

Recent Findings Relating to Firefighter Safety Zones

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Abstract—Designation of safety zones is a primary duty of all wildland firefighters. Unfortunately, information regarding what constitutes an adequate safety zone is inadequately defined. Measurements of energy release from wildland fires have been used to develop an empirically based safety zone guideline. The basis for this work is described here.

Introduction

Wildland firefighting by its nature is inherently dangerous. There have been 699 wildland firefighters die in fire related accidents between 1910 and 1996 in the United States; 384 of those were directly related to fire entrapments (National Wildfire Coordinating Group 1997). Wildland firefighters must consider all risks to themselves and others when approaching, suppressing, and managing wildland fire, and then take appropriate action to minimize those risks (National Wildfire Coordinating Group 2004).

One of the critical decisions made by fire fighters on any wildland fire is the identification of suitable safety zones; areas where firefighters can safely wait for the fire to burn around them (Beighley 1995). The term “safety zone” first appears in official literature in the United States in the aftermath of the Inaja fire where 11 firefighters were killed and the United States Forest Service issued a report that highlighted the need for better training and recommended that all firefighters identify safety zones at all times when fighting fire (McArdle 1957; Ziegler 2007). The United States 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). Safety zones should be available and accessible in the event that fire behavior or intensity increases suddenly making current suppression tactics unsafe. We propose that the primary variable of interest be safety zone radius or its operational equivalent safe separation distance (SSD).

Until 1998, regulatory agencies responsible for wildland fire management in North America did not provide quantitative information about safety zone characteristics other than that proposed by Butler and Cohen (1998), which was included in the Fireline Handbook (National Wildfire Coordinating Group 2004). All wildland firefighters in the United States are required to identify safety zones when working on or near fire. However, results from a survey of perceived size of area or

distance required to be safe from fire, conducted as part of a presentation to groups of wildland fire managers in 1999 and 2000, indicated wide discrepancies in size and/or distance (Steele 2000). In that study, more than 330 firefighters were shown pictures of vegetation, listing the time of year (summer, fall, winter, spring), air temperature, relative humidity, and seasonal rainfall. Each firefighter was then asked to predict the size of area or separation distance from flames to remain safe from injury. When shown pictures of fire burning under the stated conditions, 51 percent of the participants increased their estimates of the required safe separation distance while 8 percent decreased their estimates. The survey indicated that the minimum safe distance from fire estimated by firefighters varied by three orders of magnitude. The study presented in this paper highlights the difficulties faced by firefighters in visualizing representative fire behavior given weather and vegetation conditions and in estimating safe separation distances from fires.

Past research funded by the Interior Fire Coordinating Committee (IFCC) resulted in the development of a theoretical model for quantifying firefighter safety zones (Butler and Cohen 1998). The model simulated the spatial distribution of radiant energy in front of a linear vertical flame. An approximate correlation was derived from this model that indicated a minimum separation between the firefighter and fire should be equal to four times the flame height. Unfortunately, the paucity of quantitative measurements of radiant and convective energy distributions from wildland fires prevented evaluation of the model by comparison with measurements. Instead, the authors compared the predicted minimum separation distances recommended by the model against data and records from past fires. The comparison indicated that the model was at least reasonably accurate over the four test cases that were explored. Recognizing the need for further evaluation of the model, in 2003 the Joint Fire Science Program (JFSP) funded a Rapid Response Team (JFSP project 03-2-1-03) to explore through direct measurement and theoretical modeling the accuracy of safety zone guidelines and assess their effectiveness in protecting firefighters from injury. Field measurements were collected on fire incidents in Florida, Arizona, Montana, California, Oregon, Washington and Idaho. These data were used to calculate the distribution of energy in and around

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those fires (Butler and Cohen 2000). Measurements and analysis of fires and safety zones on flat terrain showed that current safety zone guidelines were adequate with the assumption that both the fire and safety zone were on flat terrain. Additional guidelines were developed that related safety zone size in acres to flame height in feet and to account for changes in safety zone size necessary to accommodate equipment and multiple personnel. An additional outcome was that locating safety zones on slopes introduces additional complexity that was not addressed in the existing guidelines. It was recommended that future efforts focus on developing guidelines for safety zones on slopes where the effect of convective heating may be significant.

