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Review

Wildland firefighter safety zones: a review of past science and summary of future needs

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Abstract. Current wildland firefighter safety zone guidelines are based on studies that assume flat terrain, radiant heating, finite flame width, constant flame temperature and high flame emissivity. Firefighter entrapments and injuries occur across a broad range of vegetation, terrain and atmospheric conditions generally when they are within two flame heights of the fire. Injury is not confined to radiant heating or flat terrain; consequently, convective heating should be considered as a potential heating mode. Current understanding of energy transport in wildland fires is briefly summarised, followed by an analysis of burn injury mechanisms within the context of wildland fire safety zones. Safety zone theoretical and experimental studies are reviewed and a selection of wildland fire entrapments are examined within the context of safe separation distances from fires. Recommendations are made for future studies needed to more fully understand and define wildland firefighter safety zones.

Additional keywords: fire intensity, firefighter safety, safety zones, wildland fire.

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Introduction

Nine hundred wildland firefighters died in fire related accidents between 1910 and 2006 in the United States, 411 of those were directly related to fire entrapments (National Wildfire Coordinating Group 1997, 2004; Mangan 2007). Injury data from the period 1990 to 2006 indicates that nominally 21% of firefighter deaths are caused by fire entrapments, 23% by aircraft accidents, 23% by vehicle accidents and 22% by heart attacks (Cook 2004; Mangan 2007). As a consequence of 11 firefighters being killed on the Inaja fire in 1957 the US Forest Service recommended that firefighters identify safety zones at all times when fighting fire (McArdle 1957; Ziegler 2007). This recommendation has been further developed into a requirement for all wildland firefighters. It is the intent that safety zones be available and accessible in the event that fire behaviour or intensity increases suddenly making current tactics unsafe (Beighley 1995). The US Forest Service defines a safety zone as ‘a preplanned area of sufficient size and suitable location that is expected to protect fire personnel from known hazards without using fire shelters’ (National Wildfire Coordinating Group 2004).

Steele (2000) summarises the results of an informal survey of 330 firefighters who were shown pictures of vegetation and provided with descriptions of season, air temperature, relative humidity and seasonal rainfall. They were then asked to predict the size of area or separation distance from flames to remain safe from injury. The minimum estimated safe distance varied by three orders of magnitude suggesting that firefighters struggle to visualise fire behaviour and estimate safe separation distances.

More than 50 years after the Inaja fire, firefighters continue to be injured or killed by fire entrapments. Wildland fire area burned is projected to double by the mid-21st century (Vose *et al.* 2012). One of the primary challenges faced by wildland firefighters is to estimate fire behaviour before implementing tactics and then continually adjust estimates as conditions change through the burning period. Given the priority for identifying safety zones in fire management activities, a relevant question is ‘Why don’t we know more about how to define effective safety zones?’ The answer most likely depends on several issues. One is that energy transport in fires is complicated and difficult to measure (Viskanta 2008). Another is the difficulty associated with quantitative estimates of fire intensity or flame geometry from ocular observations. Additionally, firefighters are often moving to new locations throughout a day. Thus they must revise their estimates of fire behaviour based on changes in weather, terrain or fuels. These facts suggest that further efforts are needed to define effective safety zones and identify methods for implementing this information in wildland fire management tactical decisions.

The objectives of this study are to define the primary factors that should be considered within the context of safety zones, briefly review current understanding of heat transfer in wildland flames, summarise current knowledge of fire related injury, compare safety zone models to past fire entrapments and suggest future research needs.

Problem definition

The fundamental question associated with safety zones is defining the minimum separation distance between the fire and firefighter required to prevent injury. The safety zone size or safe separation distance (SSD) problem can be divided into three topic areas: (1) determination of the fire energy source strength; (2) calculation of burn injury as a function of heating magnitude and duration and (3) estimation of distance from the fire to prevent injury. The following sections discuss each of the topic areas.

Energy transport

SSD is dependent on fire intensity and heating mode (i.e. conduction, radiation and convection), and heating duration. Energy is transported from wildland fires primarily by two heating modes: (1) radiative energy transport and (2) convective energy transport (Butler *et al.* 2004*a*; Yedinak *et al.* 2006; Anderson *et al.* 2010). Historically it has been stated that, at least for crown fires, radiant energy transport dominates the energy exchange process (Albini 1986). Indeed, some cases exist where radiation dominates fire energy transport, for example a fire spreading through grass in the absence of wind would seem to be driven by radiant heating ahead of the flaming front, or a large crown fire with minimal ambient wind would also be characterised by primarily radiant heating although in both cases it is difficult to separate the radiant heating from the advective influence of lofting and ignition from burning embers that act as ignition pilot sources. However, recent studies suggest that convective heating plays a critical role in fire spread (Yedinak *et al.* 2010; Frankman *et al.* 2013*a*), for example a fire burning through grass in the presence of a very strong ambient wind. The wind causes the flames to reach ahead of the burning front preheating vegetation far in advance of the fire through direct contact between the flames and unignited fuels. In this case, convective energy transport would dominate energy transport and fire spread.

Radiative energy

A person standing near a camp fire would feel primarily radiative energy. Radiative energy source strength is dependent on the source temperature raised to the power of four thus small increases in flame temperature can result in large increases in radiated energy.

Various studies have reported measurements of energy transport from biomass fuelled flames; a few are summarised here. Packham and Pompe (1971) measured radiative heat flux from a fire in Australian forest lands. Heating reached 100 kW m^{-2} when the flame was adjacent to the sensor and 57 kW m^{-2} when the sensor was a distance 7.6 m from the flame (King 1961), no description of flame dimensions were provided. Butler *et al.* (2004*b*) presented temporally resolved irradiance measurements in a boreal forest crown fire burning primarily in jack pine (*Pinus banksiana*) with an understorey of black spruce (*Picea mariana*). Irradiance values reached 290 kW m^{-2}, flames were 25 m tall and fire spread rates were nominally 1 m s^{-1}. Morandini *et al.* (2006) measured time-resolved irradiance values from flames burning in 2.5 m tall Mediterranean shrubs (*Olea europea*, *Quercus ilex*, *Arbustus unedo*, *Cistus monspeliensis* and *Cytisus triflorus*). Radiative heat fluxes peaked at 1, 2.2 and 7.8 kW m^{-2} for distances to flames of 15, 10 and 5 m. Silvani and Morandini (2009) measured time-resolved radiative and total heat fluxes incident on the sensor in fires burning in pine needles and oak branches. For the burn conducted on a slope of 36% with flame heights of 5.6 m, the peak radiative and total heating at the sensor were 51 and 112 kW m^{-2}, implying that convective heating was nominally of the order of the radiative heating. Frankman *et al.* (2013*a*) report measurements from fires burning in a variety of vegetation and terrain. Irradiance from two crown fires burning in lodgepole pine (*Pinus contorta*) peaked at 200 and 300 kW m^{-2} with flames reaching 30 m, convective fluxes were 15 to 20% of the peak radiative fluxes. Peak irradiance associated with fires in grasses and leaf and pine needle litter in southern longleaf pine (*Pinus palustris*) reached 100 kW m^{-2} with a mean value of 70 kW m^{-2} for flames nominally 2 m tall, convective heating was equal to or greater than the radiative flux. Fires burning in sagebrush (*Artemisia tridentata* subsp. *Wyomingensis*) dominated ecosystems generated peak radiant energy fluxes of 132 kW m^{-2} with a mean value of 127 kW m^{-2} for flames less than 3 m tall, peak convective heating was 20 to 70% of the radiative heating magnitudes on slopes of 10 to 30%. Napier and Roopchand (1986) report an average incident radiant flux of 7.5 kW m^{-2} 159 m away from liquefied natural gas flames 80 m tall and 31 m in diameter.

