Final Report for JFSP funded project entitled:

Characterization of Firefighter Safety Zone Effectiveness

JFSP Project 03-2-1-03

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Executive Summary

Perhaps one of the most critical decisions made on wildland fires is the identification of suitable safety zones. Past fire entrapments and near misses (e.g. Thirtymile fire, Price Canyon, and South Canyon Fires) illustrate the need to continually assess and improve our understanding of wildland fire behavior and associated firefighter safety guidelines.

Current firefighter safety zone guidelines are based on a theoretical model of radiative energy transfer from a linear fire front burning across flat terrain. The model is based on the assumption that the energy transfer process (at least for safety zones) is dominated by radiant energy transfer. When published this model had not been compared against measurements of energy transfer, simply because data did not exist. Funding from the Joint Fire Science Program (JFSP) was used to explore through direct measurement and theoretical modeling the accuracy of current 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. The data were used to develop physically realistic models of wildland flames and theoretically calculate the distribution of energy in and around those flames.

Measurements and analysis support current guidelines with respect to radiant heating from the flames; however, they also illustrate the importance of considering convective energy transport in the context of safety zones in mountainous terrain. Results from this and other studies have been used in S-course training and in firefighter safety zone guides found in the Incident Response Pocket Guide and the Fireline Handbook. This fact alone indicates the wide ranging impact that this JFSP sponsored research has had on wildland firefighter safety.

Figure 1 View from rock slope used for safety zone in Thirty-mile fire.

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Introduction

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 Butler and Cohen (1998) model simulated the spatial distribution of radiant energy in front of a linear vertical flame. The flame was assumed to be isothermal at 900°C and an emissivity of 1 (Catchpole et al. 1998). The distribution of radiant energy in front of the flame was calculated as a function of flame height and distance from the flame. The minimum safe distance for a firefighter to be from a flame was calculated as that corresponding to a radiant incident energy flux level of 7.0kW-m^{-2}. 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. For a circular safety zone this would be equal to the safety zone radius.

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 fire entrapments.

Recognizing the need for further evaluation of the model, the Joint Fire Science Program Board of Directors provided financial support to equip a team to collect additional data and perform an in-depth analysis of the safety zone model.

Methods

The primary objective was to evaluate safety zone model and if needed modify it. Measurements of fire intensity were obtained by deploying arrays of radiometers (devices that measure radiant energy emitted by the fire). These sensors were positioned to measure the vertical distribution of radiant energy emitted by the approaching flames (see figure 2). Small gauge shielded thermocouples (flame temperature measurements) provided measurements of flame and air temperatures during passage of the flame front. Pitot-static type velocity probes (devices designed to measure air flow direction and magnitude) were positioned to sense the magnitude and direction of air flow before, during, and after the fire

Figure 2 Instrument package deployed in eastern Oregon.

passes. The sensor packages were deployed ahead of spreading fires.

The team consisted of one full time instrument technician (GS-9 or GS-11), one full time mechanical engineer (GS-7 term appointment), and the Principal Investigator (GS-13). All team members were fireline qualified.

The information collected using the sensor packages provided direct measurement of the relative magnitudes of the radiant and convective energy emitted during the fire, information needed for an accurate evaluation of current safety zone models.

Flame geometry was obtained by analysis of video images of the fire collected from visual image video cameras mounted in fire proof enclosures located inside or near the burned area. The camera enclosures were used successfully in a wide range of fire intensities and fuel types.

Results and Discussion

Measurements of energy distribution from fires were collected from fires in Alaska, Montana, Idaho, Oregon, Arizona, Florida, Washington and northern Canada. The dataset collected in Arizona was particularly rich. The data were used to “tune” the flame model. Figure 3 presents a theoretical flame with the base to tip temperature distribution determined from *insitu* measurements of both heat flux and temperature.

