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Firerighter Safety Zones: A Theoretical Model Based on Radiative Heating

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Abstract. Quantitative information regarding safety zone size for wildland firefighters is limited. We present a 3-surface theoretical model that describes the net radiant energy transfer to a firefighter standing a specified distance from a fire of specified height. Model predictions compare favorably with qualitative data from entrapments on four wildfires and two previously published models. Calculations indicate that for most fires, safety zones must be greater than 20 in wide to ensure firefighter survival. A general rule-of-thumb derived from this work is that a safety zone radius must be equal to or greater than 4 times the maximum flame height.

Keywords: Net radiant energy transfer; entrapment; wildfires; safety zones.

Introduction

Firefighter safety is a primary concern in both initial and extended attack on wildfires. Unfortunately, situations arise wherein firefighters are threatened and even trapped by fire. Firefighters in the U. S. Forest Service are taught to take action to prevent entrapments. One of the required actions is that firefighters actively identify areas to which they can retreat to escape injury. These areas have been labeled safety zones.

Beighley (1995) defined safety zone as "an area distinguished by characteristics that provide freedom from danger, risk, or injury." The National Wildfire Coordinating Group (USDA/USDI 1995) has defined safety zone as: "An area (usually a recently burned area) used for escape in the event the line is outflanked or in case a spot fire causes fuels outside the control line to render the line unsafe ... areas that can be used with relative safety by firefighters and their equipment in the event of blowup in the vicinity." Although safety zones have been the topic of much discussion among firefighters, few quantitative studies have been reported (Alexander 1994, 1995).

Continued occurrence of firefighter entrapments suggests a need for increased understanding about safety zones. What may not be clear are the factors that determine the size of a safety zone necessary to prevent firefighter injury. We present a mathematical model-describing safety zone size as a function of flame height and distance from the flame. Predictions are compared against data from four wildfires.

Convective energy transport is not addressed in this study. Without a doubt, convection can play a major role in energy transfer between a fire and firefighters in its vicinity. For example, it is not uncommon for firefighters to observe intensely burning fire whirls. When close to the edge of a forest canopy, a wind-driven crown fire can generate turbulent eddies that will migrate some distance ahead of the fire front. In these cases, convection is a major energy transfer mechanism. Quantitative information on the magnitude and effect of convective heating in front of wildfires is needed.

Previous Work.

Some of the information required to specify safety zone size is the rate of energy transfer from the flame to its surroundings and the effect of that energy on humans.

Only a few reported studies directly address the distribution of energy in front of a wildland fire. Bond and Cheney (1986) described measurements made in 9 in diameter clearings overburned by a crown fire with 25 in flame heights. Air temperatures were measured with radiation shielded, naturally aspirated, platinum resistance thermometers located 2 and 5 in above the ground. They measured peak air temperatures of 300°C at the center of the clearing. Survival would have been unlikely without the protection of a fire shelter.

Others have discussed the design and performance of fire shelters under different heating regimes and the characteristics of a fire shelter deployment site (King and Walker 1964; Jukkala and Putnam 1986; Knight 1988). A fire shelter is a device used to protect firefighters from injury in a fire. Fire shelters currently approved for use by U. S. Forest Service firefighters consist of pup-tents constructed of lightweight highly reflective aluminum foil and fiberglass. All U. S. Forest Service firefighters are required to carry a fire shelter with them while working on or near the fire.

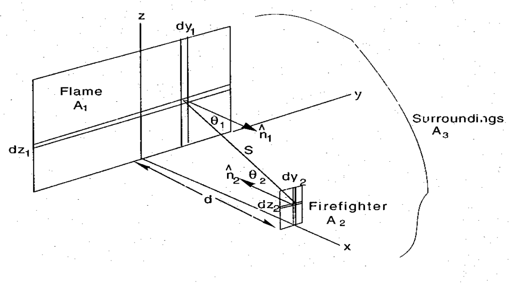
As one would suspect, it is difficult to find analytical studies reporting the effect of heat on human skin. Most of the work that has been done was performed on prisoners of war during World War 11 or on military volunteers in later studies. Green and Schinike (1971) state that 12 kW-m^{-2} will cause injury, no exposure time is given. Others suggest that the upper limit of incident radiant heat flux on bare skin that can be sustained without injury for a short time (less than 2 minutes) is approximately 2.3 kW-m^{-2} (Stoll and Greene 1959; Budd and Cheney 1984; Fogarty 1996).