Safety zone studies have assumed that radiative heating is the primary heating mode. In reality, radiative energy emission is a volumetric phenomenon; however, in an attempt to simplify the complex physics associated with definition of the soot particle density and size as required for volumetric determination of flame irradiance safety zone studies have been based on a solid planar flame surface approach. Sullivan *et al.* (2003) studied solid surface flame models and concluded that the challenges associated with defining the temporal and spatial fluctuations in flame temperature and emissivity preclude any increase in simulation accuracy possible if they were allowed to vary spatially. Flame angle over the range 0 to 30° from vertical seems to affect radiant energy transport minimally (Catchpole *et al.* 1998) as do flame widths greater than three times the flame height (Wotton *et al.* 1999). Flame height or length, temperature and emissivity are difficult to quantify, especially if a firefighter has not worked in similar conditions, error in their estimation from ocular observations can be one of the primary sources of uncertainty in estimating fire energy release rates.

Convective energy

If a person standing near a camp fire placed their hand above the flame they would feel primarily convective heating. Convective energy transport is dependent on the difference between the temperature air and the solid surface being cooled or heated and on the velocity of the gas flowing over the surface and to a lesser extent on the gas density. It has been stated that there are no findings reported in the technical literature that indicate convective energy transport is as significant as radiant energy transport, primarily based on the assumption that buoyancy of heated gases would result in vertical transport reducing the effect on persons or objects located some distance laterally from the flames (Gettle and Rice 2002). Recent work has shown that instantaneous peak convective energy fluxes inside flames may significantly exceed the radiant fluxes although convective heating based on 2 s moving averages are nominally 70% of similarly averaged radiant heating values (Frankman *et al.* 2013*b*). Measurements of flame geometry ahead of a spreading fire front suggest as slope exceeds nominally 30%, flames begin to attach to the surface and high temperature gases are convected along the slope (Viegas 2004). The implication is that convective heating near the ground increases with slope.

Burn injury

Fire related injury to humans occurs through three mechanisms: (1) inhalation of toxic gases poisoning biological functions, (2) inhalation of hot gases resulting in tissue swelling to the point of impeding air exchange to the lungs and (3) thermal injury to skin either through convective or radiative heating. Ideally, the wildland firefighter safety zone should be selected to prevent injury from any of these mechanisms.

Toxic gas inhalation

Inhaled irritants of sufficient concentration can cause pulmonary irritation, tissue inflammation, pulmonary oedema and ultimately death (Hartzell 1996; McLean 2001). Toxic gas inhalation in fires is primarily caused by inhalation of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN) or oxygen (O_2) depletion. Inhalation of CO results in anaemic hypoxia or low blood O_2 levels. Generally lethal CO concentrations are formed in fuel rich environments (Babrauskas 2001). Carbon dioxide, although present in wildland fires, is generally low in toxicological potency outside of the flame envelope. Inhalation of HCN blocks utilisation of O_2 by cells; the heart and brain are particularly susceptible to this chemical, within the context of wildland fire HCN poisoning is of relatively low probability (Hartzell 1996). Oxygen depletion can be significant in the vicinity of fires, a drop in atmospheric O_2 from the standard ambient value to 17% impairs motor coordination; further decrease to 14% leads to mental impairment, loss of consciousness occurs for levels below 10% and can lead to fatality in less than 5 min. Flame chemistry implies that low oxygen levels are possible, but only within the flame envelope and, therefore, are of secondary consideration for burn injury as inhalation of hot gases and external skin surface injury would also be present (http://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/, accessed 6 January 2013). Toxicological effects of smoke inhalation on firefighter health remains a relevant topic of wildland fire research.

Respiratory tract injury

Upper airway burn injury due to inhalation of hot gases leads to tissue swelling and airway obstruction. Lung tissue damage sufficient to compromise respiratory function may not present immediately, but can occur 12 to 48 h post injury and is unlikely to occur without severe respiratory tract and external skin burn injury (Moritz *et al.* 1945; McLean 2001). Dry air of 300°C will cause respiratory tract injury in less than one second, air temperatures of 203°C will cause respiratory tract tissue swelling and possibly blockage in less than 3 min, air temperatures as low as 120°C may cause difficulty breathing and injury with exposure exceeding 10 to 15 min (NORSOK 2001). Tests on canines indicate that severe respiratory tract trauma occurs for dry air temperatures above 327°C, whereas steam at nominally 100°C causes severe injury in half the time (Moritz *et al.* 1945). Others have shown that humid (approximating saturation) air at 60°C can cause severe respiratory tract injury for exposures of several minutes or longer; however, the source of high levels of water vapour must be ambient rather than the combustion process as water vapour content in air due to the combustion reaction is not likely to exceed 10% above that of the ambient air mass (Purser 2009). Asphyxiation due to inhalation of hot gases does not occur without burns to the exterior skin of the victim as the burn injury mechanism is the same for respiratory tract and external skin tissue (Tredget *et al.* 1990). Fig. 1 presents time to incapacitation and time to second degree burn injury for convective heating of respiratory tract or external skin surfaces (DiNenno *et al.* 1995; NORSOK 2001).

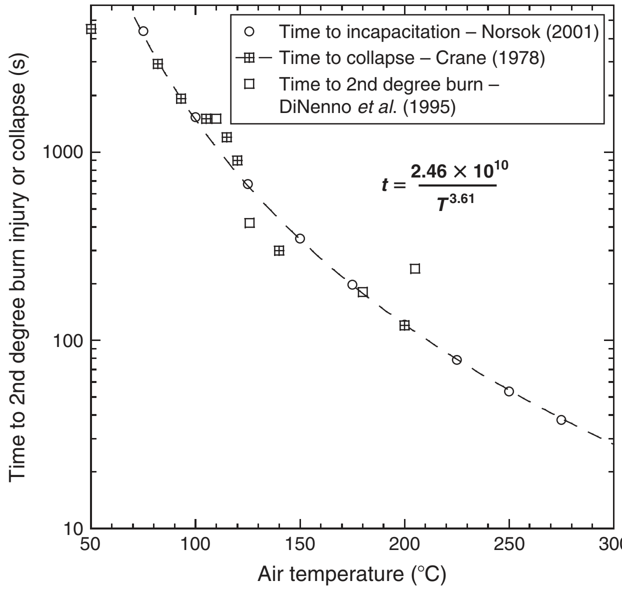

Fig. 1. Time to burn injury of bare exposed skin subjected to convective heating in dry air (DiNenno *et al.* (1995), table 2–8.9), indicated by white squares; and time to incapacitation due to thermal injury to respiratory tract tissue (NORSOK 2001), indicated by circles. Time to collapse as summarised by Crane (1978) shown by crossed squares. Crane (1978) proposed the fit based on physiological considerations for a healthy adult male in 'usual business attire'. Fit to data is least-squares power law fit where *T* is air temperature (°C).

