

The effect of terrain slope on firefighter safety zone effectiveness

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Abstract

The current safety zone guidelines used in the US were developed based on the assumption that the fire and safety zone were located on flat terrain. 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 $7.0\text{kW}\cdot\text{m}^{-2}$. Current firefighter safety guidelines are based on the assumption that radiant energy transfer is the dominant energy transfer mode. Intuition, professional observations, and the few experimental measurements that have been reported indicate that when fires are located on slopes or ridges convective energy transfer may reach distances equal to 2 to 4 or more flame lengths ahead of the fire front. This implies that the current safety zone guidelines may be invalid in some situations where the safety zone and/or fire are on slopes. A research project supported by the Joint Fire Science Program is underway to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes. The new guidelines will depend on multiple variables including: fire characteristics (flame length or height), site characteristics (e.g. slope percent), and relative location (i.e. chimney, ridge, midslope, ridgetop).

Additional Keywords: Fire behavior

Introduction

Perhaps one of the most critical decisions made on wildland fires is the identification of suitable safety zones for firefighters during daily fire management operations. To be effective (timely, repeatable, and accurate), these decisions rely on training and judgment. The current safety zone guidelines used in the US and published in the Incident Response Pocket Guide (IRPG) and Fireline Handbook were developed based on the assumption that the fire and safety zone were located on flat terrain. 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 $7.0\text{kW}\cdot\text{m}^{-2}$ which was determined to be the level at which exposed human skin will develop a 2nd degree burn in less than 90 seconds. 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. When fires are burning on flat terrain, convective energy transfer is primarily upward in the plume while radiant energy transfer occurs out ahead of the fire front. Current firefighter safety guidelines are based on the assumption that radiant energy transfer is the dominant energy transfer mode.

Experimental measurements have verified the accuracy of this assumption but have also indicated that when fires are burning on slopes convective energy transfer can be significant. Intuition, professional observations, and the few experimental measurements that have been reported indicate that when fires are located on slopes or ridges convective energy transfer may reach distances 2 to 4 or more flame lengths ahead of the fire front. This implies that the current

safety zone guidelines may be invalid in some situations where the safety zone and/or fire are on slopes. It is also clear from site visits to designated safety zones on numerous wildland fire incidents that considerable ambiguity exists regarding identification or creation of true ‘safety zones,’ versus ‘deployment zones.’

A new research project supported by the Joint Fire Science Program is underway to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes. We expect the guidelines will depend on multiple variables including: fire characteristics (flame length or height), site characteristics (e.g. slope percent), and relative location (i.e. chimney, ridge, midslope, ridgetop). Special emphasis is focused on the effect of ‘chimneys’ and other terrain features that produce dangerous levels of convective heating ahead of the fire front.

Approach

The approach for this study followed several phases:

- 1) Measure convective/radiant energy transport in fires across a range of slopes and fuel types. Two instrument packages have been developed: 1) The Fire Behavior Flux Package (FBP) and 2) the Video Acquisition Box (VID). The FBP packages measure 27cm by 15 cm by 18 cm and provide an insulated protective enclosure for datalogger, sensors and other electronics. The standard instruments consist of radiometers that measure total and radiant energy fluxes, small-gauge thermocouples (nominally 0.13mm diameter wire) that sense flame and air temperature, and pitot-static type velocity probes that sense the magnitude and direction of airflow before, during, and after the fire passes. The VIDs are approximately ½ the size of the FBP and provide digital video imagery of the fire as it burns past the FBPs. Collecting video imagery not only allows us to observe the actual footage of the fire behavior, but also provides insight into our data analysis.
- 2) Numerical Simulations: We are using measurements to ‘tune’ and validate theoretical heat transfer models. Simulations of fire on slopes are being conducted (fig. 1). The fire is simulated as low velocity jet in a cross flow. The calculations are being explored to develop relationships between fire intensity, slope, cross wind flow strength and fire intensity. Fire growth is being explored using existing spatial fire models like FARSITE and the newly available Wildland Fire Dynamics Simulator (WFDS) developed at the National Institute for Standards and Technology (NIST). Measured and modeled convective and radiant energy distributions around the fires will be applied to human burn injury limits to determine appropriate separation distances and associated safety zone sizes.
- 3) Survey of firefighters: Fire managers and fire crews will be surveyed to determine what they believe is the most effective method for communicating the results of the analysis. It is likely that the results will depend on a number of variables including slope angle, wind speed, fire intensity, and slope shape. Because there are multiple variables, a model with multiple variables will be required. This precludes a simple model like that derived from the original safety zone analysis (Butler and Cohen 1998).

