A study of the impact of slope and wind on firefighter safety zone effectiveness

Final report for JFSP Project 07-2-1-20

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Executive Summary/Abstract

The term safety zone was first introduced into the official literature in 1957 in the aftermath of the Inaja fire that killed 11 firefighters. Since then identification of safety zones has been an integral task for all wildland firefighters. The work that resulted in the current guidelines used officially in the U.S. is based on radiant heating, flat ground and no wind. This project has as its primary objective an analysis of current safety zone guidelines within the context of wind and slope. Four tasks were completed to accomplish the analysis: 1) summarize current understanding of energy transport in natural fires, 2) collect measurements of heating from fires-specifically on slopes, 3) using the measurements as a basis perform computer simulations of energy transport for different slopes and fire intensities, and 4) based on the results from the simulations recommend a modified safety zone size rule to account for slope and wind. A literature review was completed in year 1. Years 2 and 3 focused on the collection of measurements of energy transport from fires in Alaska, Montana, Oregon, California, Idaho, Georgia, Texas, and Florida. Computer simulations explored relations between energy release, wind, slope, and fire intensity in years 3 and 4. Data and findings were analyzed in years 4 through 6. This project has directly resulted in publication of one doctoral dissertation, more than 12 conference and workshop presentations, and eight peer reviewed manuscripts with five additional manuscripts in preparation.

Ultimately, measurements, literature review, and simulations suggest that current guidelines should be modified to account for flame size, slope, and wind. Three options were identified: 1) a rule based solely on simulated or measured energy release from fires; 2) a rule based on an aggregation of published models for separation distances; 3) a rule based on measurements and simulations that link fuel and environment descriptors to safety zone size. Options 1 and 2 are less desirable as they do not explicitly account for slope or wind and require firefighters to observe or estimate fire intensity or flame height. Option 3 is recommended and has led to a recommendation of a modified safety zone guideline which includes an additional multiplier for slope and wind and is based on vegetation height rather than flame height. A draft guideline was released in July, 2014. It is considered preliminary due to the limited data and analysis. Recent discussion with fire managers who have implemented this proposed guideline suggest that further effort is needed to communicate the conditions underwhich slope should be considered—that is for a safety zone on a ridge top, how close does the safety zone need to be to edge of the ridgetop to require consideration of the slope? It is apparent that this modified guideline should include additional information about location. Future work should focus on collecting additional measurements of energy transport in fires on slopes and in wind, surveying fire managers and firefighters regarding the proposed guideline, and completing further simulations of energy transport from fires on slope. Work will also be directed at developing better ways to implement the guideline. Because the rule will be multidimensional, it will require pocket cards, mobile device applications and computer applications.

Clearance distances needed to minimize damage to communication and power transmission infrastructure in natural lands were also analyzed. The analysis suggested that sufficient heat is present to cause considerable damage to these systems, and that judicious vegetation thinning can minimize this risk. A report has been prepared that presents the findings, additional work is planned provided funding can be secured.

Analysis of firefighter entrapments over the past 90 years suggests that advances in understanding of fire, changes in fire management policy, and better firefighter work practices can save lives. The work performed with support from JFSP in this study has resulted in new understanding about how energy is released from fires and its implications to firefighter safety. Clearly, the answer is not complete and additional work is needed.

A study of the Impact of Slope and Wind on Firefighter Safety Zone Effectiveness

JFSP Project 07-2-1-20 Final Report

1.0—Introduction

As a consequence of 11 firefighters being killed on the Inaja Fire in 1957 the United States Forest Service recommended that wildland 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 (Beighley 1995). It is the intent that safety zones be available and accessible in the event that fire behavior or intensity increases suddenly making current tactics unsafe. 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 Coodinating Group 2004). Regardless of agency efforts to mandate safety zone use 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 Coodinating Group 1997, 2004; Mangan 2007). Analysis of injuries and fatalities in wildland firefighters from 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). Policy and work practice changes in 1960 (implementation of the requirement for all wildland firefighters to have safety zones, the ten standard fire orders and the watch out situations) resulted in a decrease in the annually averaged firefighter entrapment rate from more than 6 per year (prior to 1960) to nominally 4.5 per year (post 1960). In the aftermath of the South Canyon fire further policy and work practice changes (including the development of a safety zone rule of thumb, work rest ratio, turn down assignment process, etc.) resulted in a further decrease in annually averaged fatalities to nominally 2.5 firefighters per year until 2013 when the average rate increased to more than 3 per year (as a result of the Yarnell Hill fire). These data suggest that improved understanding of fire, changes in policy and changes in work practices can save lives. While not all firefighter entrapment fatalities and injury are associated with failure to identify or properly use safety zones; it seems that additional benefit can be gained from continued focus on this topic.