Burn injury

Skin is composed of an outer layer (epidermis) covering the dermis with the deepest layer or subcutaneous tissue composed of fatty tissue. Burn injury is dependent on the magnitude and duration of the heating event. Severity of injury depends on total energy absorbed and the depth to which the collagen protein in living cells is heated to the point that it denatures causing cell death (necrosis). Injury is directly proportional to the time that skin cell temperatures exceed 44°C with instantaneous epidermal destruction occurring at 72°C. First degree or superficial burns are caused by injury to the outermost layer of skin (epidermis) and are characterised by redness, swelling and pain. Treatment involves cooling or application of soothing ointments. These types of burns heal quickly without residual scarring. Second degree or partial-thickness burns affect both the outer skin and the dermis or inner skin. Skin subjected to this level of burn is mixed red or white, often has blisters and is quite painful. Third degree or full-thickness burns result when burn injury extends to the hypodermis or subcutaneous tissue and can affect underlying bone, muscle, nerves and tendons. Third degree burns are generally not painful other than the surrounding areas of partial-thickness burn injury due to damage to nerve tissue. The risk for infection and other complications is high and often result in permanent disfigurement (Walls *et al.* 2009).

The effects of heating of the exterior surface of the skin are similar whether the heating mechanism is conduction, convection from hot gases or air, or incident thermal radiation individually or in combination (Bull and Lawrence 1979; Purser 2009). Therefore, it is logical that an analysis of the injury level due to radiant plus convective heating can be deduced where the combined effects are additive within the limits defined for radiant heating based studies (Purser 2009). Raj (2008*a*, 2008*b*) indicates that some studies have claimed that only 2% of burn victims suffer solely from thermal radiation burns, implying that most burns are due to convective heating from exposure to hot gases or objects. For adults mortality is directly proportional to victim age and extent of burn injury, 50% probability of survival is predicted for a 40-year-old victim with injury over 50% of their body surface (Bull 1971).

No significant effect is observed for skin pigment colour over the range of wavelengths between 1 and 2.4 μm (Hardy *et al.* 1956). Buettner (1951) and Raj (2008*b*) estimate an absorption of incident radiant thermal energy of 60 to 80% for exposed human skin.

Burn injury data are primarily based on tests where a small area of skin (nominally 5 × 10 cm) is exposed to a high intensity electrical heating source held close to the skin until pain or blistering occurs (Stoll and Chianta 1969). Based on such tests regulatory exposure limits for thermal radiant heating vary from 1.5 to 7 kW m^{-2}. As a point of comparison, the maximum radiant energy that can be received from sunlight on the earth is nominally 0.8 kW m^{-2}. Data from a series of tests where incident radiant flux levels, clothing exterior and skin temperature were monitored when exposed to thermal radiation produced by a nominally 5 m tall flame burning in a pool of liquefied natural gas showed that for exposure levels of 4 to 6 kW m^{-2} no direct injury was observed. The researcher reported mild pain at exposure levels above 6 kW m^{-2} in 30 s. Others note that a short-term exposure to 6 kW m^{-2} is survivable for 90 s (http://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/, accessed 6 January 2013). The scientific foundation for many of these levels is not known (Raj 2008*b*); however, it appears that most are based on reanalysis of data and models presented by Eisenberg *et al.* (1975) and Stoll and Green (1959).

A single layer of clothing with a 4-mm air gap between the clothing and skin reduces radiant energy transport to the skin by nominally 50 to 70% (Stoll and Chianta 1969; Stoll and Chianta 1971; Ripple *et al.* 1990; Raj 2008*a*). McLean (2001) found that Nomex as an outer layer with an equal mixture of wool or cotton as undergarment provided the best protection in terms of radiant energy transmission reduction and reduced susceptibility to ignition. He also states that increasing the insulating layers further reduces energy transport to the skin, but the benefits are offset by the physiological load to the wearer associated with increased perspiration, physical encumbrance, hyperthermia and range of motion impairment. In an unpublished study, M. Y. Ackerman reports measurements of burn injury using instrumented manikins exposed to heating from natural gas burners. The data show an increase in time to injury by 2 to 3 for clothed *v.* unclothed skin (Fig. 2). If clothing does fully ignite the probability of death is 40 to 100% (Torvi *et al.* 2000; O'Sullivan and Jagger 2004). No studies were found relating the effectiveness of clothing in reducing convective heating, but some attenuation is likely. A fire retardant material may increase the duration of survivable flame engulfment, but may not provide airway protection.

For many of the regulations and standards used throughout the world the criteria for human exposure are specified only by heat flux magnitude; logically time of exposure is also critical. Eisenberg *et al.* (1975) and Hymes *et al.* (1996) propose the following correlation for burn injury based on magnitude of heating and duration of exposure. $V = tI^{4/3}$ where t is time in seconds, I is absorbed heat flux (radiant and convective) in kilowatts per square metre and V is thermal dosage unit (TDU). A TDU of nominally 500 represents onset of second degree burn and nominally 1% fatality for humans wearing protective clothing, a value of 1050 represents extensive second degree burns and onset of third degree burns to exposed skin, a value of 2300 is 50% lethality (Hymes *et al.* 1996; O'Sullivan and Jagger 2004). More recently it has been proposed that burn injury be related to the cumulative energy exposure which is the product of heating magnitude and time: the limits are 164 kJ m^{-2} for bare skin and 244 kJ m^{-2} for skin covered by one layer of clothing (Ripple *et al.* 1990; Torvi *et al.* 2000). A heating magnitude of 7 kW m^{-2} would correspond to respective exposure times of 37 and 35 s for the TDU and cumulative dosage methods. As a point of comparison direct measurements of energy exposure by the author of the work reported here indicated pain in approximately 10 s at an exposure of 8 kW m^{-2}. Other burn injury models are available, some based on burn tests