Other studies have explored the performance of fabrics used in firefighter clothing (Braun and others 1980; Behnke 1982; Bond and Cheney 1986). These studies have led to several proposed testing methods that do not require human subjects. The data reported by Braun and others (1980) suggest that when firefighters wear Nomex cloth (210 g-m^{-2}), second degree bums will occur after 90 seconds at incident radiant heat fluxes of approximately 7 kW-m^{-2}. The Nomex shirts and trousers currently used by wildland firefighters in the U. S. have fabric weights of 190 and 280 g-m^{-2} respectively.

Analytical Model

We present a mathematical model based on a 3-surface radiative enclosure. This model is used to predict the net radiant energy transfer to a firefighter from a flame as a function of flame height and the distance between the firefighter and the flame. The flame was approximated as a flat sheet of given height and width with uniform temperature and emssivity (figure 1). The firefighter was approximated as another flat surface. Gray diffuse radiant exchange was assumed.

Figure 1. Schematic of geometry used in mathematical model.



Laboratory and field measurements suggest that a flame radiative temperature of 900°C and emissivity of 1 are appropriate for large wildland fires. Assuming that the firefighter's clothing was subject to some radiative heating, we assigned a surface temperature of 45°C to surface 2 with an emissivity of 0.8 (Incropera and Dewitt 1985). The surroundings act as an energy sink, absorbing energy emitted by the flame and reflected from the firefighter; however, they do not significantly affect the net energy transfer to the firefighter. The surroundings were assumed to be approximately 22°C with an emissivity of 1.

The net radiant flux q_i on surface i can be defined as:

$$q_i = A_i (J_i - G_i)$$

Where radiosity J_i from surface i with emissivity ε_i and temperature T_i is:

$$J_i = \varepsilon_i \sigma T_i^4 + (1-\varepsilon_i)\, G_i$$

The Stefan-Boltzman constant σ is approximated by 5.67 x l0^{-11}kW-M^{-2}-K^{-4}. Irradiation G_i incident on surface i with n being the total number of surfaces can be defined as:

(3)
$$G_i = \sum_{j=1}^{n} F_{i-j} J_j$$

The radiant view factor between the flame and firefighter (F_{1-2}) is the fraction of radiant energy leaving the flame (surface 1) that arrives at the firefighter (surface 2). Mathematically it is expressed as:

$$F_{1-2} = \frac{1}{A_1} \int\int_{A_1 A_2} \frac{\cos\ \mu_1 \cos \mu_2}{\pi S^2}\, dA_2 dA_1 \qquad (4)$$

Where A_1 and A_2 are the respective surface areas with differential areas dA_1 and dA_2 . m_1 *and* m_2 are the angles between the respective surface normal vectors $\tilde{n}_1$ *and* $\tilde{n}_2$ and line of length S connecting the differential areas.

We numerically integrated equation 4 to obtain the radiation view factors and then solved equations 1 through 4 to obtain $q_{2'}$. Solutions were computed assuming flat terrain.

Discussion

Webster (1986) presents work by Tassios and Packham (1964) that discusses theoretical values of incident radiant heat on a firefighter. They predict a maximum heat flux of 60 kW-m^{-2} incident on a firefighter standing 6 m from a 21 in tall flame. Fogarty (1996) combined work reported by Leicester (1985) and Thomas (1963) to develop a model that predicts incident radiant energy on firefighters as a function of fireline intensity and distance from the fire.

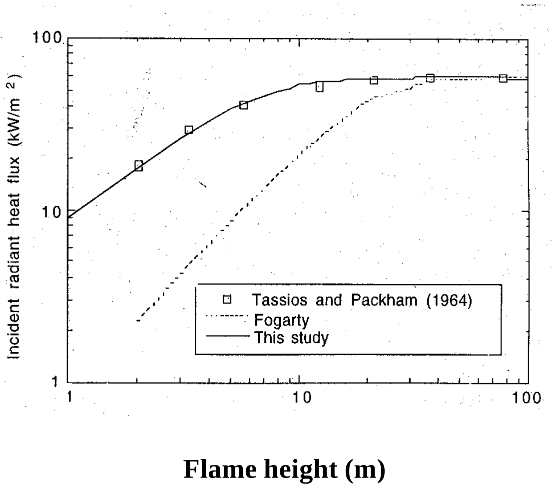


Figure 2. Comparison between previous models and that presented in this study. For this comparison we assumed a flame temperature of 1200 K and flame width of 20 m, the firefighter was approximated a ' s a flat surface I m wide by 2 m tall located 6 m from the flame.