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 behavior prior to 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 behavior 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 primary objective of this study was to define the primary factors that should be considered within the context of safety zones when the fire is burning under the influence of wind or slope. The safety zone size or safe separation distance (SSD) problem can be divided into three research questions: 1) What is the fire energy source strength; 2) How does that energy cause burn injury as a function of heating magnitude and duration; and 3) What is the relation between energy source, burn injury and distance from the fire? These questions were addressed through three steps: 1) a review of relevant literature, 2) direct measurements and observations of energy release in wildland fires, and 3) a series of virtual experiments using sophisticated fire modeling tools. The findings from these efforts are summarized below. An additional objective of this project was to evaluate the vegetation clearances needed to prevent fire induced damage to power transmission, distribution and telecommunication infrastructure in wildland settings.

1.1—Energy Transport

SSD is dependent on the fire intensity, energy is transported from wildland fires primarily by two heating modes: 1) radiative energy transport and 2) convective energy transport (Butler *et al.* 2004; Yedinak *et al.* 2006; Anderson *et al.* 2010). 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 propagated by radiant heating ahead of the flaming front, or a large crown fire with minimal ambient wind would also be characterized 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.* 2012), 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 where direct impingement of hot gases and flames propagates the flames. Intuitively in this case convective energy transport would dominate energy transport and fire spread.

1.1.1—Measurements

Radiation and convection heat transfer play complementary roles in wildland fire spread (Anderson 1969). Their relative contributions depend in a complex way on the prevailing wind speed, fuel distribution, buoyancy-induced in-drafts, terrain slope, *etc*. A variety of measurements have been collected from fire experiments including but not limited to flame spread rate (Fons 1946; Hottel *et al.* 1965; Catchpole *et al.* 1998), high speed photography to determine flame shape (Anderson 1968), and flame temperature (Anderson 1968; De Mestre *et al.* 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. This balance is critical to understanding how large safety zones need to be. Thus one of the primary objectives of this study was to measure energy transport in laboratory and naturally burning fires.

As part of this study 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 *et al.* 2010b). The measurements were combined with a theoretical model of particle temperature as a function of heating mode, duration, and magnitude. The results indicate 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). The second set of experiments characterized radiant and convective energy proportioning in fires burning through beds of wood shavings and pine needles. The results from the laboratory experiments show the effect of discrete fuel elements on energy transport. Radiation transfer is sensed long before flame arrival, the convective heating occurs abruptly when the combustion occurs. Convective cooling is evident during intervals of radiative pre-heating prior to flame arrival, and during high-amplitude turbulent fluctuations after flame arrival. Successively stronger convective heating pulses are exhibited immediately prior to ignition in nearly all cases, suggesting that convective energy transport may be critical to the flame "jumping" across discrete fuel gaps. The influence of ambient wind field seems to be primarily demonstrated through increased convective heating just before and after ignition. However, wind does not necessarily result in increased cumulative heat load. It appears that in both the buoyancy- and wind-driven experiments the energy levels significantly exceed that required to effect ignition. Finally, the flame spread rate data suggest that the advance of the combustion front is primarily influenced by the strength of the convective flow, either buoyancy- or wind-driven.

Figure 1--Preparing equipment for helicopter sling load into safety zone research location.

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 2013 (Figures 1-3). These measurements comprise more than 60 separate instrument deployments (Figure 4). 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% 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% of the radiative heating magnitudes.

Measurements of heating levels in different vegetation types are shown in Figure 4. The burn injury threshold of 7 kW-m^{-2} is displayed. Based on the vegetation-type groupings, the decay in intensity with distance can be simulated using a model of the form m/r^n were m is a constant, r is distance from the flame, and n is an exponent (-0.75 for these data). The values for m seem to scale nominally with the observed peak total heating values measured in each grouping, the exponent (n) was held constant. The largest discrepancy between this model and the data occurs for the moderate intensity crown fire data.

The data presented in figure 4 suggest that there is a possibility of grouping heating rates by vegetation type. Such a grouping might be useful in a safety zone model. One option for a new safety zone model would be to base it on these data, that is develop a purely empirical formulation.

Figure 2--Fire researchers deploying sensors in black spruce forest in central Alaska.

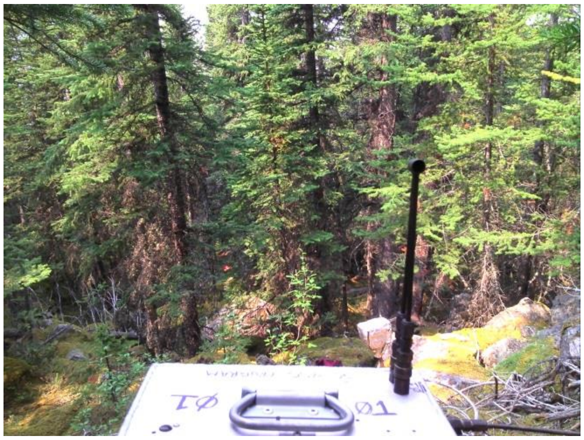

Figure 3—Sensors in Engleman spruce forest.

1.2—Fire Induced 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) trauma associated with extensive 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. We focused on mechanisms # 2 and # 3 in this study. Burn injury is dependent on both magnitude of heating and duration of heating. Traditionally, burn injury limits have been magnitude based. Recent research in this area has developed burn injury standards based on both heating magnitude and heating time. This study incorporates this newer burn injury mechanism.