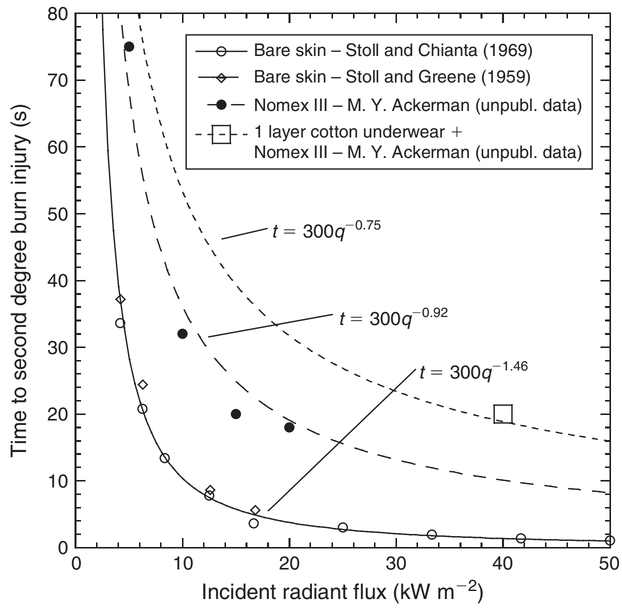

Fig. 2. Comparison of injury times for bare skin and skin covered with a single layer of fire retardant cloth (Nomex III, DuPont Inc.).

on animals, others a reanalysis of existing data (Bull 1971; Lawrence 1991; Lees 1994).

Safety zone models

Although the term safety zone was officially adopted in 1957 in the US, no quantitative studies of safety zone attributes are found in the formal wildland fire literature until the work by Green and Schimke (1971) where correlations for distance to prevent burn injury on flat ground and steep slopes from radiated energy for an infinitely long fire front based on a burn injury threshold of 12.6 kW m^{-2} are presented as a function of burning index. The SSD between firefighters and flames was 0.5 to 1.0 times the flame length for flat terrain and 0.8 to 1.5 times the flame length for steep terrain (70% slope). The authors suggest that minimum SSD should be increased by 50% for fires burning on steep slopes.

More recently, Butler and Cohen (1998*a*) presented results from a solid planar surface flame model (finite rectangular area of specified width and height and inclination angle) of uniform flame temperature and emissivity. The model was used to calculate the distribution of energy in front of the fire for flat terrain based on radiant heating only. The maximum energy exposure limit used for their analysis was 7 kW m^{-2}. They assumed a flame width of 20 m, flame emissivity of 1.0, flame temperature of 1200 K. A linear curve fit to their results suggests a minimum SSD of four times the flame height as a rule-of-thumb for wildland firefighters. Their work is the basis of official wildland firefighter safety zone guidelines in the United States (National Wildfire Coordinating Group 2004).

Although not specifically a safety zone model, Cheney *et al.* (2001) propose the name Dead-Man Zone for the location where fires entrap firefighters who do not retreat to a safety zone. They analyse three fire entrapments in Australia and conclude that parallel or indirect attack tactics present unique and in many cases elevated risk of entrapment. Their analysis suggests that in forested vegetation, obscured views of the fire can provide a false sense of security.

Zárate *et al.* (2008) simulated SSD from flames using a solid surface flame model based on a view factor approach similar to that of Butler and Cohen (1998*a*). They assume a flame temperature of 1200 K, flame emissivity of 1, atmospheric transmissivity of 1 and flame width of 20 m. They conclude that there is no appreciable increase in minimum safe distance for flame widths greater than 20 m. Their model compares well with the measurements of Knight and Sullivan (2004) with respect to energy release from flames. They suggest a mean SSD of 4.8 flame heights for an exposure limit of 4.7 kW m^{-2} and 3.8 times the flame height for an exposure limit of 7 kW m^{-2}. They recommend a 20% increase in SSD to account for convection.

Rossi *et al.* (2011) simulated radiant energy transport from wildland fires using a solid planar surface flame model for the purpose of determining SSD for maximum allowable radiant flux exposure of 4.7 kW m^{-2} for bare human skin and 7 kW m^{-2} for clothed skin. Their results are presented in terms of flame-width-to-flame-length ratios. They identify two zones: Zone-1) flames narrower than 50 m where SSD varies directly with width-to-flame-length ratio and Zone-2) flames wider than 50 m where the SSD is a constant multiple of the flame length for all flame widths. The constant is dependent on the flame temperature. They find that the zone 2 SSD for low temperature flames (i.e. 873 K) is 2.3 times the flame length whereas a flame temperature of 1353 K requires nominally 9.5 flame lengths for the 13 vegetation fuel types associated with the BEHAVE fire prediction system (Andrews 1986). A flame temperature of 1473 K leads to a zone 2 minimum SSD of 12 flame lengths for the 13 vegetation models.

Baxter (2011) reports an experimental characterisation of SSD from fires burning through grasses where areas 10 m in diameter were cleared of all vegetation within 50 × 40-m burn plots. Heat flux sensors were placed at various locations around and distances inside the 10-m circles. Fires then were allowed to burn up to and around the cleared circles. The data suggest that along the edge of the circle opposite the approaching fire energy fluxes remained below the minimum limits for burn injury. They also suggest a separation distance of nominally 6.7 times the flame height (~1.25–1.75 m) is required.

One caveat with the reported work is that some results are reported in terms of flame length, others in terms of flame height and the work by Rossi *et al.* (2011) in terms of the width-to-length ratio. Butler and Cohen (1998*a*) argue that flame length should be used as it is always equal to or greater than flame height but that flame height is more easily observed by firefighters. Reformatting the results into common variables indicates that two zones should be considered for SSD (Fig. 3). Zone 1 is for flames less than 10 m tall. In this zone the minimum safe distance from the flame decreases rapidly with flame height from a high of 10 times the flame height for short flames to nominally 2 to 4 times the flame height for flames above 10 m tall. For flames less than 10 m tall all three models provide similar results; but for flames 10 to 30 m tall the Zárate

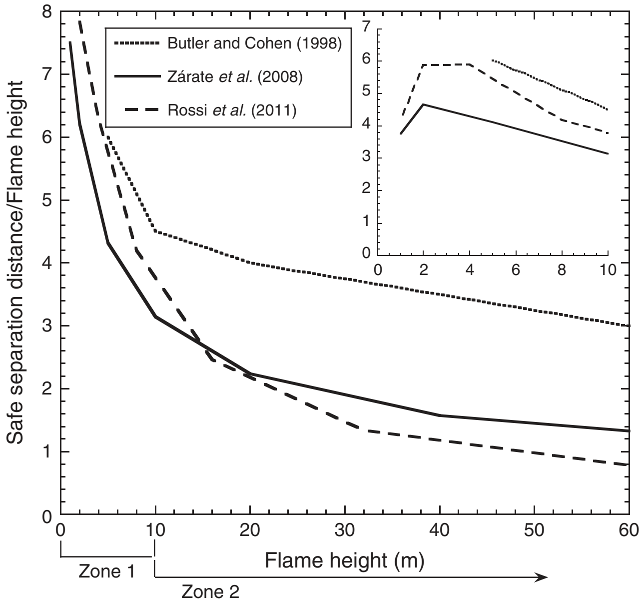

Fig. 3. Comparison of data from published models for firefighter safety zones for 20 m-wide fire front. Inset figure represents models when accounting for reduced emissivity for flames less than 5 m tall. Emissivity is calculated based on absorption coefficient of 0.7 and absorption path length equal to the flame height.