Green and Schimke (1971) discuss safety zones principally in the context of fire break size; they present required separation distances as a function of burning index. Unfortunately they did not provide sufficient information to relate firebreak size to flame heights. Figure 2 presents predictions from the model presented in this study and those from the models presented by Tassios and Packham (1964) and Fogarty (1996). We assumed a flame temperature of 1200 K, flame and firefighter emissivities of unity, 20 m wide flame and 1 m wide by 2 m tall firefighter. Our model quantitatively matched that of Tassios and Packham (1964); however, it does not agree so well with Fogarty's (1996) model for flame heights less than 20 m. The agreement between the models shown in figure 2 lends credibility to the model presented herein--differences can be attributed to variations in flame temperature, surface dimensions, emissivities and model geometry. The fact that we could only find three studies relating fire behavior to firefighter safety zones indicates that lack of quantitative information on this subject.

Predictions for a range of separation distances and flame heights are shown as surface contours in Figure 3. Clearly, the incident radiant heat flux is strongly dependent on distance from the flame and flame height. We selected an incident heat flux level of 7 kW-m^{-2} as the maximum level tolerable by firefighters wearing Nomex clothing and protective head and neck equipment.

The trends shown in Figure 3 suggest that in most cases safety zones must be relatively large. We compared separation distances predicted by our model against those reported on four wildfires: the Mann Gulch Fire, the Battlement Creek Fire, the Butte Fire and the South Canyon Fire.

The Mann Gulch Fire overran 16 firefighters on August 5, 1949. Only the foreman and two crew members of the 18-man smokejumper crew survived.

The fire crew were hiking up a steep, as much as 76 percent, slope. The fire was approaching them from below and was burning through an open stand of scattered, mature (60 to 100+ year old) *Pinus ponderosa* (ponderosa pine) with a grass understory. Flames were 10 m high (Rothermel 1993). Recognizing that the fire was outrunning them and had approached to within 50 m of the crew. The foreman stopped and lit an escape fire with the intention that the crew could lie down in the burned out area to escape the main fire. Rothermel (1993) indicates that the escape fire burned about 90 m before the main fire overran it. Assuming an elliptical shape for the burned area, with its width approximately half the length, the safety zone created by the escape fire would have been about 45 m wide. Figure 3 indicates a minimum safety zone size of 40 to 50 m.

The Battlement Creek Fire occurred in western Colorado during July, 1976 (USD1/USDA 1976). The fire burned on steep slopes covered with 2 to 4 m high *Quercus gambeli* (Gambel oak). Flames were estimated to be 7 to 10 m above canopy. Four firefighters were cut off from their designated safety zone. When the fire overran them, they were lying face down on the ground without fire shelters in an 8 m wide clearing near the top of a ridge. Tragically, only one of the four survived, and he suffered severe burns over most of his body. Figure 3 suggests that for this fire, a minimum safety zone size is 40 m, with 55 m being preferable. Clearly, the 8 m wide clearing did not qualify as a safety zone.

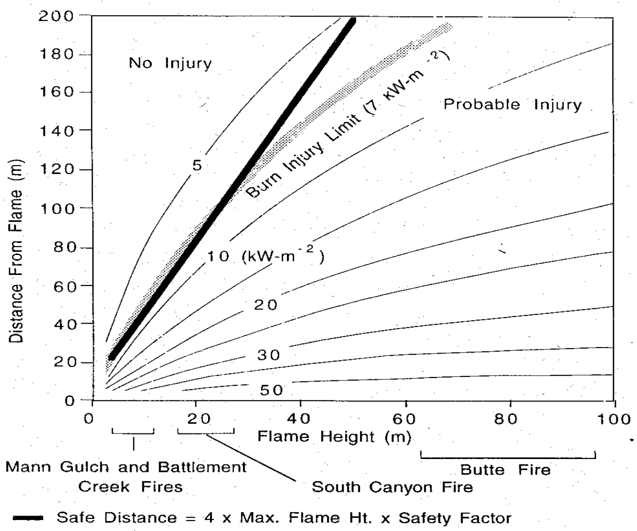


Figure 3. Lines represent predicted net radiant heat flux to a firefighter as a function of flame height and distance from the flame. It is assumed that the firefighter is wearing fire retardant clothing (Nomex) and protective head and neck equipment. Heavy shaded line represents burn injury threshold (7 kW-M$_{2}$).

Flame heights were reported to be 60 to 100 m high on the Butte Fire. It burned on steep slopes covered with mature *Pinus contorta* (lodgepole pine) and *Psuedotsuga menziesii* (Douglas-fir) during August 1985 (Mutch and Rothermel 1986). Figure 3 indicates a minimum required separation distance of approximately 240 m. In fact, safety zones 90 to 125 m in diameter were prepared (Mutch and Rothermel 1986). This was not sufficiently large to meet the definition of a safety zone, as indicated by the fact that 73 firefighters had to deploy in fire shelters to escape the radiant heat.

