is consistent with the analysis of risk source data. Surprisingly thermal injuries, being those resulting from heat transfer were the least probable (0.002 conditional probability). This conflicts with data reported by FEMA (2011, 2012) which identifies a significantly higher thermal injury occurrence rate. The number of thermal injuries reported in this study may be lower than the true number of injuries because many incidents may remain unreported. The probability of “Nil” injuries occurring represents “Near Misses” where no injury was actually sustained and is the third highest amongst reported injuries sustained. Again, this figure may be lower than the true number of near misses that occur during incidents because of a lack of report completion when near misses occur.

Table 8.7 reports the conditional probability of a specific injury occurring given an injury occurs during the specified activity. Across all activities, the “Nil” injury or ‘near miss’ is prevalent. This is consistent with previous findings and suggests a large number of incidents occur with the potential to cause injury, but do not actually cause injury in the specific case reported. Psychological injuries are also well represented throughout the reports, particularly where the potential or realisation of human trauma is present (for instance Road Crash Rescue and Suicide Response). In the case of reported injuries during Suicide Response it is suggested it is likely the "Not Reported" values should also be psychological injuries even though they have not been documented as such in the relevant reports.

Table 8.7. Conditional probability of specific injury during incident operations.

Operation	Injury	Conditional Probability
Breathing apparatus operations	Nil	0.300
	Back	0.150
	Knee	0.150
	Head / spinal	0.100
	Heat illness	0.100
	Neck	0.100
	Ankle	0.050
	Shoulder	0.050
Bushfire fighting operations	Eye	0.253
	Knee	0.141
	Nil	0.131
	Back	0.081
	Inhalation	0.061
	Leg	0.061
	Ankle	0.051
	Shoulder	0.051
	Foot	0.030
	Heat illness	0.030
	Finger	0.020
	Neck	0.020
	Arm	0.010
	Chest	0.010
	Elbow	0.010
	Face	0.010
	Multiple	0.010
	Psychological	0.010
	Wrist	0.010
Direct brigade alarm response	Eye	0.800
	Knee	0.200
Driving operations	Nil	0.800
	Back	0.033
	Ear	0.033
	Leg	0.033
	Psychological	0.033
	Shoulder	0.033
	Wrist	0.033
Firefighting operations	Inhalation	0.434
	Back	0.092
	Heat illness	0.067

	Knee	0.064
	Nil	0.064
	Shoulder	0.046
	Head / spinal	0.034
	Leg	0.028
	Arm	0.024
	Multiple	0.018
	Foot	0.015
	Hand	0.015
	Ear	0.012
	Psychological	0.012
	Ankle	0.009
	Elbow	0.009
	Eye	0.009
	Finger	0.009
	Neck	0.009
	Abdominal	0.006
	Chest	0.006
	Hip	0.006
	Face	0.003
	Groin	0.003
	Thermal	0.003
Hazardous material operations	General	0.500
	Inhalation	0.417
	Heat illness	0.083
Road crash rescue operations	Psychological	0.600
	Back	0.100
	General	0.082
	Face	0.045
	Absorption	0.018
	Inhalation	0.018
	Shoulder	0.018
	Ankle	0.009
	Arm	0.009
	Finger	0.009
	Groin	0.009
	Hand	0.009
	Heat illness	0.009
	Hip	0.009
	Ingestion	0.009
	Knee	0.009
	Multiple	0.009
	Neck	0.009
	Nil	0.009

	Wrist	0.009
Rescue (other than RCR) operations	Psychological	0.306
	Inhalation	0.194
	Back	0.083
	Nil	0.083
	Absorption	0.056
	Shoulder	0.056
	Ankle	0.028
	Elbow	0.028
	Groin	0.028
	Hand	0.028
	Ingestion	0.028
	Knee	0.028
	Not reported	0.028
	Wrist	0.028
Suicide response operations	Psychological	0.800
	Not reported	0.200

Analysis reveals thermal injuries account for a relatively insignificant conditional probability of only 0.003 during Firefighting activities only. No thermal burns are reported during Bushfire or other response. This is in stark contradiction to the probability of thermal injuries reported in United States statistics (FEMA, 2012). However, it is hypothesised that this may be due to under reporting of thermal injuries, or due to thermal injuries being referred to as injuries to specific body parts without reference to the burn trauma, or due to differences in firefighting tactics between Australia and the United States which may result in different mechanisms and frequencies of injury.