et al. (2008) and Rossi *et al.* (2011) models are similar. Zone 2 is characterised by flames greater than 10 m tall. In this zone, the SSD to flame height ratio decreases slightly with large increasing flame height and can be approximated by a constant multiplier between SSD and flame height. Butler and Cohen (1998*a*) selected 4 times the flame height whereas Zárate *et al.* (2008) and Rossi *et al.* (2011) suggest 1.5 to 2 times the flame height. The differences in the model results are likely due to variations in the simulation geometry and solution methods. However, flames reaching this size are also associated with high intensity fire behaviour and as such represent greater risk in terms of burn injury for short duration exposures. Therefore, although the ideal scenario presented by the mathematical models suggests SSD to flame height ratios of 2 to 4 for these tall flames, the variability in fire intensity argues for ratios erring on the conservative side (i.e. 4). Table 1 summarises the results from the published studies.

The high SSD to flame height ratio for flames less than 10 m tall is based on models that assume high flame emissivity. Although difficult to measure, flame emissivity is a local phenomenon and depends on the absorption coefficient of soot or smoke in the flames (essentially how much of the thermal radiation is absorbed by the soot along the path followed by the radiation) and the path length or flame thickness (Quintiere 2006). An effective flame emissivity can be calculated as $\varepsilon = 1 - e^{(-kL)}$ where ε is emissivity, k is the absorption coefficient (m^{-1}) that varies from 0.2 to 1 for typical biomass flames (Drysdale 1985; Àgueda *et al.* 2010) and L is the absorption path length (m). Generally, it is accepted that wildland flames thicker than 3 m have an emissivity approaching unity (Butler *et al.* 2004*a*). High emissivity surfaces will more efficiently radiate energy than low emissivity surfaces. Emissivity decreases rapidly for flames less than 2 to 3 m thick, reaching a value approaching zero for infinitely small and thin flames (Pastor *et al.* 2002; Planas-Cuchi *et al.* 2003; Sudheer and Prabhu 2012). The path length is equivalent to flame thickness or depth and is dependent on the fuel load and burning residence time of the fuel elements. Recent observations of fires in various vegetation types suggest that flame depth varies from 0.5 to 3 times the flame height (Frankman *et al.* 2013*a*). Radiant energy emitted from the flames scales directly with flame emissivity. The inset figure in Fig. 3 presents the modified SSD to flame height ratio for flame models where emissivity is reduced linearly with flame height for flames less than 5 m tall. The results suggest that SSD to flame height ratio peaks at ~6 for flames 2 to 4 m tall and then decreases for shorter flames. In general, it can be concluded that an SSD rule based on a constant multiplier of flame height or length is inaccurate for flames shorter than 5 m.

Rossi *et al.* (2011) conclude that radiant energy transport is dependent on flame geometry, suggesting that wind and slope are critical to accurate determination of safety zone size, which implies that convective energy transport and spotting should be considered as well as the need for field measurements to validate the energy transport models. All of the studies presented to date have considered only radiant heating. The reasons are likely due to several factors, including the complexity associated with convective heating, the paucity of data and knowledge about convective heating magnitudes in wildland fires and the assumption that due to buoyancy the bulk of the hot gases are advected upward away from the ground surface. Recent measurements (Butler *et al.* 2004*a*; Frankman *et al.* 2013*a*) suggest that although radiant energy transport is significant in wildland fires, convective energy transport can exceed radiant heating. Consequently, it is not clear that convective heating can or should be ignored.

With respect to absorption of thermal radiation by atmospheric moisture, Raj (2008*a*, 2008*b*) suggests that atmospheric absorption can reduce energy transport from flames; however, work by Frankman *et al.* (2008) indicates that absorption of thermal radiation from wildland flames due to water vapour in the air is less than 16% for distances equal to 10 times the flame height.

Case studies

Fire case studies can provide anecdotal information about the performance of safety zones and protective equipment under real life conditions. Unfortunately, in many cases insufficient information about fire intensity, environmental conditions, specific attributes of the entrapment site such as vegetation height, and clearing size is available to accurately assess the entrapment in the context of safety zones. Table 2 summarises some fires that occurred over the last 80 years in the United States in the context of safety zone effectiveness; certainly other similar incidents have occurred in other areas of the world and likely would provide similar information. The cases reported here were selected based on the information provided about the fire, environment and safety zones (if applicable), the accessibility of the written records and to represent a range of terrain and vegetation conditions.

The Blackwater fire occurred in eastern Wyoming during August, 1937. During the passing of a cold front, winds caused a rapid change in fire behaviour and intensity killing 15 firefighters and injuring another 36 (Brown 2003; Brauneis 2005). Fatalities occurred in several groups, for the purposes of this safety zone analysis the focus is on a group of 41 firefighters led by Ranger Post. The firefighters had been building a fireline above the fire, when it was realised that fire had moved below them and was burning upslope. They retreated to a rocky outcropping on a ridge that was 30 to 50 m from vegetation. The fire was burning in old growth Douglas-fir (~15 to 20 m tall) up narrow draws on both sides of the fire crew. Flame heights were estimated to be nominally 1.5 to 3 times the tree height. Post instructed the men to get down on the ground, but several panicked in the heat and tried to run. Exposed skin sustained severe burns; clothing became so hot that some men tore it off, sustaining additional burns. Men extinguished burning embers on one another's clothes. Most of those who remained in place on the ground survived. This entrapment illustrates the increased protection provided by even a single layer of clothing and the advantages gained by lying face down when entrapment is unavoidable. The separation distance from the fires was ~1 to 2.5 flame heights. Statements by firefighters suggest that heating was due to both radiant and convective modes.

The Battlement Creek fire occurred on 17 July 1976 in western Colorado where three firefighters were entrapped and killed and a fourth was severely burned when they attempted to retreat to a safety zone (US Department of Interior 1976). When they realised that they were going to be overrun by the fire they removed their canvas vests and moistened their hats, shirts, and trousers with water then lay face down in mineral soil. They

Table 1. Summary of past studies

Conclusions and the model in Butler and Cohen (1998*a*) assume: flame temperature 1200 K, burn threshold 7 kW m^{-2}, flame emissivity = 1, flame angle = 0. Abbreviations are W, flame front width; Fl, flame length; Fh, flame height; SSD, safe separation distance