Current safety zone guidelines for wildland firefighters are based on the assumption of flat ground, no wind, and radiative heating only. Recent measurements in grass, shrub and crown fires indicate that convective heating can be significant especially when fire is burning under the influence of wind or slope. Measurements and computer modeling supports this finding and suggests that convective energy transport should be considered when assessing safety zone effectiveness any time wind or slope is present. The results of the research are presented along with recommendations for modifications to current safety zone guides.

There has been a general decline in fatalities on a per year basis from 1925 to present (dashed line, right vertical axis) as well as average fatalities per year based on Cook's analysis (solid line, left axis) (Cook 2004) (figure 1). When considering the information presented, two observations come to mind: 1) it appears that there is a 3 to 5 year periodicity in the large entrapment years (that is more than 8 fatalities occur every 3 to 5 years), and 2) there is an indication that over the past 20 years we are seeing a large entrapment every 15+ years. Given these observations, one is prompted to ask what caused the decreases in annually averaged entrapments (red solid line), and what efforts can lead to further declines in injuries?

The decrease in average annual fatalities appears to have occurred around 1960, just three years after the Inaja Fire where the term safety zone was developed and promoted by

the Forest Service. In 1960, the 10 standard fire orders and 13 watchout situations were also implemented. The 13 watchouts were subsequently modified to 18 watchout situations. In the absence of any other obvious causal factors one could argue that the implementation of the concept of safety zones, the 10 standard fire orders and the watchout situations contributed to a decrease in fatalities from more than 6 to around 4 per year after 1960. Between 1960 and 1990 the trend remained essentially constant at approximately 4.5 fatalities per year.

In 2000, annual average fatalities decreased from 4.5 to approximately 2 per year. The major fire event for this period was the South Canyon fire where 14 firefighters were killed (Butler and others 1998). The decrease in annually averaged fatalities in this period could be intuitively associated with the policy and fire incident management changes that were implemented in the wake of the South Canyon Fire. Additionally, quantitative safety zone guidelines were published in 1998 (Butler and Cohen 1998). One interpretation is that the policy, work practices, additional information, and training developed after the South Canyon fire did have a beneficial impact on future fatalities. One could argue that the quantitative safety zone guidelines contributed to that decline. Again the implication is that changes to policy, work practice and enhanced situational awareness can save lives.

The rise in the red curve from 2002 to present is due to the Yarnell Hill fire where 19 firefighters were killed. Comparing this event to the South Canyon Fire in 1994 suggests that there may be a tendency for large entrapment events to occur every 15 to 20 years. However, considering the decrease in annually averaged entrapments around 1960 and 1995 there is evidence that cultural, political, and work practice changes can save lives.

In general it has been widely accepted that fire spread is driven primarily by radiative energy transport. The relative contributions of radiation and convection heat transfer depend in a complex way on the prevailing wind speed, fuel distribution, buoyancy-induced in-drafts, terrain slope, and so on. A variety of measurements have been collected from fire experiments including but not limited to flame spread rate (Fons 1946; Hottel and others 1965; Catchpole and others. 1998), high speed photography to determine flame shape (Anderson 1968), and flame temperature (Anderson 1968; De Mestre and others 1989). However fewer observations of fire intensity in terms of total, radiative, and convective heat levels have been reported. Consequently the relative balance between radiative and convective heating is largely undetermined. Thus one of the primary objectives of this project was to collect direction measurements of energy transport in laboratory and naturally burning fires.