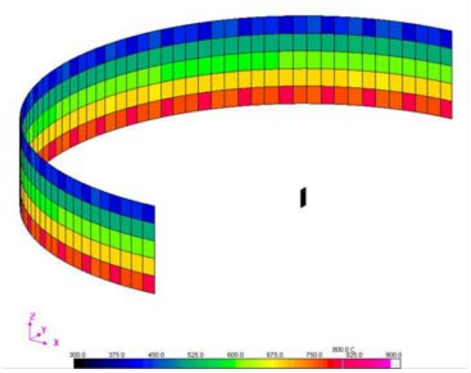

Figure 3 Theoretical flame based on temperature and heat flux measurements. Tip of flame is 400°C and base is 800°C with linear distribution between the two extremes. Black surface at center of semicircular flame is simulated firefighter at center of safety zone.

Once confident in the flame model, various flame scenarios were simulated (i.e. linear, semicircular and tilted). Based on the 7kW-m^{-2} second degree burn injury limit, minimum separation distances were calculated for each type of flame. Figure 4 illustrates the tilted semicircular flame. The minimum separation distance for this scenario was 3.5 times the flame height. In all cases the minimum separation distance was less than 4 times flame height. We believe the radiation model to be relatively accurate; however the uncertainty in the burn injury limits and flame height estimation are still large (rough estimate is +- 50%). Therefore we continue to support the current rule of thumb that minimum separation distance in safety zone should be at least 4 times the flame height.

The comparisons also indicated that one guideline was potentially inaccurate.
It was that the safety zone size in acres could be obtained by dividing flame height in feet by 8 to get size in acres

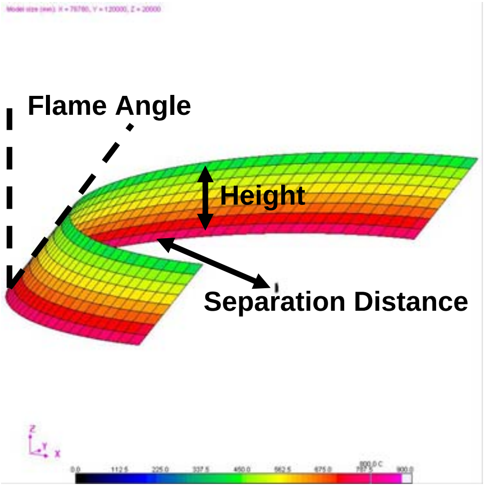

Figure 4 Flame with 40 degree tilt. Minimum calculated separation distance equal to 3.5 times the flame height.

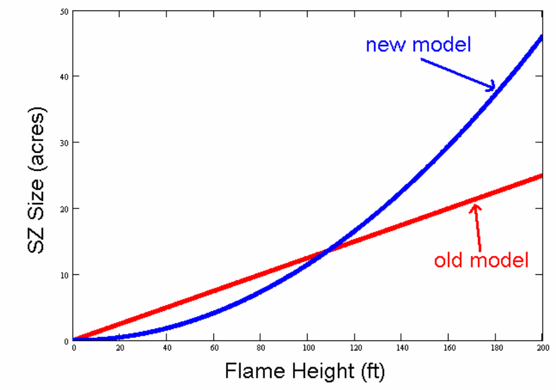

Figure 5 Some users prefer a model that relates safety zone size in acres to flame height. A few years ago it was proposed to use flame height in feet divided by 8 to get size in acres (red line). This model was based on a flat front fixed width flame and is not accurate for the semicircular flame front. Rather it is proposed that we use Flame height squared divided by 900 (blue line).

(figure 5). This model was based on a linear front fixed width flame and is not accurate for the semicircular flame front. Rather it is proposed that we use Flame height squared divided by 900 or alternately the linear approximation that minimum safety zone size in acres is equal to the flame height in feet divided by 4 could be used.

We also explored the difference between a linear and semicircular flame front when the more realistic vertically decreasing flame temperature profile is used. We had received comments that the safety zone model overpredicted minimum separations distances. For example firefighters indicated that they could stand much closer to a 4ft tall flame than the 16ft indicated by the safety zone model. Our simulations indicated that the incident radiant flux was approximately 33% lower for identical separation distances when comparing the semicircular and the linear flame fronts. However, we support the existing model for the following reasons: The semicircular front represents the worst case scenario; 2) flame heights are difficult to estimate; 3) exposure to the heating is often less than the 90 seconds; 4) the original model and these simulations are for exposed bare skin and do not account for the insulating protection provided by loose clothing; and 5) shorter flames are often not as efficient at radiating energy to the firefighters. Again, the conclusion was to take a conservative approach and continue to support the existing safety zone model and guidelines.