Study	Objective	Assumptions	Findings	Conclusions	Recommendations
Green and Schimke (1971)	Fuel break design and size.	Radiant heating only, burn threshold 12.6 kW m^{-2}.	SSD = 0.5 Fh for light brush, 0.8 Fh for medium brush, 1.4 Fh for heavy brush.	Minimum width of 60 m for all fuel breaks.	SSD increases by factor of 0.5 for steep slopes
Butler and Cohen (1998*a*)	Minimum separation distance.	Radiant heating only, flat terrain, flat flame model, burn threshold 7 kW m^{-2}, flame temperature 1200 K.	Model matches data and fire incidents.	Convective heating and turbulence from large fires would increase minimum size, fire shelter reduces energy below threshold for all separation distances greater than 15 m.	Rule-of-thumb that minimum SSD is 4 times flame height.
Cheney *et al.* (2001)	Dangers for firefighters when working at indirect attack.	Analysis of three firefighter entrapments.	Direct attack safest method, wet methods best for indirect attack, indirect attack is defined as any time that firefighter is more than 2 m from fire edge.	Time to retreat to safety zone decreases by 50% for 10% slope and by 75% for 20% slope.	
Zárate *et al.* (2008)	Minimum separation distance.	Radiant heating only, flat terrain, flat flame model, flame temperature 1200 K.	Two regimes found, within few metres of flame SSD varies strongly with flame height. SSD not dependent on flame width for values of width >20 m.	Recommends heating threshold of 4.7 kW m^{-2}, which gives SSD of 4.8 Fh. 7 kW m^{-2} threshold gives SSD of 3.8 Fh.	20% increase recommended for consideration of convection.
Rossi *et al.* (2011)	Minimum separation distance.	Radiant heating only, flat terrain, flat flame model, flame temperatures 873, 1353 and 1473 K.	Two regimes found, SSD = f(flame temperature, emissivity, burn threshold, flame width).	For W/Fl <50 SSD = f(W/Fl), for W/Fl >50 SSD = 8 times Fl.	Convective heating and spotting should be considered, Actual fire data needed for comparison with model.
Baxter (2011)	Safety zone size in grass fuels.	None-direct measurements.	Minimum SSD is 6.7 times Fh.		Measurements needed in stronger winds.

Table 2. Case study fire data

For the Injury data, F indicates fatalities, I indicates firefighters injured but not killed, and E indicates number of firefighters entrapped but not injured or killed. ROS, rate of spread

Fire	Date	Location	Injury	Fuel type	Fuel load	Air temp.	Relative humidity	Wind	Slope	Flame depth	Flame height	ROS	Distance between firefighters and flames	Fireline intensity	SSD/ Fh
					($kg\,m^{-2}$)	(°C)	(%)		($m\,s^{-1}$)	(%)	(m)	(m)	($m\,s^{-1}$)	(m)	
($MW\,m^{-1}$)															
Blackwater	21-Aug-37	WY	F-15 I-36	Old growth Douglas-fir	2–3[A]	~30	~6	3	20–30	>200	~30–80	–	>30–50	>40[B]	1–2.5
Mann Gulch	5-Aug-49	MT	F-13 E-1	Grass – Timber	0.4[C]	36	<10	8	20–70	–	4–10[D]	2–4	13–25[D]	15–30[E], 11[C]	0–2.5
Loop	1-Nov-66	CA	F-10 I-12	Chamise, Sage, Sumac	2–6	20–25	10–15	<27	50–70	>10	~10	5–11	15–100	0.3–0.7[B]	~0.5–1
Battlement Ck	17-Jul-76	CO	F-3 I-1	Frost killed Gambel Oak >4 m tall 1–2 m at fatality site	1–2[F]	33	28	13	20–60	>40	9–14	0.5–1.5	~5	11–68[B]	0.3–0.5
Butte	29-Aug-85	ID	E-73	Mature lodgepole pine and Engelmann spruce	2–4[A]	19	20	3.6	9	>100	60–100	0.37–1.6	90–125	44[B]	0.8–2
S. Canyon-1[G]	6-Jul-94	CO	E-8	Gambel oak	1–2[F]	27	10	13–18	60	>100	16–29	2.85	160	100–380[F]	5–10
S. Canyon –2	6-Jul-94	CO	F-14	Gambel oak	1–2[F]	27	10	13–18	60	>100	16–29	2.85	1–10	100–380[F]	0.03–0.6
Thirtymile-1	10-Jul-01	WA	F-4	Douglas-fir	–[H]	30	~10	0	0–30	>30	30–60	0.7	5–7	39–100[F]	0.1–0.3
Thirtymile-2	10-Jul-01	WA	I-1 E-11	Douglas-fir	–[H]	30	~10	0	0–30	>30	30–60	0.7	30	39–100[F]	1–2
Ahorn	28-Jul-07	MT	0	Lodgepole	2–4[A]	–	–	–	40–120	>100	30–80	–	70–150	~30–40[B]	2–5
Salt	29-Aug-11	ID	E-3	Lodgepole	–	–	–	–	0	–	30–60	–	15–30	–	1–4
Baxter (2011)	2010	AB (Canada)	0	Grass	0.4	11	50	3	0	–	1.25–1.75	0.83	10	6.5[B]	5.7–8

[A]Based on estimate from digital photo series (Ottmar *et al.* 2000).
[B]Estimated from fire data and heat of combustion of 19.5 $kJ\,kg^{-1}$.
[C]Alexander *et al.* (2009).
[D]Alexander *et al.* (2009), Rothermel (1993), Butler and Cohen (1998*b*).
[E]Rothermel (1993).
[F]Estimated from BEHAVE plus.
[G]There were 14 firefighters who were killed but the focus here is on the 8 smokejumpers that were entrapped on the lunchspot ridge and survived in fire shelters (Butler *et al.* 1998*a*).
[H]The specific location of the entrapment was a rock scree slope and road, however nearby were stands of Douglas-fir and lodgepole pine.

covered their heads and faces with the moistened vests. During the burn-over two of the individuals stood up at different times and ran down the ridge apparently trying to get through the fire. The remaining two firefighters stayed in place until the heat had subsided. The shirt on the back of one of the firefighters had burned entirely off his back, he died within 10 min. The two firefighters who ran into the fire were found dead. Autopsies indicated that all three died from asphyxiation. The entrapment site was a section of the fireline located near a steep slope up which the fire burned. Slope at the entrapment site was nominally 20%. The entrapment site was exposed to winds and would have experienced high intensity fire behaviour. The firefighters experienced both radiant and convective heating. The separation distance from vegetation was nominally 0.3 to 0.5 times the flame height (estimated at 9 to 14 m). This entrapment resulted in mandatory use of fire shelters and fire resistant clothing for all wildland firefighters in the United States. It is possible that moistening their clothing resulted in increased burn injury (Behnke 1984). The effect of water in raising clothing thermal conductivity is now taught in firefighter courses.

The Butte fire occurred on the Salmon National Forest during August of 1985 (Rothermel and Mutch 1986). The fire increased in intensity on the afternoon of 29 August forcing 73 firefighters to retreat to pre-established safety zones and deploy fire shelters. The fire burned in mature Engelmann spruce (*Picea engelmanii*), Lodgepole pine (*Pinus contorta*) and subalpine fir (*Abies lasiocarpa*). Flame heights were observed to greatly exceed the tree height. Safety zones nominally 100 m across were constructed. Heat was intense enough to force firefighters to deploy fire shelters and move within the shelters to the opposite side of the safety zone from the fire. One firefighter remarked that without fire shelters there would have been injuries or worse. The separation distance from vegetation was nominally 0.8 to 2 times the flame height.