Measurements

As part of the study presented here, two sets of laboratory experiments were designed to develop new understanding into the mechanisms driving energy transport in wildland fire. The first explored the influence of convective heating on single particle heating (Frankman and others 2010b). The

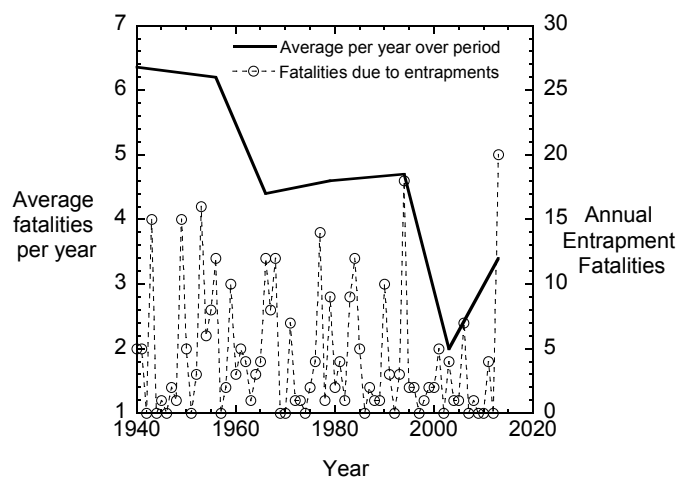


Figure 1—Wildland firefighter entrapments from 1940 to present. Dashed line represents annual entrapments (right axis), solid line represents entrapments averaged over a 8- to 12-year period on an annual basis (left axis).

measurements were combined with a theoretical model of particle temperature as a function of heating mode, duration, and magnitude. Results indicated that ignition of fine dead fuel elements is unlikely by radiative heating alone and then only under circumstances where the fire is very intense (i.e., crown fires). However convective heating and piloted ignition is critical for lower radiant heating levels.

Laboratory fuel configurations are largely limited to packed fuel beds composed of a variety of different fuel types (Fons 1946; Hottel and others 1965; Van Wagner 1967; Anderson 1968; Pagni 1972; Konev and Sukhinin 1977; De Mestre and others 1989; Butler 1993; Catchpole and others 1993; Catchpole and others 1998; Santoni and others 1999; Dupuy 2000). Fuel arrays composed of generally homogeneous randomly oriented fuel elements have been shown to provide nominally consistent fire behavior and repeatability. However, the mechanism by which flame spreads across a gap from one fuel element to another is not well understood. No direct/simultaneous measurement of radiation and convection in wildland fires has been reported in the archival literature. Further, the temporal dynamics of the convective and radiative flux have gone unexplored. As part of this work, a series of laboratory experiments were performed to characterize radiant and convective energy proportioning in fires burning through beds of wood shavings and pine needles. The experiments and measurements are described in detail elsewhere (Frankman 2009; Frankman and others 2010a).

The results from a fire in grass are presented in figure 2. Radiation transfer is sensed long before flame arrival; however, it is accompanied by rapid short duration convective heating and cooling. The convective heating increases abruptly when the combustion occurs. Radiant heating is characterized by relatively (in comparison to convection signal) steady heating through the flame approach, burning and departure. Convective heating fluctuates widely from heating to cooling.

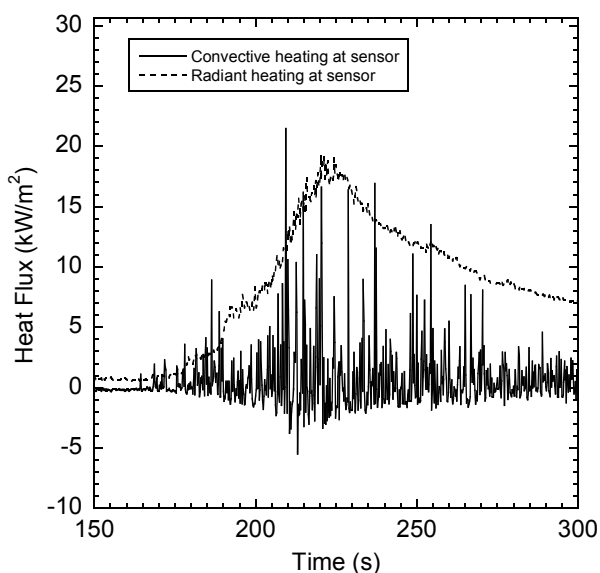


Figure 2—Direct measurements of radiant and convective heating from fire in 0.5 m tall grass. Negative heat flux indicates that energy is being absorbed by the air or essentially that convective cooling is occurring.