1.3—Safety Zone Models

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

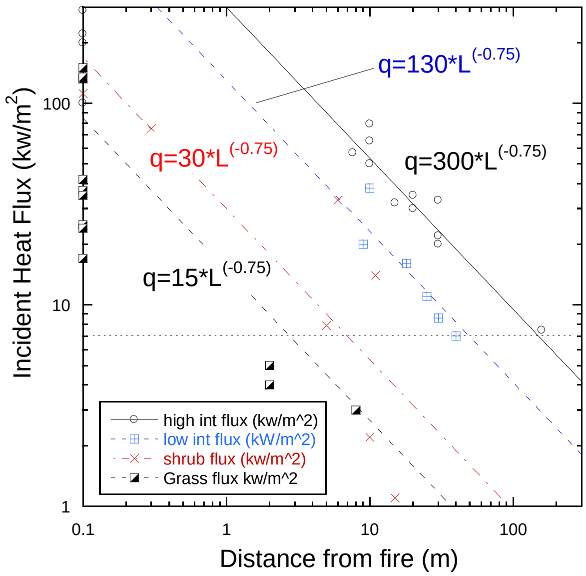

Figure 4—Exponent based energy release models of field measurements.

minimum SSD should be increased by 50% for fires burning on steep slopes.

Butler and Cohen (1998) 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 1200K. 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 Coodinating Group 2004).

While not specifically a safety zone model, Cheney *et al.* (2001) propose the name Dead-Man Zone for the location where fires entrap firefighters who can not retreat to a safety zone. They analyze three fire entrapments in Australia and conclude that parallel or indirect attack tactics present unique and in many cases elevated risk of entrapment, while direct attack poses the least risk.

Zarate' *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 (1998a). They assume flat terrain, flame temperature of 1200K, 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. They also assume flat terrain, constant vertical flame temperature, flame emissivity of 1, atmospheric transmissivity of 1. 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 a low temperature flames (i.e. 873K) is 2.3 times the flame length while a flame temperature of 1353K 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 1473K leads to a zone 2 minimum SSD of 12 flame lengths.

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.

Baxter (2011) reports an experimental characterization of SSD from fires burning through grasses where areas 10 m in diameter were cleared of all vegetation within 50 m by 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 to 1.75 m) is required.

The Butler-Cohen, Rossi et al, and Zarate' et al models are depicted in Figure 5. This form of presentation suggests two potential zones: zone 1 is associated with flames less than 10 m tall and strong dependence of SSD on flame height. Zone 1 suggests that when firefighters are working in vegetation or conditions that are conducive to flames less than 10 m tall they should consider the SSD to flame height ratio to be greater than that associated with larger flames. Zone 2 represents flames greater than 10 m tall, where the models suggest a nominally constant relation between SSD and flame height. The Butler-Cohen model is the most conservative in all cases suggesting greater SSD for both zones. Zone 2 is associated with the four times flame height rule of thumb. The Rossi and Zarate' models suggest zone 2 relation of two times flame height.

All of the studies 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; Frankman *et* *al.* 2012) suggest that while radiant energy transport is significant in wildland fires, heating magnitudes due to convective energy transport can exceed radiant heating. Consequently convective heating should be considered.

1.4—Case Studies

Fire case studies can provide anecdotal information about the performance of safety zones and protective equipment under real life conditions. For this study 12 entrapment cases were evaluated (Butler 2014). 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 case studies illustrate that firefighter entrapments occur across the entire range of fire intensities, fuel types, and terrain. Generally injury and death occur not in designated safety zones, but when crews are in transit attempting to reach a safe area; however there have been some deployments in safety zones. We attempt to analyze both cases. Generally speaking entrapments have occurred in small areas with separation distances less than 2.5 times the flame height.

When these and other entrapments are displayed over the modeled safety zone SSD it is clear that the nonlinear nature of the simulations is supported (Figure 5). For example the data captured in the experiments described by Baxter (2011) and So. Canyon 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 depict unsurvivable conditions which correlate