For example, inhalation injuries appear over-represented in the data which is considered surprising given the significant respiratory protection available to responding crews(DFES, 2013, 2014 & 2015a). Analysis of descriptions with the reports suggests a significant proportion of inhalation exposures may be due to partial-face fitting respiratory protection masks that do not completely prevent ingress of smoke and other products of combustion. This has been rectified since the study commenced, through the implementation of full face respirators available for firefighting personnel. The conditional probability of heat illness occurrence also warrants attention with prevalence amongst all operations and responses that require the responder to wear structural firefighting Personal Protective Equipment (PPE). Wearing PPE requires significant physical effort.

Review of the conditional probabilities detailed above should assist incident controllers having enhanced evidence based awareness of potential consequences and likelihoods prior to their occurrence during an emergency incident. Analysis of the conditional probability of injury given an injury occurs during each of the specific operations will also facilitate the review and improvement of strategic and tactical planning; personnel relief requirements; the potential effectiveness of PPE; and even guide the potential development of targeted prophylactic physical training programs.

Table 8.8 provides useful data to facilitate the development of evidence based risk mitigation strategies prior to and on the incident ground. Physical Strain recurrently accounts for high, if not the highest, level of Risk Source giving rise to a reportable incident across almost all activities. This finding is consistent with the previous results of both this study and FEMA (2011) and reaffirms the notion that firefighting is extremely physical in nature. By comparison, Moore-Merrill *et al.* (2008) reported that physical strain was the second highest contributing factor to firefighter injury in the United States (the first being a lack of situational awareness).

Table 8.8. Conditional probability of specific initiating events (Risk Sources) during incident operations.

Operation	Injury	Conditional Probability
Breathing apparatus operations	Physical Strain	0.550
	Impact	0.150
	Entrapment	0.100
	Equipment failure	0.100
	Communications	0.050
	Electrical	0.050
Bushfire fighting operations	Physical Strain	0.515
	Exposure - smoke	0.253
	Exposure - chemical	0.061
	Impact	0.051
	Thermal	0.051
	Exposure - asbestos	0.030
	Equipment failure	0.020
	Exposure - psychological	0.010
	Violence	0.010
Firefighting operations	Physical Strain	0.358
	Exposure - asbestos	0.315
	Impact	0.104
	Exposure - hazmat fire	0.073
	Exposure - smoke	0.037
	Thermal	0.034
	Equipment failure	0.024
	Communications	0.012
	Exposure - chemical	0.009
	Exposure - psychological	0.009
	Blast/Explosion	0.006
	Exposure - noise	0.006
	Operator error	0.006
	Not reported	0.003
	Violence	0.003
Hazardous material operations	Exposure - chemical	0.583
	Exposure - asbestos	0.333
	Physical Strain	0.083
Road crash rescue operations	Exposure - psychological	0.600
	Physical Strain	0.209
	Exposure - biohazard	0.164
	Exposure - asbestos	0.018
	Impact	0.009
Rescue (other than RCR) operations	Exposure - psychological	0.306
	Physical Strain	0.278
	Exposure - asbestos	0.194

	Exposure - biohazard	0.111
	Impact	0.056
	Equipment failure	0.028
	Exposure - chemical	0.028

Psychological Exposure was also well represented in the data, particularly amongst incident response involving human life and trauma including Road Crash Rescue and Suicide Response. This again supports previous findings of the study.

Exposure to various contaminants was also prevalent throughout the majority of fields. This may be significant as potential effects may be mitigated through appropriate strategic and tactical response; appropriate PPE and suitable decontamination procedures (DFES, 2015 & 2015a).