Four firefighters were killed on the Thirty-mile fire on 10 July 2001 in central Washington (Anon. 2001). The fire was burning in pine and Douglas-fir. When fire conditions changed, the escape route was blocked and firefighters retreated to the base of a large rock scree slope. Firefighters deployed their fire shelters in two groups, one group of 6 firefighters ~20 m above a road in the rock scree, a second group deployed along the road. These two groups are identified in Table 2 as Thirtymile-1 and Thirtymile-2. Both groups experienced heating and strong gusts during the 10 to 15 min they were in the fire shelters. During the deployment one of the firefighters in the first group stood up and moved to the shelter of the crew van, another moved to the river. The four remaining firefighters in the upper group were killed. The crew van was relatively undamaged, whereas another vehicle parked ~70 m up the road near some vegetation burned. Post fire inspection of the site indicated scorching of the lower portion of tree stems near the deployment site. A nominally 10 m long × 0.8 m in diameter dead rotten log near the upper deployment site was scorched only along the half of its length closest to the fatality site. These localised scorch patterns are similar to observations of scorch patterns that occurred in the area of the large fire whirl on the Indians fire in 2008 (USDA 2008) and suggest that at least the upper site may have been subject to a fire whirl or low level high temperature jet that contributed to the heating and fatalities. The separation distance from vegetation was nominally 0.1 to 0.3 times the flame height for the upper group and 1 to 2 for the lower group.

One firefighter deployed a fire shelter on 28 July 2007 when working as a lookout on a fire in central Montana on the Ahorn fire (Anon. 2007). The vegetation was a continuous forest of lodgepole pine and other similar species. The fire had been burning for nearly two weeks. When fire behaviour increased through the day the firefighter decided to retreat to a safety zone consisting of a ridgetop meadow on a south facing 40% slope above the fire. The meadow was nominally 150 m wide and more than 1000 m long. The firefighter deployed his fire shelter nominally 150 m upslope from the forest canopy and remained in it for ~18 min. He did not feel intense heating and the separation distance from the nominally 30 to 80 m tall flames was 70 to 150 m. Smoke and heat were advected up the slope below the firefighter. The separation distance was 2 to 5 times the flame height. This case identifies survivable conditions.

Often one of the hopes arising from accidents where firefighters are injured or killed is that lessons can be learned and new procedures or knowledge implemented that will prevent the reoccurrence of future similar tragedies. Such is the case for the South Canyon fire that occurred in 1994 in central Colorado where 14 firefighters were killed (Butler *et al.* 1998*a*). As a direct result of this accident and under recommendations from an independent review (Anon. 1996) the US Forest Service implemented new procedures directed at facilitating information exchange from weather forecasters, modified work–rest guidelines, formalised wildland firefighter leadership development and stricter firefighter qualification standards.

Other fire entrapments are presented in Table 2, including the Mann Gulch fire where 13 firefighters were killed in 1949 when they tried to escape uphill from a fire burning below them (Rothermel 1993; Alexander *et al.* 2009). In conclusion, the case studies illustrate that firefighter entrapments occur across the entire range of fire intensities, fuel types and terrain. Generally, injury and death occur for separation distances less than 2.5 times the flame height. Vegetation, atmosphere and geographical conditions that promote greater uncertainty in fire behaviour likely lead to the greatest potential for risk of injury. It is critical that information presented in case studies include a description of the vegetation, the weather, the terrain and specifically the fire behaviour that was observed. Information about the local characteristics of the entrapment site such as distance to vegetation and terrain slope are also critical.

Fig. 4 presents the flame size and separation distances for the incidents in Table 2 in graphical form. When these and other entrapments are displayed over the modelled safety zone SSD it is clear that the nonlinear nature of the simulations is supported. For example the data captured in the experiments described by Baxter (2011) fit the low flame but greater separation distances associated with zone 1. The conditions associated with the Mann Gulch, Loop, Battlement Creek and Thirtymile-1 fires depict unsurvivable conditions. Comparison between the models and the Ahorn, Thirtymile-2, South Canyon, Butte and Blackwater fire data suggest that for zone 2, the Butler-Cohen model overpredicts SSD but Zárate *et al.* (2008) and Rossi *et al.* (2011) models are minimally survivable, implying that SSD to flame height ratios should lie between the two studies.

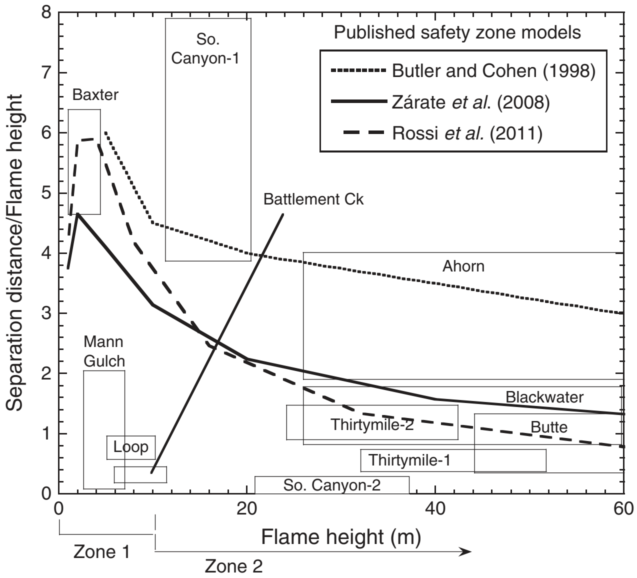

Fig. 4. Comparison of data from published models for firefighter safety zones for 20 m-wide fire front to data from fire case studies. Models are adjusted for flame emissivity based on same factors as described in Fig. 3.

Other considerations

Escape routes

Escape routes are the paths that firefighters must travel to reach a safety zone in the event of a change in fire behaviour. Clearly, a complete analysis of safety zone effectiveness is not possible without considering the time it takes a fire crew to get to a safety zone before arrival of the fire. Cheney *et al.* (2001) note a doubling of flat terrain fire spread rate for slopes of 18% and another doubling for slopes of 36%. They also note that often firefighters overestimate distance to fires when observing fire through a forest and are thus lulled into a false sense of security. Butler *et al.* (1998*b*) proposed that the difference in time for the fire to reach the safety zone be compared against firefighter travel time along their escape route as another method for assessing safety zone and escape route effectiveness as a function of vegetation type and environmental conditions. Three studies report data on firefighter travel rates for various vegetation, firefighter crew types and slope (Butler *et al.* 2000; Ruby *et al.* 2003; Alexander *et al.* 2005, 2013). Travel on moderate slopes (i.e. 26%) is 30% slower than those on flat terrain. Dropping packs and tools increased travel rates by 20%. Travel rates increase by 40% when moving over moderately improved and marked trails.