Below we discuss the methods that are being used to analyze firefighter safety zones on slopes. The results will be used to develop guidelines for wildland firefighters in the US.

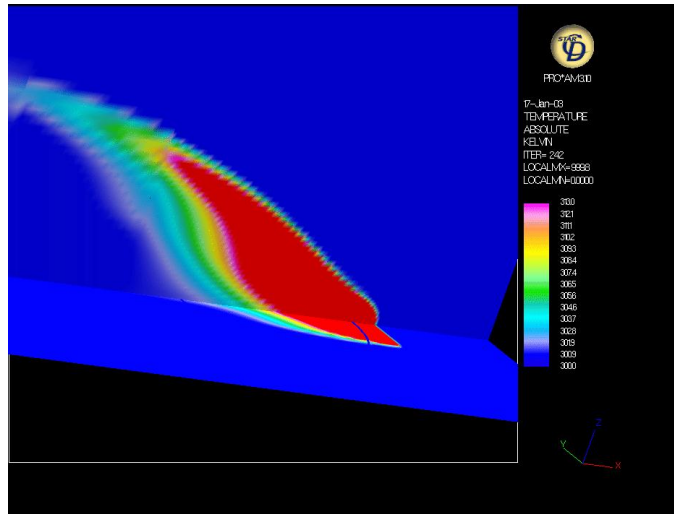


Fig. 1--Image of numerical simulation of jet in cross flow used to simulate a fire on slope under influence of wind.

Discussion

Injury can occur by one or several means in fire. It is primarily associated with the maximum incident flux and is not necessarily aligned with the primary modes of energy transport: radiation, convection, and conduction (DiNenno *et al.* 1995). The data presented in table 1 below identify the limits of exposure.

Table 1—Summary of heat injury modes and limits.

Heating Mode and Indicator	Injury type and time
Conduction	
43 (110F)	Pain
60 (140F)	Pain in 1 s, burn in 10s, severe burn in 100s
100 (210F)	Severe burn in 1 s
Convection	
180 (350F) dry	Burns in 3 minutes
120 (250F) dry	Burns in 7 minutes
32 (90F) 100% rh	Burns in 30 minutes
150 (300F) 100% rh	Max breathing temperature according to Nat. Res. Council of Canada
Radiation	
4.2 Kw/m ²	Pain in 10s
10 kW/m ²	Pain in 5 s, 1% fatality in 40s
25 kW/m ²	Severe pain 10s, 100% fatality in 60s
30 kW/m ²	Pain in 1-4s, full burn in 10-15s

Note that injury by conduction occurs at relatively low temperatures. Injury by convection occurs through two means: both heating of the external surface of the body and injury to the throat and mouth. Convective injury is sensitive to air temperature and relative humidity. Higher relative humidity results in more severe injury at lower temperatures. Injury from radiant heating is dependent on incident energy flux.

Measurements of energy release from fires are being used to develop new understanding into the distribution of radiant and convective energy in and around naturally spreading fires. Fig. 2 is a summary of heat flux measurements reported (Frankman *et al.* 2010). In general the heat flux measurements suggest that convective energy is 75% of radiant energy. There seems to be a correlation between slope and radiant energy flux. However, little or no correlation between slope and convective energy flux. The convective and radiant heating rates are more than sufficient to generate injury. The primary challenge is to predict the distribution of that energy around the fire front. This is the objective of the numerical simulations.