Breathing Apparatus operations are amongst the most hazardous of all firefighting activities. These operations involve the use of self-contained breathing apparatus in atmospheres not conducive to life due to the presence of smoke, heat, oxygen deficiency and/or excessive temperature [28]. During Breathing Apparatus operations, teams of two firefighters will work in close proximity to, or inside, burning structures. Typically they rely on a single line of firefighting hose for fire protection. The margin for error is therefore understandably narrow and the severity of potential consequences comparatively high (as reported in Table 7.9). Breathing apparatus operations are extremely physical in nature and this is represented by a conditional probability of 0.55 that the responsible risk source for the reportable event will be Physical Strain. Analysis also revealed a conditional probability of Impacts being the responsible risk source for the reportable incident of 0.15. It is suggested Impacts (as compared with Explosion / Blasts) are more likely to occur within a burning structure. Subsequently, this figure may be reduced through the defining of organisational risk acceptance thresholds. In turn, this would facilitate a reduction in the potential for incident controllers committing crews to internal firefighting in the absence of life involvement because of a perceived internal or external obligation to do so.

Table 8.9 provides the comparisons between actual reported consequence severity and potential consequence severity for each Activity. Analysis reveals the conditional probability of moderate to catastrophic potential consequence severity is higher than actual reported consequence severity across all Activity groups. In part this may be explained by the lack of subsequent reports or follow up detail for consequences that may have a long period of latency (for instance psychological exposures, or exposures to contaminants), or for injuries that are initially reported but worsen over time. Results of this analysis also support previous findings of the prevalence of “Nil” reported injuries in that there is a high conditional probability of ‘near misses’ within the incidents reported.

Table 8.9. Conditional probability of actual and potential consequence severity during operations

Operation	Consequence Severity	Actual	Potential
Breathing apparatus operations	Insignificant	0.300	0.000
	Minor	0.700	0.150
	Moderate	0.000	0.400
	Major	0.000	0.250
	Catastrophic	0.000	0.200
Bushfire fighting operations	Insignificant	0.818	0.000
	Minor	0.131	0.505
	Moderate	0.040	0.101
	Major	0.010	0.212

	Catastrophic	0.000	0.182
Driving operations	Insignificant	0.967	0.133
	Minor	0.033	0.100
	Moderate	0.000	0.100
	Major	0.000	0.167
	Catastrophic	-	-
Firefighting operations	Insignificant	0.933	0.031
	Minor	0.034	0.147
	Moderate	0.021	0.199
	Major	0.012	0.098
	Catastrophic	0.000	0.526
Hazardous materials operations	Insignificant	1.000	0.000
	Minor	0.000	0.000
	Moderate	0.000	0.000
	Major	0.000	0.083
	Catastrophic	0.000	0.917
Road crash rescue operations	Insignificant	0.973	0.000
	Minor	0.018	0.073
	Moderate	0.009	0.218
	Major	0.000	0.027
	Catastrophic	0.000	0.682
Rescue (other than RCR) operations	Insignificant	0.972	0.000
	Minor	0.000	0.111
	Moderate	0.028	0.306
	Major	0.000	0.056
	Catastrophic	0.000	0.528
Suicide response operations	Insignificant	1.000	0.000
	Minor	0.000	0.133
	Moderate	0.000	0.000
	Major	0.000	0.000
	Catastrophic	0.000	0.867

Further analysis reveals that, based on actual consequence severity, there was a conditional probability of zero (0.000) for a consequence of catastrophic severity occurring across the entire Activity range. This result is not consistent with numerous international studies (FEMA, 2011 & 2012; Moore-Merrell et al., 2008) and whilst acknowledging the differences in incidents responded to in different jurisdictions, this result potentially suggests Western Australian firefighting strategies are safer than those utilised by international counterparts. By comparison, a mean potential consequence of catastrophic severity revealed a conditional probability across all Activities of 0.408 (standard deviation of 0.328). These results represent a significant potential for increased severe injury, permanent disability and even death amongst the study group, and should be considered in the establishment of the internal context for risk management during dynamic emergency operations.

8.6 Implications for frontline firefighters and IMT's

In the absence of any similar studies within Australasian fire services, this chapter provides important qualitative and quantitative data that can be used to improve risk management during dynamic emergency operations. When considered together with literature reviewed, the results of the first study explicitly reject any notion of the validity of "dynamic risk management" being a stand-alone process for managing risk during emergency situations. For best practice to be realised, the architectural structure or process of risk management as defined in ISO31000 cannot change. The context in which risk management is completed may vary in dynamic emergency situations compared to that of corporate boardrooms; however, it is this unique and dynamic context of emergency situations that only further requires the risk management process to be completed in its entirety each and every time risk is assessed and subsequently managed.