Fire whirls

Historical accounts identify instances where large fire whirls measuring tens to hundreds of metres in diameter have separated from the primary fire front and transported large quantities of gas and burning debris significant distances resulting in property damage, human injury, and death (Forthofer and Goodrick 2011). In general, there are features that seem to be consistent in fire whirl formation: low to medium ambient winds, a source of vorticity – although many sources of vorticity are present in spreading fires, some common geometrical factors around which fire whirls seem to form are L-shaped fire lines, multiple interacting fire plumes, turbulence in the lee side of ridges, bifurcated smoke columns and vorticity associated with the passage of a frontal boundary (Forthofer and Goodrick 2011). Firefighters should be aware of the potential for large fire whirls to form. On the Indians fire in northern California in 2008, four firefighters were injured when a large fire whirl (100 m in diameter) that had been moving with the fire front, changed directions and moved across a paved road. Up until this time, firefighters were aware of its presence and were even recording video of the phenomenon while observing it from the road. When positioned in safety zones, firefighters should remain cognizant of surrounding fire behaviour and in the event that a large rotating fire whirl forms take action to avoid it.

Convection

Current firefighter safety guidelines in the United States are based on the assumption that radiant energy transfer is the dominant energy transfer method and that the fire is burning on flat terrain. Published safety zone guidelines include specific statements noting this fact. Intuition, professional observations and the few experimental measurements that have been reported indicate that when fires are located on slopes or ridges or in strong winds convective energy transfer may reach distances equal to 2 or more flame lengths ahead of the fire front. This implies that the current safety zone guidelines may be invalid in some situations. Additional assessment of the effect of convective heating on safety zones is needed.

Wildland–urban interface

In some instances, wildland firefighters have identified and used areas around and inside structures in the wildland–urban interface as safety zones. The primary questions associated with this activity are (1) do vegetation clearance and construction practices associated with structures apply to SSD and (2) can the inside of structures be used as safety zones. Significant effort has focussed on understanding construction and vegetation management techniques to reduce and prevent structure ignition (Cohen 2000). Within the context of structure ignition from wildland fires three sources are identified: (1) firebrands lofted from burning vegetation 2 km or more away; (2) direct spread of fire from surrounding vegetation to the structure and (3) exposure to radiant or convective heating sufficient to cause ignition. Fire brand ignition is dependent on the source of brands and the presence of ignitable receptors on the structure. Receptors might be interior corners on roofs, walls or decks where brands can accumulate in sufficient quantity to ignite structure materials. Regarding the generation of brands, wildland vegetation treatments would have to be applied up to several kilometres from homes to reduce brand generation. Direct ignition depends on materials used to construct the structure, construction techniques, vegetation management near the home and the presence of ignitable materials around the exterior of the home (Cohen 2000; Manzello *et al.* 2006). Exposure of the structure to radiant and convective heating sufficient to cause ignition is the mechanism most closely approximating the wildland firefighter safety zone problem. In the context of ignition through exposure to heating, current understanding suggests that a separation distance between flammable vegetation and the structure of 10 to 40 m is sufficient to prevent ignition (Cohen 2000; Cohen and Stratton 2008). Once ignited, the structure does not become fully involved in burning for some time after the wildland fire event (Quarles *et al.* 2010); thus, in an emergency situation, wildland firefighters should consider using a structure as a safety zone. However, this should only occur if the structure has been evaluated for susceptibility to ignition and involvement in the fire. For example, a structure consisting of aged weathered wood with exposed sites for ember accumulation or ignition by exposure to heating is less desirable than a structure with intact painted continuous surfaces that extend ignition and fire involvement time. Additionally, the firefighters should consider the primary vegetation that will be burning around the structure, a structure in a forest setting with aged trees and significant down and dead woody fuel where wildland fire residence time would be extended would be less desirable than one surrounded by vegetation that burned relatively quickly. Clearly, SSD for safety zones should exceed the separation distance for structure ignition, but structures can provide protection from wildland fires as long as firefighters can exit the structure before it is fully involved and after the wildland fire has moved on.

Conclusions

State of science

Many questions remain regarding how energy is generated and released from wildland flames. It is only recently that measurements have identified the range of heating magnitudes that can be expected from wildland flames. Perhaps variable temperature and emissivity flame models would be beneficial; however, the prediction of fire behaviour, especially during dynamic fire operations can be very difficult even with access to sophisticated computer models and hardware. The studies reported to date suggest that heating levels of 6 to 7 $kW\,m^{-2}$ generally represent burn injury limits. Current firefighter safety guidelines in the United States are based on the assumption that radiant energy transfer is the only energy transfer method and that the fire is burning on flat terrain. Published safety zone guidelines include specific statements noting this fact. The models reviewed here (Butler and Cohen 1998*b*; Zárate *et al.* 2008; Rossi *et al.* 2011) suggest that SSD is not accurately approximated by a constant multiplier of flame height for flames less than 10 m tall; however, as flames exceed 10 m tall separation distance can be approximated as 2 to 4 times the flame height depending on which model is followed. Fire intensity varies widely across spatial scales and is strongly associated with local vegetation, terrain and atmospheric conditions. It is difficult to pick a single metric representative of fire intensity that is easily recognised and communicated. Ideally SSD should be assessed as a function of fuel and environmental descriptors; however, safety zone models presented so far have focussed on flame descriptors. Intuition, professional observations and the few experimental measurements that have been reported indicate that when fires are located on or adjacent to slopes or ridges, convective energy transfer may reach distances equal to 2 to 3 or more flame lengths ahead of the fire front (Frankman *et al.* 2013*a*). This implies that the current safety zone guidelines underestimate SSD in some situations and that the effect of convective heating on SSD should be considered. Recent measurements suggest that in the context of wildland firefighter safety zones on slopes an accurate accounting of energy transport requires consideration of both convective and radiative heating. The inclusion of convective heating implies that slope steepness, ambient wind, and safety zone geometrical location relative to terrain slope are all relevant.

Future needs

Significant progress has occurred over the past 2 decades in quantifying the factors that assure a safe area of refuge for wildland firefighters. However, additional efforts are needed in the following areas: (1) the development of understanding how convective energy transport affects safety zone considerations, (2) additional understanding of how clothing type, number of layers and coverage affect burn injury, (3) determination of the best descriptor to use in defining safety zone size or SSD relative to fire intensity (i.e. is flame geometry adequate or are models of the fire environment and fuels required), (4) improved knowledge of travel rates over various terrain and slopes, (5) integration of escape route travel time in the assessment of safety zone effectiveness, (6) improved tools for predicting and communicating fire behaviour, (7) when and how bodies of water can be used as safety zones and the unique concerns associated with their use, (8) improved understanding about how firefighters implement fire behaviour understanding and knowledge to determine if an area is survivable and (9) determination of the optimum methods by which firefighters can apply safety zone standards effectively, efficiently and accurately.

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