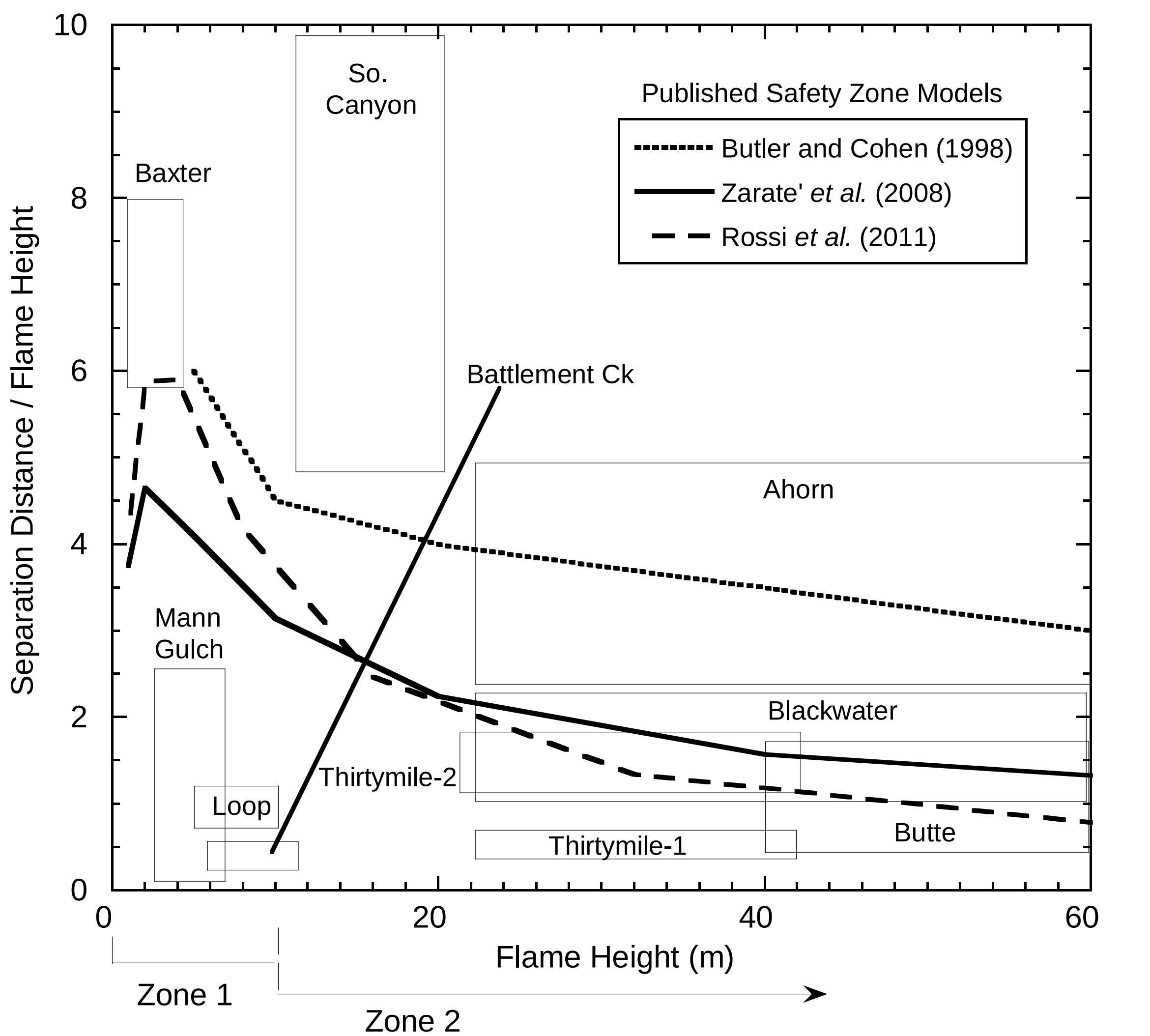

Figure 5--SSD models compared to data extracted from fire incident reports.

with zone 1 separation distances. Comparison between the models and the Ahorn, Thirtymile-2, Butte, and Blackwater fire entrapment data suggest that the Butler-Cohen model over predicts SSD but Zarate' et al. and Rossi et al. models are most closely aligned with deployment zones and thus are minimally survivable in the context of safety zones. These comparisons imply that SSD to flame height ratios should lie between the two model groups for zone 2 and 1.

Vegetation, atmosphere, and geographical conditions that promote greater uncertainty in fire behavior 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 behavior that was observed. Information about the local characteristics of the entrapment site such as distance to vegetation and terrain slope are also critical.

2.0—Fire Simulation

Fire burning on slopes is a complex phenomenon (Figure 6). Recognizing that we would be unable to fully explore the range of fuels, slope, and wind through direct measurements in fires, the final phase of this effort focused on simulating energy transport and burn injury and then using the simulations to develop correlations between environmental descriptors and SSD. The tool selected for this effort was the Fire Dynamics Simulator (FDS) (McGrattan *et al.* 2010). An idealized replication of "real" conditions was formulated while keeping the simulation simple enough to permit the simulations to be completed in a reasonable time frame. The variables that were explored were terrain slope, wind speed, fire energy release (reaction intensity), flaming zone depth, and burn time.

The computational domain was 12 m wide, by 120m long and 25 m higher than highest virtual sensor. Heat release rate, pool extent (along longitudinal axis of simulation domain), and burning time defined fire energy release. Pool extent varied from 1 to 4 m. Fire duration varied from 10 to 30 s, fire energy release was based on reaction intensity as defined for fuel models 2, 5 and 10 (Anderson 1982) for late summer drought conditions as specified in Rothermel (1991). One hour fine dead fuel moisture was 4%, 10-hour was 5%, 100-hour was 6%, live fuel moisture was 78%. Based on these conditions the reaction intensity was 196, 618, and 1237 kW m^{-2} for the three fuel models respectively. Energy release followed a modified top hat distribution where the energy release rate ramped from zero to full specified value over a 1 s period, then full energy release for the burning duration and a linear decrease in energy release to zero over a 1 s period. Wind flow was computed for 30 s prior to initiating the simulated flame to allow the flow field to stabilize. Slopes varied from 0 to 100%, wind varied from 3 to 15 m s^{-1}. Cells were 1 m by 1 m by 1m. A symmetry boundary condition was applied to both lateral sides of the computational domain.