The data presented in this chapter identified recurrent thermoregulatory and critical incident related risk trends across all activity groups. These trends are significant because they are associated with greater potential for serious consequences of hospitalisation or long term disability compared to less severe, but more frequently occurring, physical strain related injuries. In terms of affecting risk management during frontline operations, these results suggest Incident Controllers need to take enhanced steps to mitigate thermoregulatory related and physical strain related risks. Proactive management may include enhanced mobilisation and rotation of personnel at incidents to reduce physical loading, whilst the risks may be reactively managed through implementation of active recovery procedures and medical monitoring of crews at incidents by qualified medical practitioners to ensure it is safe for them to continue working. Both during and post the emergency phase of incidents, the Incident Controller should ensure crew mental welfare is managed to reduce the exposures to psychological events.

During almost all types of operational response the potential for major or catastrophic adverse outcomes is present. The potential consequence is consistently greater than the actual consequence realised in the data analysed. This may be explained by the mitigating effects of post event barriers (PPE, physical conditioning of personnel, etc.) or simply the personnel involved escaped more serious injury due to a combination of events that led to them being close to the impact, as opposed to being in the direct line of impact. In light of this finding it is important that incident controllers and operational personnel remain vigilant to the potentially 'normalising' effect of recurrent exposure to potentially catastrophic, albeit low frequency, situations.

8.7 Implications for urban planners

Firefighters *will* put themselves in harms way to protect vulnerable communities. Through careful and appropriate urban design that considers potential wildfire behaviour, defendability of communities, evacuation requirements and firefighter tenability using evidence based fire engineering analysis, urban planners can enhance the safety of communities in areas prone to wildfire and the firefighters that protect them.

9. Conclusions

9.1 Introduction

This section details the key outcomes from each Chapter.

9.2 Key outcomes for frontline firefighters, fire behaviour specialists and IMT's

9.2.1 *Chapter 1 - Wildfire fuels*

1. Vegetation structure plays a critical role in the development and severity of wildfires. During periods of elevated fire weather conditions, mega-wildfires in through continuous vegetation structures (particularly in forest and woodlands), no amount of resources or water (see Chapters 4-6) will be able to suppress the head fire. Firefighting strategies in these situations should therefore focus on areas of opportunity where vegetation structure, particularly surface, near surface and elevated fuels are limited and the vegetation geometry does not support a continuous wildfire front. The removal of fuel immediately adjacent to assets and communities through 'dry' firefighting strategies such as backburning (see Chapter 4) may need to be considered early in firefighting campaigns.

9.2.2 *Chapter 2 – Wildfire behaviour and characteristics*

1. Chapter 2 covers the basic modelling of wildfire development and behaviour. As the suitability of firefighting strategies are gauged against these inputs it is essential that all firefighters, fire behaviour specialists and IMT's alike not only understand the presented models, but are effective in accurately applying them. Incorrect predictions may result in inappropriate strategies being devised, leaving frontline personnel exposed to overwhelming wildfire conditions with potentially fatal consequences (see Chapters 5 and 7). Whilst fire behaviour specialists are required to accurately and competently predict wildfire behaviour, all personnel from firefighters to the IMT should be able to verify predictions thereby increasing the margin for safety for both firefighters and the community.

9.2.3 *Chapter 3 – Modelling wildfire radiant heat flux*

1. When considering the defendability of urban areas where the geometry of vegetation fuel beds prevents landscape scale wildfire behaviour:
    i. The case studies presented in Chapter 3 indicate potential significant over-estimation of radiant heat flux using the approach outlined in AS3959 in cases involving non-combustible obstructions and point-source ignition fires for a minimum of 20m separation from the fire front. This is significant as it is in this distance that wildfire flame radiation is considered to have its greatest impact (Cohen & Butler, 1996; Newman et al, 2013). Such situations are common in urban environments. The results demonstrate the importance of appropriately considering fuel geometry, wildfire behaviour, and the effect of shielding structures when calculating radiant heat impacts on buildings and emergency responders within urban environments where vegetation fuel bed geometry prevents wildfires reaching landscape proportions.
    ii. Over estimation of potential radiant heat flux impacts could, in turn, result in firefighters not being deployed to suppress wildfires and defend homes as a result of over-estimation of wildfire behaviour that indicates suppression efforts are not suitable, resulting in avoidable house loss and impacts on communities. This may occur as firefighting suppression thresholds are related to wildfire behaviour parameters throughout

jurisdictions internationally. Where inappropriate predictions fail to consider vegetation geometry that does not support the assumptions of landscape wildfire modelling, otherwise defendable areas may be left unguarded due inappropriate evaluation of suppression strategies.