To complement the laboratory measurements, time-resolved irradiance and convective heating were measured in natural and prescribed wildland fires from Alaska to Florida on a variety of terrain types and under a broad range of burning conditions between 2006 and 2010. These measurements comprise more than 50 separate instrument deployments. The measurements show that convective transfer varies widely in magnitude over time whereas irradiance is much less variable in time, increasing nearly monotonically with approach of the flame front and declining exponentially with its passage. Irradiance beneath crown fires peaked at 300 kW m^{-2} , peak irradiance associated with fires in surface fuels reached 100 kW m^{-2} with a mean value of 70 kW m^{-2} ; the peak for fires burning in shrub fuels was 132 kW m^{-2} with a mean value of 127 kW m^{-2} . Crown fires in lodgepole pine (*Pinus contorta*) resulted in 2 second averaged convective fluxes from 15 to 20 percent of the peak radiative fluxes. However, fires in surface fuels characteristic of a southern longleaf pine (*Pinus palustris*) ecosystem showed convective heating equal to or greater than the radiative flux. Fires burning in sagebrush (*Artemisia tridentata* subsp. *Wyomingensis*) dominated ecosystems produced peak convective heating 20 to 70 percent of the radiative heating magnitudes.

Figure 3 presents energy levels as a function of vegetation type which is intended to be a surrogate for fire intensity. A burn injury threshold of 7 kW m^{-2} is displayed. Based on these groupings, the decay in intensity with distance can be simulated using a model of the form m/r^n where m is a constant, r is distance from the flame, and n is an exponent (0.75 for these data). The values for m scale nominally with the observed peak total heating values measured in each grouping, the exponents (n) were held constant. The largest discrepancy between this model and the data occurs for the moderate intensity crown fire data. These data are based on measurements over a range of topographical and vegetation types. Also the arbitrary nature of the grouping could alter the results. However, there is

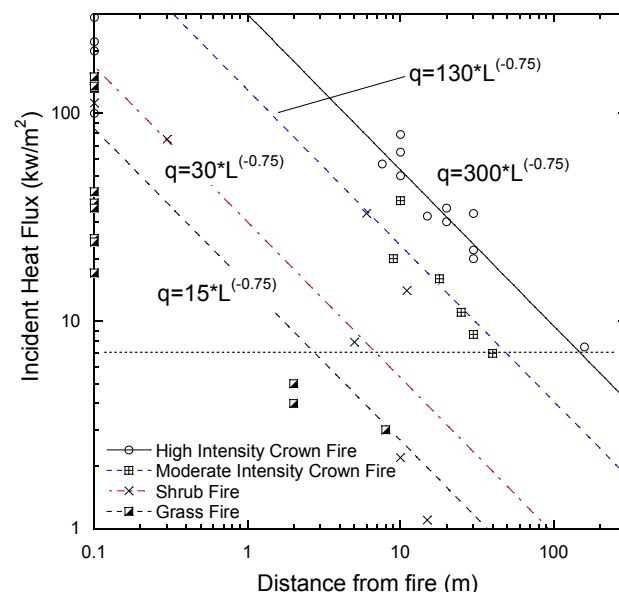


Figure 3—Exponent based models for energy decay with distance for wildland fires. L represents distance from fire.

some intuitive comfort derived from the correlation between peak total heating values and the constant multiplier values.