2.3 Burn Injury Calculation

It is desired that the core burn injury calculation account for both heating magnitude and heating time. For each simulation thermal injury limits were calculated based on heating magnitude and duration as a function of distance from the fire.

Figure 6—Fire burning through instrument site in Alberta Canada.

2.4—Safety Zone Preliminary Rule

Based on current findings relative to energy transport from wildland fire in the presence of slope and wind, the following safety zone rule is proposed as a potential candidate to replace the current rule-or-thumb: SSD=8 Δ Hveg where SSD is safe separation distance or radius of the safety zone, Δ is the slope/wind factor from table below, and Hveg is vegetation height. The equation is nondimensional which means that as long as the user is consistent any units will work (i.e. if vegetation height is in feet than the SSD is in feet). The value for Δ given in the table 1 below is based on wind in mph and slope in %. But the actual value for Δ is nondimensional. So as an example, if a firefighter were working on fire burning in sage brush that was 3 ft tall. The proposed safety zone was located in an area with a general slope of 15% and the wind speed expected for the upcoming burn period was 10 mph, and based on past and current weather it is expected that the fire will burn with moderate intensity, the value for Δ would be 2. Thus the safety zone should be large enough to provide a minimum separation from sage brush of 8 x 2 x 3 ft=48 ft. If the vegetation height were given as 1 meter than the SSD would be 8 x 2 x 1m = 16 m. An additional distance would be required to provide space for crew and equipment. Generally a crew of 20 people would require an additional 5 to 10 ft of radius, addition of a vehicle would require an additional 5 ft in radius.

The area highlighted in orange corresponds to conditions underwhich large natural openings are required. In many cases the required sizes are so large that if they do not exist naturally, they are not practically possible to construct. Otherwise alternative tactics should be considered such as additional lookouts to

Table 1—Proposed safety zone rule adjustment factor.

Δ	Slope (%)				
		0	20	>30	Fire Intensity
Wind (mph)	0	1 1 1	1 1.5 2	2 2.5 3	Low Medium High
	10	1.5 2 2	2 2.5 3	3.5 4 5	Low Medium High
	>20	2.5 3 3.5	3.5 4 5	5 6 6	Low Medium High

monitor fire activity, enhanced methods to exit fire area, or modified decision points that would trigger egress earlier in the burn period.

The multiplier selection should be determined based on current and forecast weather, fuel conditions and fire behavior. For example a situation where the fire is or will be burning at what could be considered higher than normal intensity would use a higher multiplier than the multiplier selected for moderate or low intensity.

3.0—Telecommunications and power transmission clearing standards

As part of this study JFSP asked the principal investigator to investigate vegetation clearance distances required to prevent thermal damage to power transmission, distribution and telecommunication infrastructure.

Clearance standards in the US have been specified primarily from the standpoint of preventing ignition due to arcing from the power line to ground or vegetation, rather than preventing fire-caused damage to poles towers or lines. In the United States each state can specify clearances from vegetation to prevent ignition of fires. The general guideline is 3.3 m (10 ft) of clearance from high voltage power lines (Anon 2011); however there are no such standards for separating power lines, utility poles, junction boxes, and microwave towers from vegetation to prevent thermal damage from fire.

For this study Forest Service researchers reviewed literature for clearance guidelines and material thermal properties and then analyzed simulations of fire and heating distances for various equipment installations. The literature search indicated no standards other than the single 10 ft clearance.

Vegetation clearing distances depend on three variables, the intensity of the fire, the time of heating, and the thermal properties of the item of interest.

To further explore the question, computer simulations based on the Fire Dynamics Simulator (FDS) developed at the National Institute of Standards and Technology (McGrattan *et al.* 2010) were performed. The analysis assessed the impact of fires in various fuel types on power transmission lines, telecommunication lines, utility support poles of wood, steel and fiberglass, microwave towers, and ground located transformer and junction boxes. FDS was formulated to simulate fires burning in three types of natural fuels (grass, brush, conifers) based on fire intensity data collected through direct measurements in fires in a range of fuels, topographical, and weather conditions (Frankman *et al.* 2012).

3.1 Findings

3.1.1 Overhead Conductors

Analysis and expert opinion indicates that power transmission and distribution conductors typically do not fail in wildland fire settings, primarily from the standpoint of residence time of the fire. If conditions exist where residence time is expected to exceed a minute or so (say a large accumulation of large diameter dead and down vegetation) then failure could occur. Table 2 below presents recommended clearance distances.