We explored the factors affecting safety zone effectiveness when located on slopes or ridges. Intuitively it is expected that when safety zones are located above upward spreading fires that occupants may be exposed to convective energy transfer from the fire; however no data exist to support and quantify this assumption. The current firefighter safety zone model addresses only radiant energy transfer, it does not account for

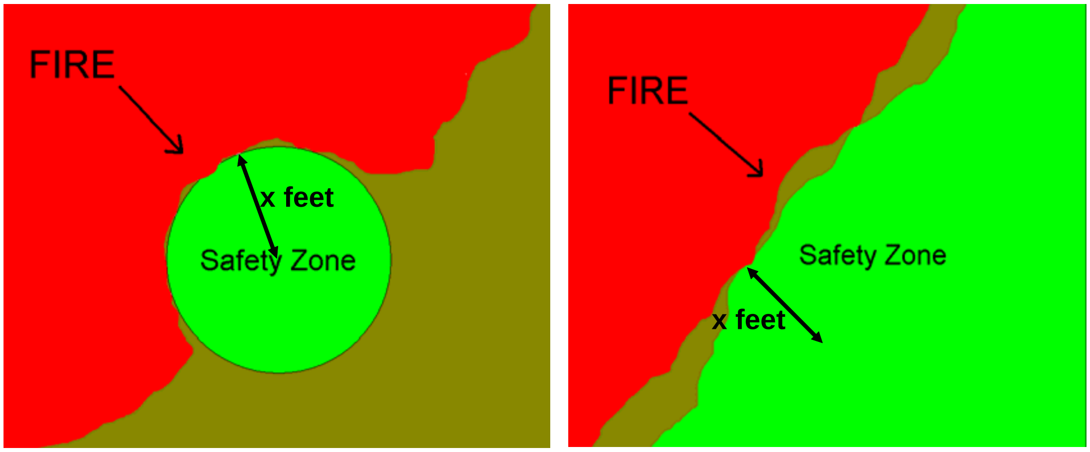

Figure 6 Comparison of safety zone shape based on theoretical model.

convective heating. Data gathered as part of this study indicate that convective heating is not significant on level terrain at distances greater than nominally 2 flame lengths from the fire. However, intuitively, it is expected that when safety zones are located on slopes or ridges convective heating may play a significant role and can be on the order of the radiant energy heating rates. Thus when safety zones are located above upslope spreading fires radiant energy transfer may be reduced but the additional contribution due to convective heating will probably more than compensate for the decreased radiant transfer. Therefore, increased safety zones size adjustments or alternate tactics should be considered. In all cases the distance from combustible vegetation should be maximized as seemingly green vegetation can participate in the flaming front when heated by both radiation and convection.

An additional factor is that firefighter escape route transit times are strongly dependent on slope. Firefighting tactics should be adjusted when safety zones and escape routes require up or down slope travel.

A secondary objective was to use the theoretical model to evaluate safety zone shape as a factor in safety zone effectiveness. Figure 6 presents the scenarios explored. Simulations indicate that for the linear fire front case, separation distance can be reduced as compared to the semicircular fire front and circular safety zone. Given the many uncertainties and assumptions associated with the model we recommend that the more conservative circular model be applied (the current model).

Products

Deliverables specified for this project were:

1-Collect field measurements of heating rates from full scale wildland fires.

This has been accomplished, the data were used to develop a physically realistic flame model for the heat transfer simulations.

2-Evaluate the accuracy of the current safety zone model using the measurements.
The data were used to develop a new flame model with variable temperature field. Simulations were performed to explore the accuracy of the published safety zone model.

3-Explore the importance of safety zone shape on safety zone effectiveness.
Simulations using the improved flame model explored the impact of safety zone shape on safety zone effectiveness.