9.2.4 *Chapter 4 – Wildfire suppression*

1. Wildfires, particularly mega wildfires such as those experienced in late 2019 and early 2020 throughout Australia are dynamic and complex disasters that require significant interstate and international resourcing over prolonged durations. When such events occur they will inevitably impact life and property as well as overwhelming firefighting efforts. Chapter 4 discussed the strategies available to firefighters, their limitations, and where the evidence suggests they may be successful. Detailed and accurate planning is required to be completed by IMT's and fire behaviour specialists to ensure firefighting operations are suitable and to minimise the potential for firefighter injury. When applied correctly and in the right context, the findings of new research including Table 4.15 and the RUIM may assist IMT's to achieve this.
2. As will be the case in many landscape scale wildfires and mega wildfires, detailed predictions and analysis of wildfire behaviour in itself is insufficient. Care must be taken to bridge the theory – practice gap and ensure planning is operationally relevant. The research presented in this chapter demonstrates that even in mild conditions, the head fire will often be unstoppable where it occurs in continuous vegetation fuel bed geometry. This is further supported by the findings presented in Chapters 5 and 6.The use of existing wildfire scars and prescribed burns for wildfire suppression can only be considered opportunistic and with marginal chance of success unless the burn scar is both recent (within 2-3 years) and significant in area. As climate change continues to result in worsening fire conditions, frontline firefighters, IMT's and fire behaviour specialists need to apply increased scrutiny to fuel bed structure and geometry, focusing suppression efforts where fuels are discontinuous and broken.

9.2.5 *Chapter 5 – Firefighter tenability*

1. It is concerning that existing operational wildfire suppression thresholds do not systematically or quantifiably take account of wildfire behaviour (*RoS, I* and L_F) combined with the associated potential radiant heat flux received by firefighters attempting suppression activities in a landscape scale wildfire scenario. Current fire behaviour-linked suppression guidelines do not specifically address the tenability of environmental conditions in the proximity of the flaming zone where firefighters are often working to suppress the fire. Once tenability thresholds are considered it is evident that offensive, direct attack on the head of large wildfires is extremely hazardous to firefighters under all but the mildest of conditions.
2. Consideration of radiant heat flux also reveals how truly dangerous defensive rural urban interface firefighting is. Firefighters exposed to head fire fronts will potentially be subjected to levels of radiant heat that are capable of causing severe incapacitating burns in as little as five seconds in elevated fire weather conditions and higher fuel loads. Incident Controllers and fire crew leaders must therefore carefully consider whether properties and the occupants that shelter insider them are defendable or whether the credible risk to their own crews is too high. As discussed in Chapter 7, firefighters have a personal risk tolerance higher than that of their commanding officers, this means that frontline firefighters are more likely than their ranking officers to commit themselves to defending occupants from insuppressible wildfire fronts. This is potentially due to firefighters' own personal expectations that they should put themselves in personal danger to protect and

rescue civilians, whist officers also consider the responsibility of keeping their crews safe and potential greater reaching consequences on the firefighter's family should they be severely injured or killed during wildfire suppression operations (Penney, 2019).

3. As opposed to being part of an RUI strategy, sheltering inside or behind firefighting appliances during the passage of a wildfire front should be considered an absolute last resort only. Instead, firefighters should seek refuge in suitable structures well before the expected impact of the wildfire front and emerge to salvage property where they are able to do so. Committing to a RUI defense by positioning firefighters in between a landscape scale forest wildfire front and private property or critical infrastructure with the expectation that suppression efforts will be either safe or successful is at best, reckless. Even the intervention of aerial firefighting suppression is unlikely to be sufficient to make this approach safe or effective. Given the extreme danger associated with RUI firefighting, it should be considered only as a contingency plan except in extreme circumstances where large populations of vulnerable communities including school, nursing homes and hospitals cannot be safely evacuated prior to the arrival of the wildfire front.