Table 2: Recommended clearance distances for overhead lines.

	Vegetation Clearance from Overhead Transmission Lines (m)	
	Bare wire	Insulated wire
Grass/litter	N/A[5]	N/A[5]
Low Brush	N/A[5]	15
Tall Brush[2]	50[3]	-
Crowns	53	115

[2] Tall brush was not simulated in USFS study.
[3, 4]based on rough approximation of trend in observed data.
[5]clearance distance much less than nominal height of conductor.

3.1.2 Towers and Poles

Poles and towers have been observed to fail due to heating from wildland fires (Figure 7). For this study, wood, steel, aluminum, and pultruded fiberglass utility poles were modeled as vertical rectangular prisms with surface temperature sensors at different heights along the pole. The results suggest steel towers provide the greatest resistance to fire induced damage with performance of intact non-aged wood also very high.

Ignition of wood poles is strongly dependent on the age and condition of the pole. Poles that display a uniform exterior surface are much less susceptible to ignition from heat and lofted embers than poles that are aged with large deep vertically oriented fissures in the surface. The advantage of wood poles and towers is that they typically do not fail catastrophically, but rather burn through over some finite time period, while steel or aluminum towers and poles if heated sufficiently can fail suddenly during the peak heating period. Thus interruption of the power grid can occur during the fire event with steel and aluminum structures but likely an hour or so after the fire event for wood support structures.

The most conservative approach would be to apply the greatest values from either study to each condition.

3.1.3 Junction Boxes

The analysis considered thin wall steel junction and transformer boxes. PVC insulated cable at the center of the box was modeled. In no cases did the cable temperature reach the critical threshold prior to the failure temperature of the steel. Therefore the limiting case was the steel box temperature.

3.5.6—Microwave Towers

The study considered microwave towers (guyed or free standing). Towers and guy wires are typically constructed of galvanized steel may also be constructed of fiberglass and wood. In many cases the limiting factor is likely the insulated signal wires leading from a signal station at the base of the tower to the tower. In the case of free standing towers, the clearance distances should be developed based on the limiting material. For guyed towers additional consideration should include clearance around guy wires. Simulations found that a 12 m vertical clearance and 4 m horizontal clearance was adequate for towers and guy wires.

The findings based on the simulations should be considered preliminary. Further testing and computer simulations should explore additional slope, wind, and fire intensity ranges. In all cases further analysis should be accompanied by systematic field observations of scorch heights and damage to support towers and conductors for a range of vegetation types and topographical conditions. Such observations can be used to verify theoretical and computational results. It would also be very instructive to build a stronger link between operational fire models and the energy transport model used here to link vegetation and environment factors more directly to the energy transport modeling.

Figure 7 -- Wood power distribution pole that has collapsed due to fire. Image taken on the French Fire in central California.

Table 3: Utility tower separation results from different fuels

Material	Temperature (°C/°F)	Reaction	Grass Clearance (m/ft)	Brush Clearance (m/ft)	Crown Clearance (m/ft)
Wood	300/572	Wood chars indefinitely	4/13	8.5/27	25/80[1]
Steel	538/1000	Steel softens and breaks	0	2/6	20/65[1]
Aluminum	162/325	Begins to loose strength	7/22[2]	11/35[2]	20/65[1,4]
Fiberglass	350/662	Pole changes shape	3/10	5/16	-[3]

[1]depends on slope and wind exposure see Table 5 for additional information.
[2]based on combined XCEL energy and USFS analysis.
[3]this material not simulated.
[4]it seems that further analysis is required as intuitively AL should require greater clearance distance than steel.

4.0—Management Implications

The findings relative to safety zones have broad implications to all wildland firefighters and fire managers. While there is not yet sufficient understanding to finalize the question of the impact of slope and wind on safety zone size, for many cases (high winds and steep slopes) it is clear that if natural openings in the dominant vegetation are not sufficiently large then alternate tactics will be required as the sizes are so large to preclude mechanical construction. Thus fire management teams and fire crews must consider alternatives such as early retreat from areas that may be at risk as thresholds are met. They must use lookouts more efficiently and effectively, and they should consider modifying work schedules to allow more work to be completed during periods of lower burning and then moving crews from areas at risk during the peak burning periods. For example, crews working on the fireline could wake up earlier in the morning so that they can be on the fire at day break and then work through the morning, withdrawing to safety areas as fire intensity peaks in the afternoon. Additional work is needed to define when a safety zone is subject to slope considerations or when it is sufficiently distant from the slope to warrant flat terrain consideration. Finally the topic of escape routes and safety zones should be considered jointly rather than as independent activities. Very little information exists for evaluating the effectiveness of escape routes. Many fatalities have occurred while fire crews were attempting to reach a safe area. Perhaps additional emphasis on frequent validation of escape route transit time is warranted. Finally, this study does not address the topic of safety zones in wildland urban interface where structures can be considered as safety zones.