4-Explore the impact of slope on safety zone effectiveness.
Simulations and measurements illustrated the importance of convective heating for safety zones located on slopes. While some measurements were made, convective heating is a complex phenomenon and additional measurements and simulations are required. However, the research team did make some recommendations relative to safety zones on slopes.

5-Incorporate findings into current firefighter training.
The findings from this study have been incorporated into firefighter S-course training, the Incident Response Pocket Guide and the Fireline Handbook. The original publication (Butler and Cohen 1998) is available online.

Additional unexpected products from the effort include the improvement of a field deployable fireproof instrumentation package that quantifies energy release rates, air temperatures, and air velocities in wildland flames. This instrument package can be linked to fireproof *insitu* video cameras with the dataloggers and cameras automatically triggered by the arrival of the fire front. These methods and instruments have been used to support a wide variety of other JFSP sponsored research projects.

Appendix A presents the product summary in a table format.

Figure 7 Flames approach ski lift in Alberta Canada. Photo courtesy of Canadian Forestry Service.

Conclusions

We would like all of our safety zones to look like that in figure 7, no burnable vegetation; however that is rarely the case. Consequently it is important to provide information to firefighters so that they can make the best decisions possible regarding safety zone effectiveness. Measurements were collected of heating rates from wildland fires. These measurements were used to develop a physically realistic flame model for use in a parametric evaluation of safety zones. Findings indicate that for flat terrain, the currently used model should not be modified, with the exception of some of the guidelines relating safety zone size in acres to flame height in feet. Safety zone shape and location (slope versus flat terrain) were explored. It is clear that locating safety zones on slopes introduces additional complexity that could not be fully explored within the resources of this effort. However, some recommendations regarding size, tactics and location relative to vegetation were presented. All of these results have been incorporated in firefighter training courses. Instrumentation has been developed specifically to quantify the magnitude and extent of convective heating associated with wildland fire.

While not a part of this study It is hoped that future support can be found to further explore the effect of convective heating, especially for safety zones on slopes, and to develop a website where firefighters can view safety zones in various fuels and configurations with an interactive interface that will promote increased awareness of the factors that affect safety zone effectiveness.

References

Butler, B.W. and J.D. Cohen. 1998. Firefighter safety zones: a theoretical model. Intl J. of Wildland Fire 8(2):73-77

Catchpole, W.R; E.A. Catchpole, B.W. Butler, R.C. Rothermel, G.A. Morris and D.J. Latham. 1998. Rate of spread of a free-burning fire in woody fuels in a wind tunnel. Combust. Sci. and Tech. Vol. 131, pp. 1-37

Appendix 1. Deliverables Table:

	Deliverable	Delivered	Status
1	**Insitu measurements of heating rates from wildland fires**.	Measurements of radiant and convective heating rates were made in prescribed and wild fires in the Western US, Canada and Alaska.	Done
2	**Safety Zone Model evaluation**.	Data collected were used to develop new more realistic flame model. Heat transfer simulations were performed to compare this new model with results from Butler and Cohen model.	Done
3	**Safety Zone Guidelines transferred to training**	Results of analysis incorporated in S-courses Incident Response Pocket Guide and Fireline Handbook.	Done
4	**Website**	Basic peer reviewed publications available. http://www.firelab.org	Done
	Powerpoint Talks	January 2003, Great Basin Hotshot Superintendent meeting	
	Other	Incident Response Pocket Guide	
		Fireline Handbook	
		S-130 Mid-2003	
		S-390 March 2005	
		Included in Entrapment Avoidance training	
		Nominated for Chief’s safety award, February, 2006	
	Unexpected Products		
	Insitu Instrument	Improved designs for *insitu* instrumentation	Done

	packages	were developed. These packages included sensors for characterizing radiant and convective energy distribution in and around wildland flames. They also included automatic triggering for the dataloggers. The packages are relatively light weight, robust and easily deployed.	
	Insitu video imagery	*Insitu* video camera packages were developed. The cameras can be linked to the *insitu* sensor packages so that the cameras are triggered to record at the same time as the dataloggers. This allows deployment well ahead of the flaming front reducing safety threats to research teams.	Done