During the afternoon of July 6, the South Canyon Fire burning in western Colorado "blewup", burning across the predominately *Quercus gambeli* (Gambel oak) covered slopes with 15 to 30 m tall flames and spread rates of 1.3 to 2.5 m-s^{-1} (USDAIUSDI 1994). Fourteen firefighters were overrun by the fire and died while attempting to deploy their fire shelters along a 3 to 4 m wide fireline on a 55 percent slope. Eight other firefighters deployed their fire shelters in a burned out area approximately 45 m wide. They remained in their shelters while three separate fire runs occurred 160 m away from them (Petrilli 1096); none were injured. Survivors felt they were far enough from the flames that survival with minor injuries would have been possible without the protection of a fire shelter (Petrilli 1996). One firefighter who did not deploy in a shelter, but remained on a narrow ridge below the eight firefighters during the "blowup" experienced no injuries (USDAIUSDI 1994). Figure 3 suggests that in this situation the safety zone must be large enough to allow 60 to 120 m separation between the firefighters and flames.

A general rule-of-thumb can be derived from Figure 3 by approximating the injury limit with a straight line. After doing so, it appears that safety zone size predicted by this model should be at least 4 times the maximum flame height. In some instances--such as the Mann Gulch, Battlement Creek and Butte fires--the fire may bum completely around the safety zone. In such fires, the separation distance suggested in Figure 3 is the radius of the safety zone, meaning the safety zone diameter should be twice the value indicated. Factors that will reduce safety zone size include reduction in flame height by thinning or burnout operations, shielding the safety zone from direct exposure to the flame by locating it on the lee side of ridges or other geographical structures, or reducing flame temperatures by applying fire retardant to the area around the safety zone.

This model did not include a safety factor. A safety factor of 2 to 4, possibly higher, would be appropriate for this situation (Baumeister 1978). This means that the distance predicted by the rule-of-thumb should be multiplied by the safety factor to obtain the recommended safe separation distance.

We calculated the net radiant energy transferred to a fire shelter like that used by firefighters in the U. S. Forest Service. The fire shelter is based on the concept that the surface will reflect the majority of the incoming radiant energy. An average emissivity for the aluminum foil exterior of a fire shelter is 0.07 (Incropera and Dewitt 1985), indicating that approximately 93 percent of the energy incident on a fire shelter is reflected away (Putnam 1991). Model predictions shown in Figure 4 suggest that heat levels remain below the injury limits for deployment zones wider than 15 m. However, this model does not account for convective heating which could significantly increase total energy transfer to a fire shelter, especially when deployed within one or two flame lengths of the fire.

Conclusions

We have presented a theoretical model that predicts safety zone sizes consistent with the information gathered from firefighter entrapments on four wildfires. The agreement between the model presented in this study and those presented in previous studies and also with the information from actual wildfire entrapments lends credibility to this work. We emphasize that this study represeents a mathematical evaluation of the radiant heat transfer from wildland fires; it does not include any convective energy transfer, which can be significant. For example, firefighters caught in the Butte and South Canyon Fires recall intense turbulent gusts and loud noise associated with the fire front's passage. It is possible that hot turbulent eddies can be generated in and around large fires. Convective heat transfer from such eddies may increase the required safety zone size.

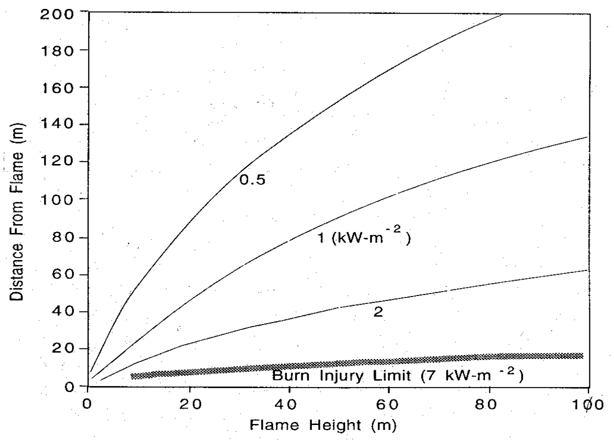


Figure 4. Predicted net radiant heat flux into a fire shelter as a function of flame height and distance between the fire shelter and flames. Heavy shaded line represents bum injury threshold (7 kW-m^{-2}).

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