The preliminary findings released in July, 2014 form the foundation for work over the next few years. There exists a critical need for additional measurements of energy release from fires at moderate to high intensity from fires burning on slopes with and without the influence of wind. Such measurements can guide computer simulations that will provide quantitative information for the further refinement of the safety zone guideline. Additionally further analysis is needed to determine at what point is nearby sloped terrain critical to safety zone size.

Regarding vegetation clearances to minimize fire induced damage to power and telecommunication infrastructure, the findings represent the only quantitative study. While other work likely exists within private industry, it is not available for public use. Further exploration and development on this question is also needed.

5.0—Conclusions and Needs

5.1—Conclusions

The funding from JFSP for this project has led to advances in understanding about how energy is released from fires, the impact of atmospheric humidity on that energy, the relative contribution of radiant and convective energy transport, and the impact of slope and wind on energy release. It is only recently that measurements have begun to quantify the range of heating magnitudes that can be expected from wildland flames. Literature review has shown that while the work performed in the 1990s by Butler and Cohen is relevant, it may be overly conservative. Many questions remain regarding how energy is generated and released from wildland flames. Computer simulations have extended our understanding of the impact of wind and slope on heating from fires, but the simulations are rudimentary and additional work is needed. The measurements, analysis and simulations completed as part of this work have provided new information about the characteristics of an adequate safety zone. However, additional ongoing focus on measurements in sloped terrain, shrub fuels, and wind driven fires are needed to further provide insight and understanding on this topic.

Recent feedback and assessment from actual use of the proposed safety zone guidelines indicate that the upper limits for safety zones associated with high intensity fire behavior are much too large (Figure 8). For vegetation on the order of 60' tall on steep slopes with strong winds the suggested area is nearly 600 acres - almost a square mile! Intuitively, at some point the area will be large enough to provide adequate protection from all fire conditions. This limit is not known. Clearly, an upper limit should be imposed in the proposed modified guideline. Future work should further define what this limit is.

Ultimately, many questions remain about firefighter safety zones and how to improve our capability to assess their effectiveness before they are needed.

5.2—Recommendations

The case studies presented above as well as the energy analysis clearly suggest that slope and wind should be considered when assessing safety zone size and location. However, the anomalies in the simulation data suggest that we did not get it totally right—additional simulations are warranted to more accurately determine how wind and slope interact to impact energy release and SSD. With a sustained effort over 3 to 5 years it seems that sufficient information will be acquired to accomplish this goal. Within this timeframe current safety zone guidelines presented in the IRPG and S-courses should be modified to reflect new findings.

Regarding the vegetation clearance distances for power and telecommunications infrastructure: in the absence of any additional information or studies the clearance distances developed from this study should be implemented.

Figure 8—Large Safety zone prepared using mechanical means on the Bald Sisters.

5.3—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 (see Table 4). Perhaps a relevant approach would be to establish a research team that would work under the guidance of an advisory committee composed of firefighters and fire managers from all experience levels. Logically, the team would have a 5 to 10 year charter with funding and authorization to address the questions surrounding entrapment avoidance in depth.

5.4 Other Considerations

5.4.1—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 not possible without considering the time it takes for a fire crew to get to a safety zone prior to arrival of the fire. Firefighter fatalities suggest that crews can and should direct additional attention at characterizing escape route transit times within the context of fire spread rates and safety zone accessibility when moving from one area to another during a work period.

5.4.2—Fire Whirls

Historical accounts identify instances where large fire whirls measuring tens to hundreds of meters 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. A recent study has identified the primary characteristics of large fire whirls that can be generated in and along fire fronts (Forthofer and Goodrick 2011). Further analysis is needed to identify conditions where such phenomena form.

5.4.3—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. 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. Continued assessment of the impact of convective heating on safety zones is needed.

5.4.4—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 focused on understanding construction and vegetation management techniques to reduce and prevent structure ignition (Cohen 2000). 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. Further analysis is needed on this topic.

5.4.5—Firefighter Clothing

Firefighter clothing provides protection by shielding skin from radiant heating and also from convective heating. Studies have shown that one layer of clothing with a 4 mm air gap between it and the skin will increase time to burn injury by a factor of three (Raj 2008). Clothing that is soiled will not appreciably change in capacity to intercept heating; however if the primary source of the dirt is oil or gas then the flame retardant properties of the clothing are compromised and in some cases the insulating properties reduced. Proper use of personal protective equipment will decrease the rate of burn injury. Continued emphasis of this fact (i.e. keep sleeves rolled down, etc.) is needed within the wildland fire community.