9.2.6 *Chapter 6 – Critical water flow rates*

1. Put simply, the effectiveness of suppression by applying water to landscape scale forest and woodlands fires drops significantly as the active flame depth of the head fire increases. By understanding this concept, as well as how vegetation structure influences fire behaviour and fire front geometry, IMT's and firefighters can more realistically assess the potential for suppression success. At the same time, if fire behaviour specialists understand these relationships, they are better prepared to describe the fire behaviour in terms that are meaningful for the IMT and frontline firefighters. The use of guiding analysis such as that presented in this and other chapters may assist IMT's determine that suppression strategies are unlikely to succeed and resources would be better spent in evacuations or allowing crews more time to prepare to defend vulnerable assets.

9.2.7 *Chapter 7 –Vehicle protection systems during entrapment and burnover*

1. The findings of this chapter should be a stark reminder to firefighters of the limitations of vehicle mounted sprinkler protection systems. Whilst vehicle protection systems including sprinklers may be successful in increasing the survivability of mild burnovers against which they've been tested, existing specifications are unlikely to afford sufficient protection against the wildfires modelled in Chapter 5. An unrealistic expectation of vehicle protection system performance may contribute to firefighters having a false sense of safety and security, and thereby being more likely to commit to suppression strategies in untenable circumstances.
2. The solution to these issues may, in part, rest with:
    i. Updated wildfire suppression training for firefighters clearly identifying the limitations of vehicle protection systems and effects of vehicle orientation during burnover events;
    ii. Greater acknowledgement by IMT's of the physical limits of wildfire suppression and an earlier consideration of defensive firefighting strategies with opportunistic 'surgical' offensive tactics;
    iii. Increased fire services investment in wildfire appliance design with a focus on passive design protection elements that mirror AS3959, particularly surrounding glazing and cabin construction.

9.2.8 *Chapter 8 – Risk in the firefighting context*

1. In the absence of any similar studies within Australasian fire services, this chapter provides important qualitative and quantitative data that can be used to improve risk management during dynamic emergency operations. When considered together with literature reviewed, the results of the first study explicitly reject any notion of the validity of "dynamic risk management" being a stand-alone process for managing risk during emergency situations. For best practice to be realised, the architectural structure or process of risk management as defined in ISO31000 cannot change. The context in which risk management is completed may vary in dynamic emergency situations compared to that of corporate boardrooms; however, it is this unique and dynamic context of emergency situations that only further requires the risk management process to be completed in its entirety each and every time risk is assessed and subsequently managed.
2. The data presented in this chapter identified recurrent thermoregulatory and critical incident related risk trends across all activity groups. These trends are significant because they are associated with greater potential for serious consequences of hospitalisation or long term disability compared to less severe, but more frequently occurring, physical strain related injuries. In terms of affecting risk management during frontline operations, these results suggest Incident Controllers need to take enhanced steps to mitigate thermoregulatory related and physical strain related risks. Proactive management may include enhanced mobilisation and rotation of personnel at incidents to reduce physical loading, whilst the risks may be reactively managed through implementation of active recovery procedures and medical monitoring of crews at incidents by qualified medical practitioners to ensure it is safe for them to continue working. Both during and post the emergency phase of incidents, the Incident Controller should ensure crew mental welfare is managed to reduce the exposures to psychological events.
3. During almost all types of operational response the potential for major or catastrophic adverse outcomes is present. The potential consequence is consistently greater than the actual consequence realised in the data analysed. This may be explained by the mitigating effects of post event barriers (PPE, physical conditioning of personnel, etc.) or simply the personnel involved escaped more serious injury due to a combination of events that led to them being close to the impact, as opposed to being in the direct line of impact. In light of this finding it is important that incident controllers and operational personnel remain vigilant to the potentially 'normalising' effect of recurrent exposure to potentially catastrophic, albeit low frequency, situations.