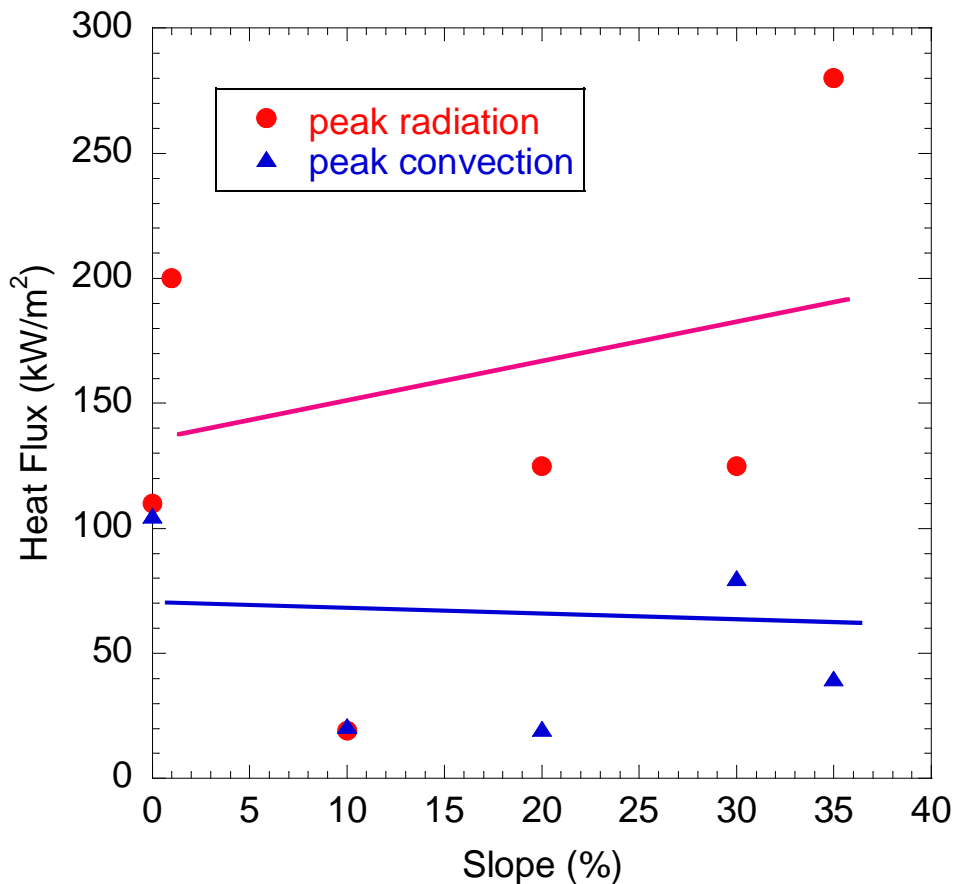


Fig. 2—Peak radiant and convective fluxes from field based measurements

Air temperatures associated with convective energy heating are difficult to determine. Measurements of air temperatures measured within a forest canopy as a crown fire burned over the sensors have been presented (Butler *et al.* 2004) (see Fig. 3). The temperatures are all significantly higher than the minimum survivable temperatures presented in table 1 suggesting that at least in the flaming region air temperatures exceed survivable limits.