Table 4 Research Needs

1) Further measurements are needed to more fully define the range of energy release rates associated with natural fires, particularly in tall shrubs like those found in the Southwestern U.S.
2) Such data would provide value to this as well as other studies exploring fire effects, emissions, and fire behavior.
3) Clearly there are questions regarding energy transport along slopes that were not addressed in this work. It would be of interest to simulate fires and SSD using a larger computational domain, more sophisticated modeling technique, and more formal theoretical rigor. Such an approach may provide both a check of current work and additional information about future questions. Such virtual datasets that could be used to further explore relations between SSD, fire, and environment descriptors.
4) This analysis has shown that convective heating should be considered any time that safety zones are selected on or near sloped terrain. However, further understanding is needed about how specific terrain features impact convective energy transfer. This should include the impact of chimneys, ridges, bowls, and draws.
5) Current work is exploring how clothing impacts firefighter safety. Work should be continued to provide more quantitative understanding about the role that clothing type, number of layers, and extent of coverage affect burn injury.
6) As the scenario becomes more complex in terms of the factors that describe the fire environment it is critical that better methods be developed to determine 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). There is work underway in the USFS and elsewhere exploring the utility of portable, wearable devices to broadcast the location of a person or vehicle as well as provide information to them about fire location, weather or other critical factors. Such technology could provide the potential for truly expecting zero injuries due to entrapments.
7) Ideally, any evaluation of safety zone effectiveness should include an assessment of time to get to the safety zone. Further measurement and understanding of how crew travel time correlates to slope, trail condition, vegetation type, and pack weight is needed.
8) Many factors affect fire intensity and spread. Improved tools for predicting and communicating fire behavior prior to ignition or changes in fire intensity are needed if firefighters are to be successful in identifying SSD prior to lighting a fire or changing location and tactics. Further effort is needed to improve the capability of firefighters in accomplishing this.
9) Development of a collection of images of safety zones in a variety of fuel and weather environments along with quantitative analysis of the effectiveness of these locations could be used in firefighter training. This library would be useful in assisting less experienced firefighters in developing an understanding of the characteristics of effective safety zones.
10) Development of a smart phone app that allows firefighters to enter fuel, weather, and terrain information to calculate SSD could provide useful capability. Such a mobile device application is under development as a proof of concept.
11) Integration of the current findings from this work in S-courses, the IRPG and in the BEHAVE prediction system as well as other fire management decision support systems.
12) Recent entrapments have occurred in the vicinity of lakes, and firefighters have retreated to lakes to escape injury. A simple analysis of the primary factors that should be considered in this situation may be beneficial as a training supplement for firefighters deployed or working in areas like the boundary waters of Northern Minnesota.
13) Additional and more indepth computer simulations of heating as a function of safety zone location in a topographical context. Questions of interest include the difference between locating a safety zone at the base of the slope or at the ridge top or in a naturally low area versus a high area.
14) Explore further the implications of safety zones within the Wildland Urban Interface.

5.5—Deliverables

The original proposal specified conference publications, journal publications, presentations and modifications to the IRPG handbook. Conference and workshop presentations were made each year, many not specified in Table 5. Eight published journal articles can be directly attributed to this work. They explore the influence of water vapor produced by the fire on energy transport around wildland fires (Frankman *et al.* 2008), attempts to develop new understanding into the ignition process of fire (Frankman *et al*. 2010a; Frankman *et al.* 2010b), measurements of energy release from actual fires (Frankman *et al.* 2012; Frankman *et al.* 2013), a presentation of the impact of vegetation management techniques on reducing fire spread (Butler *et al.* 2013) and a summary of the current state of the science relating to wildland firefighter safety zones (Butler 2014). Funding from this work also contributed to efforts to understand how wind affects fire spread (Forthofer *et al.* in press-a; Forthofer *et al.* In Press-b; Butler *et al.* in review). Additional manuscripts are in development that discuss measurements collected with some funding from this study. Manuscripts that have been published are shown identified in the reference list as indented with hyphens and bold text.

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Table 5-- Comparison of planned and actual deliverables

Planned Deliverable	**Description**	**Actual Deliverable**
Conference paper	Summary of year 1 data and analyses	(Ottmar *et al.* 2009)
Conference paper	Summary of year 2 data and analyses	(Butler and Jimenez 2009)
Journal Article	Safety zone implications for slopes	In total eight journal manuscripts can be directly attributed to this funding (Frankman *et al.* 2008; Frankman 2009; Frankman *et al.* 2010a; Frankman *et al.* 2010b; Frankman *et al.* 2012; Butler *et al.* 2013; Frankman *et al.* 2013; Butler 2014). Five additional manuscripts are under development.
Presentations	Summaries of research results will be presented at conferences as appropriate.	Annual presentation at Northern Region Fire Behavior Workshop. Most recent presentation at Large Fire Conference in Missoula MT.
Internet	Data and preliminary results will be posted online on regular basis throughout the project.	Current at www.firelab.org
IRPG, Handbook, pocket guide or other product (TBD)	Safety zone guideline updates submitted for inclusion in IRPG, S-course curricula and Fireline Handbook.	Preliminary rule released 7/2014 through JFSP, Work underway to develop mobile device app—contract in place 9/2014
JFSP Report	Final report	Submitted
Vegetation Clearance Summary	Report	An unpublished report has been released that summarizes findings to date on the topic of clearing and thinning to minimize fire induced damage to power and transmission lines. A summary has been presented and will be published in the proceedings from the Large Fire Conference held during May of 2014.

6.0—References

Publications produced as a result of work performed on this study are shown in bold text.

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