9.3 Implications for fire behaviour specialists and urban planners

9.3.1 *Chapter 1 - Wildfire fuels*

1. To partially address the issues identified in AS3959 and increase the accuracy of modelled wildfire outputs the following is recommended:
   - iii. Classification of vegetation based solely on qualitative descriptors should not over-ride the wildfire behaviour model applied to the scenario without due consideration of the wildfire behaviour expected to occur through the vegetation. Using the case study previously provided as an example, whilst the vegetation could reasonably be classified as Class A Forest or

Class B Woodlands, applying the Noble et al wildfire behaviour model to either of these options without modifying the deemed fuel loads would significantly result in over-estimation of wildfire outputs. In urban areas where vegetation geometry restricts wildfire growth, a more appropriate and accurate approach is to assess the fuel load utilising Vesta Fuel Hazard Scores and apply the correct vegetation availability factor. Further guidance on this can be found in Chapters 2 and 3; and

iv. Practitioners (both from fire services and land use planning perspectives) involved in modelling wildfire and calculating potential impacts require a sound understanding of the respective models and their limitations. Caution should be applied when attempting to 'simplify' complex equations, models or engineering concepts in standards, guidance material or documents for use by lay persons or in land use planning decisions. The profession of wildfire engineering is in its infancy and job titles do not necessarily equate to the knowledge and skills required to complete the required technical analysis or make informed and accurate decisions. This can be in part be remedied by professionalization / accreditation of the sector and greater recognition of the role of fire safety engineers with wildfire backgrounds in it.

9.3.2 *Chapter 2 - Wildfire behaviour and characteristics*

1. Perhaps the greatest implications of Chapter 2 for urban planners applies to assessments of potential wildfire behaviour in urban areas where the landscape scale wildfire behaviour assumed in AS3959 and many of the planning guidelines is not possible. Where vegetation fuel bed geometry (refer back to Chapter 1) prevents the development of a quasi-steady RoS (refer to section 2.3 of this chapter), as reported in recent studies (Penney & Stevenson, 2019), failure to adequately adjust inputs may result in the significant over-calculation of potential wildfire behaviour. This can be in part be remedied by deference in such instances to suitably qualified fire safety engineers with wildfire backgrounds that can provide quantified analysis and an appropriate level of fire safety engineering rigor to design solutions.

9.3.3 *Chapter 3 – Modelling wildfire radiant heat flux*

1. Inappropriate modelling of wildfire through landscaped gardens, public open space, road reserves, and residential areas within urban areas. In turn, land that is actually suitable for development may be identified as being subject to overestimated wildfire impact which restricts or prohibits development altogether. Typically, this may occur in urban settings where a small unmanaged vacant residential lot is modelled as supporting a landscape scale wildfire, in turn restricting or prohibiting development on adjacent and near-by lots.
2. Unnecessary requirements for over engineering and wildfire resistant construction standards of affected dwellings and structures that hinders development through either misidentification of land as being subject to unacceptable levels of wildfire impact, or through making development cost-prohibitive as a result of the level of wildfire resistant engineering and construction required.
3. In addition to the inherent safety factor incorporated within the vegetation availability factor previously discussed, the methodologies proposed also retain the assumption of a flame emissivity $\varepsilon = 0.95$, being representative of a landscape scale wildfire with an active uniform flame front depth greater than 2 m, and even potentially greater than 10 m (Poon, 2003; Sullivan, 2009). In cases where the active flame front will not reach this depth, it may also be suitable to reduce the emissivity. It is important to note that whilst the vegetation factor and modified view factor

model are applicable to all fuel types (forest, woodland, shrub, scrub, grassland, etc.), the point source acceleration model presented in Chapter 3 is suitable for treed forest and woodland structures only, as fire growth in other fuel structures may be significantly faster.

4. The models presented in Chapter 3 are not intended to address the potential radiant heat flux arising from surrounding buildings being involved in fire. In part, this is inherently considered within AS3959 through the requirement that associated structures on the same parcel of land and within 6m of the dwelling subject to enhanced construction standards, must also be constructed to that same standard. In new estates, all dwellings within the land development should be constructed to the required standard of wildfire resistance, in theory significantly reducing the potential for mass conflagration spreading between multiple houses. Due to the differences in wildfire and structural fire behaviour and radiation models as well as the difference in building and structure performance once impacted by wildfire, it is suggested that a high level of technical expertise is required to complete this process.