Empirical Model

Four heating regimes are identified for these data. The lowest being that associated with fire in grass vegetation. These measurements are best fit by a line defined as $q = 15/L^{0.75}$ where L is the distance between the receptor and the fire. The next highest heating level is associated with shrub vegetation similar to sage brush. Nominally, these shrubs are 1 to 2 m tall. The best fit for heating level as function of distance from flame is $q = 30 / L^{0.75}$. For taller shrubs (i.e., gamble oak) or low intensity crown fires the fit is $q = 130 / L^{0.75}$. Finally the most intense fires such as those typically associated with forest crowns the best fit is $q = 300 / L^{0.75}$. The horizontal dashed line represents the level at which second degree burn injury will occur in roughly 30 to 60 seconds. Logically the point at which the best fit for energy distribution crosses the burn injury limit would represent the minimum distance required from a fire in the particular vegetation type to prevent injury. Thus for the highest intensity crown fires nominally 105 m is required, for moderate intensity crown fires or fire in 2 to 4 m tall shrubs the minimum distance is 60 m, for fires in 1 to 2 m tall shrubs or grass the minimum distance is 8 m and for fires in grass less than 1 m tall the minimum separation distance is 3 m. This approach includes wind and slope implicitly in the data set. There is no direct accounting for steep slopes or strong winds. Additionally only a few data points were collected in steep terrain or windy conditions, thus this empirical model does not have a strong slope or wind component. Recent efforts have been focused on using the field measurements to tune the parameters required for a computer simulation of the energy distribution in front of a fire. The simulations are underway.

Escape Routes

Escape routes are the paths that firefighters must travel to reach a safety zone in the event of a change in fire behavior. Clearly, a complete analysis of safety zone effectiveness is impossible without considering the time it takes for a fire crew to get to a safety zone prior to arrival of the fire. Cheney and others (2001) noted a doubling of flat terrain fire spread rate for slopes of 18 percent and another doubling for slopes of 36 percent and state that firefighters often overestimate distance to fires when observing fire through a forest and are thus lulled into a false sense of security. Butler and others. (1998b) proposed that differences in time for the fire to reach the safety zone be compared against firefighter travel times along their escape route as yet 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 and firefighter crew types, and slope (Butler and others 2000; Ruby and others 2003; Alexander and others 2005). Travel on moderate slopes (nominally 26 percent) is 30 percent slower

than those on flat terrain. Dropping packs and tools increased travel rates by 20 percent. Travel rates increase by 40 percent when moving over moderately improved and marked trails. Recent firefighter fatalities suggest that considerable work should be done to increase firefighter awareness and capability to evaluate transit times within the context of fire spread rates and safety zone accessibility when moving from one area to another on wildfire incidents.

Water as Safety Zone

Water bodies have been used effectively as safety zones, but they have also resulted in some drownings. Some considerations are temperature of the water and potential for hypothermia. Immersion in even seemingly warm water can result in hypothermia in relatively little time. For moving bodies of water, the potential for the current to cause a person to lose their footing and be swept downstream is real. This is especially true if firefighters are wearing packs or multiple layers of clothing that have become soaked with water. Water quality should also be considered; immersion in fetid water could introduce unnecessary risk and may warrant looking elsewhere for safety. However, even with the above considerations, water can provide a high degree of protection from thermal damage. Even a shallow water body (as little as 0.1 to 0.3 m) will provide significant thermal protection. There have been reports of entire ponds evaporating when exposed to heating from a nearby crown fire. This does not seem possible from an energy transport point of view, but it could be associated with strong winds associated with a fire that effectively evaporate a shallow water body away. As a caveat it is important to emphasize that soaking ones clothing with water will only increase the thermal conductivity of the clothing and thereby facilitate burn injury. However, drinking water when in an entrapment can be beneficial. Further analysis of water bodies as safety zones should be considered.

Conclusions

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. The prediction of fire behavior, especially during dynamic fire operations can be very difficult even with access to sophisticated computer models and hardware. The studies summarized here suggest that heating levels of 6 to 7 kW m⁻² generally represent burn injury limits; however, a more appropriate metric is thermal dosage unit that includes both heating magnitude and exposure time. Many published studies (Butler and Cohen 1998; Zarate and others 2008; Rossi and others 2011) suggest that SSD is not accurately approximated by a constant multiplier of flame height for flames less than 20 m tall; however, as flames exceed this height, separation distance can be approximated as 2 to 4 times the flame height. Comparison between these studies and fire entrapments suggests that the Butler-Cohen model overestimates SSD, especially for large flames,

while the Zarate' and Rossi models predict minimally survivable conditions. 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 or are exposed to winds convective energy transfer may reach distances equal to 2 to 3 or more flame lengths ahead of the fire front. This implies that the current safety zone guidelines will underestimate SSD in some situations and that the impact 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.

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