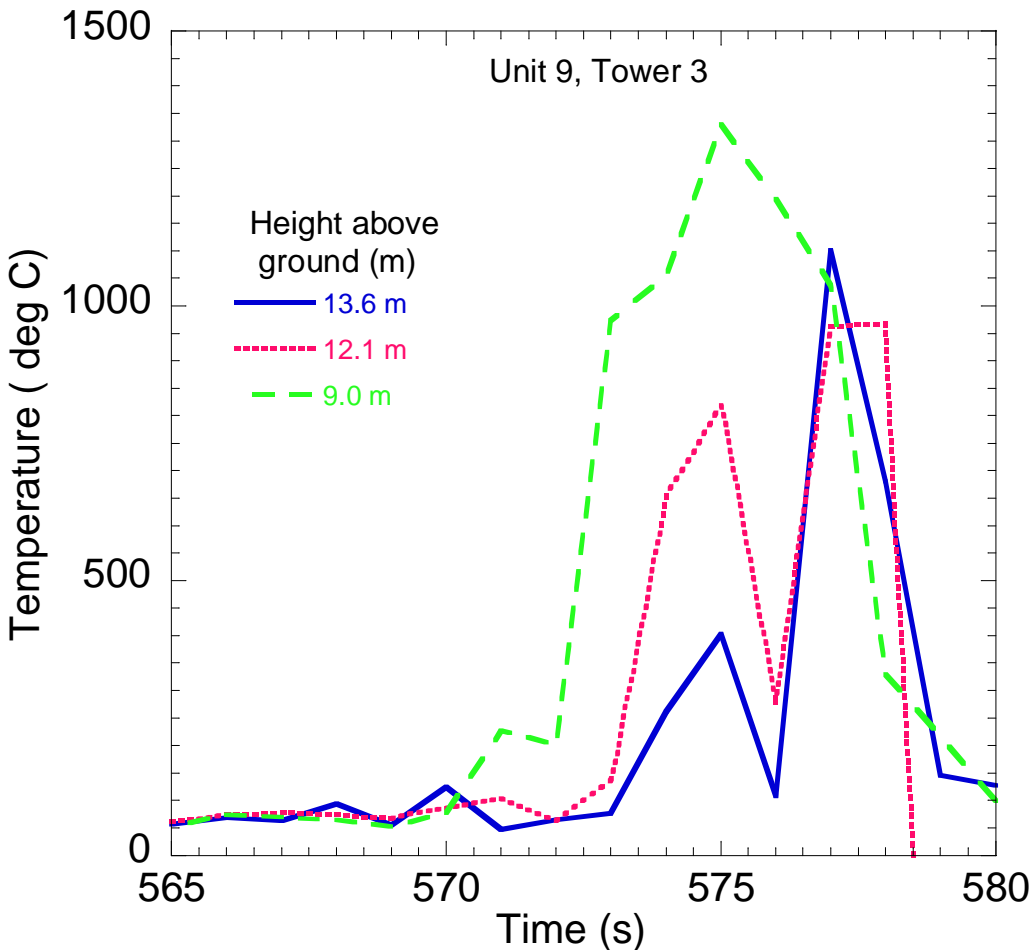


Fig. 2--Summary of measured air temperatures collected from International Crown Fire Experiments.

The challenge over the next year is to use numerical models to simulate the distribution of radiant and convective energy around the fire front. Once this distribution is known then injury limits can be related to distance from the fire front to recommend safety zone size

References

- Butler BW, Cohen J, Latham DJ, Schuette RD, Sopko P, Shannon KS, Jimenez D, Bradshaw LS (2004) Measurements of radiant emissive power and temperatures in crown fires. *Canadian Journal of Forest Research* **34**, 1577- 1587.
- Butler BW, Cohen JD (1998) Firefighter safety zones: how big is big enough? *Fire Management Notes* **Vol. 58**, 13-16.
- DiNenno PJ, Beyler CL, Custer RLP, Walton D, Watts JA, Drysdale DD, Hall JR (1995) 'The SFPE Handbook of fire Protection Engineering, 2nd Ed.' (National Fire Protection Association)
- Frankman D, Webb BW, Butler BW (2010) Time-resolved radiation and convection heat transfer in combusting discontinuous fuel beds. *Combustion Science & Technology* **182**, 1-22.