9.3.4 *Chapter 4 – Wildfire suppression*

1. By understanding wildfire behaviour and wildfire suppression strategies, urban planners can significantly influence the defendability and resilience of communities to wildfire impacts through appropriate design of development at the RUI. The research and increased analysis presented in this chapter enables wildfire impacts and potential suppression to be considered at the design stage of RUI development. Evidence based design that incorporates minimum measures for evacuations and eliminates the unrealistic expectation that firefighters will be able to defend every property will lead to more appropriate passive[6] wildfire resilient design
2. The use of design wildfires, Wildfire Engineering Briefs and Wildfire Engineering Reports, similar to the standard fire engineering processes within the urban fire engineering profession will only further increase the standard of safety in bushfire prone areas. These are detailed and complex technical documents however that required a high degree of technical knowledge and proficiency from both the engineer and the agencies involved.

9.3.5 *Chapter 5 – Firefighter tenability*

1. Current wildfire planning guidelines and policy in Australia typically set deemed to satisfy set the ‘acceptable’[7] threshold for development at $10kW^{-2}$ (NSWRFS, 2019; WAPC, 2015, 2017) for vulnerable, critical or hazardous land use[8] and between $19kWm^{-2}$ to $29kWm^{-2}$ (NSWRFS, 2019; WAPC, 2015, 2017) for standard development such as subdivision. As detailed in this chapter, $10kWm^{-2}$ is considered critical conditions for firefighters in structural PPC and breathing apparatus, with retreat required in less than 60 seconds. At the same level, for a healthy person without protective equipment, incapacitating burns are predicted in approximately 60 seconds, with severe pain and first degree burns expected to occur after substantially less exposure. By adopting these thresholds, communities are effectively being designed to be undefendable by firefighters. At $29kWm^{-2}$, firefighters in structural PPC and breathing apparatus are likely to face

[6] Passive systems do not require action or maintenance. For instance, ensuring road design allows sufficient evacuation opportunity without additional control measures is a passive measure that can be supported by appropriate and timely community evacuation messages. Firefighters being required to suppress a wildfire is an active intervention.

[7] Planning approval will typically be provided.

[8] Vulnerable land use includes schools, nursing homes, tourism etc.

incapacitating burns in less than 30 seconds. This realisation is also significant for firefighters and IMT's who are considering firefighting defense of threatened communities who must consider whether they are expected to, or are indeed themselves expecting to do the impossible and un-survivable.

2. The solution from an urban planning perspective may rest in several approaches that require consideration on a case by case basis:
   i. If development is required to be actively defendable by firefighters during the passage of a wildfire front, the maximum radiant heat impact at any point within the development needs to be within the window of safe and effective wildfire suppression. In turn, this arguably either requires extensive and permanent vegetation modification and fuel reduction around the development, or appropriate landscaping that forms part of a passive wildfire engineered design;
   ii. If development does not require active firefighter defense then the actual level of wildfire radiant heat impact can, in theory, be addressed by the application of enhanced wildfire resilient engineering construction such as that detailed in AS3959. In turn, this may also allow the fire truck related road access standards to such as those described in existing guidelines (NSWRFS, 2019; WAPC, 2015, 2017; GSA, 2012;) to be revisited;
   iii. Development of an evidence based performance based wildfire urban planning code, similar to that of the Building Code of Australia and that adopted by Tasmania (2017). This would need to go beyond the existing and largely subjective planning guidelines and carry throughout the planning and building legislation and process, as is the case in Victoria (VSG, 2019);
   iv. Professionalisation and regulation of the wildfire engineering industry. Whilst the existing Bushfire Planning and Design (BPAD) accreditation scheme is the first step in this process, the technical knowledge and expertise required of wildfire engineers arguably requires greater accreditation and regulation.

9.3.6 *Chapter 6 – Critical water flow rates*

1. The data and results presented in this chapter reinforce the implications for Urban Planners discussed in Chapter 5.

9.3.7 *Chapter 7 –Vehicle protection systems during entrapment and burnover*

1. The data and results presented in this chapter reinforce the implications for Urban Planners discussed in Chapter 5.

9.3.8 *Chapter 8 – Risk in the firefighting context*

Firefighters *will* put themselves in harms way to protect vulnerable communities. Through careful and appropriate urban design that considers potential wildfire behaviour, defendability of communities, evacuation requirements and firefighter tenability using evidence based fire engineering analysis, urban planners can enhance the safety of communities in areas prone to wildfire and the firefighters that protect them.

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