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An Analytical Evaluation of Firefighter Safety Zones.

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Abstract. Safety zone is a term familiar to wildland firefighters. However, relatively little quantitative information is available regarding necessary safety zone size. This study presents some analytical results from calculations of radiant energy transfer from wildland fires as a function of flame size and distance from the flame. Analytical results are compared with observations from four wildfires.

Introduction

Identification of a safety zone is one of the primary responsibilities of any wildland firefighter working on or near the fire. The work presented herein is directed specifically at firefighter safety zones and the factors that determine safety zone effectiveness. Radiant heat transfer calculations are presented that relate energy incident on a firefighter as a function of flame height and distance from the firefront.

Previous Work

A significant amount of discussion, mostly in training sessions, has occurred regarding firefighter safety zones. However, very few quantitative studies have been reported. Beighley (1995) defined safety zone as "An area distinguished by characteristics that provide freedom from danger, risk, or injury." The National Wildfire Coordinating Committee (NWCG) has presented definitions for three types of escape zones (i.e., safety zone, deployment zone and survival zone). The following definition for safety zone has been proposed: "A preplanned area of sufficient size and suitable location that is expected to prevent injury to fire personnel from known hazards without using fire shelters." The definitions presented for deployment and survival zones are similar to that for a safety zone with the exception that they both require that the firefighter be inside a fire shelter to escape injury (anon, 1995).

At least two types of information are required when specifying safety zone size. One is the rate of energy transfer from the flame to its surroundings and another is the effect of that energy on humans.

Only a few studies have been reported that directly address the distribution of radiant energy in front of a wildland fire. Bond and Cheney (1986) reported measurements made in 10 meter diameter clearings overburned by a crown fire with 25 meter flame heights. They measured peak air temperatures at the center of the clearing of 300°C with air temperatures remaining over 94°C for approximately 2.5 minutes. Survival would have been unlikely without the protection of a fire shelter. Fogarty (1994) and Tassios and Packham (1973) have related heat fluxes incident on a firefighter as a function of fireline intensity and distance from the flame front. Green and Schimke (1971) discuss fire break size as it relates to general fire potential indices. Others have discussed the performance of fire shelters under different heating regimes (e.g. King and Walker, 1964; Jukkala and Putnam, 1986; Knight, 1988).

As one would suspect it is difficult to find analytical studies reporting the effect of heat on human skin. After reviewing the work that is reported, we concluded that an upper limit of incident heat flux on bare skin that can be sustained without injury for a short time (i.e. less than 2 minutes) is approximately 2 kW/m^2 (Stoll and Greene, 1959; Budd and Cheney, 1984).

Still other studies have explored the performance of fabrics used in firefighter clothing (Braun et al., 1980; Bond and Cheney, 1986; Behnke, 1982). These studies have led to several proposed testing methods that do not require human subjects. Unfortunately, there is some disparity between reported values. The lack of agreement can be attributed to the large number of variables affecting the energy transfer process (i.e. weight, weave, material etc. as well as the air space between the layers of cloth ing and the skin). We concluded that for the purposes of this study, data reported by Braun et al. (1980) most closely match the expected conditions. These data suggest that when human skin is clothed in Nomex® cloth (weight 210 g/m^2) second degree burns will occur after approximately 90 seconds at incident radiant heat fluxes of 7 kW/m^2.

After reviewing the available literature, Alexander (1995), concluded that insufficient information was available to quantitatively define the physical requirements of a safety zone. A need for further work in this area has been recognized (anon, 1995).

Analytical model

A mathematical model was developed to predict the radiant energy incident on a firefighter as a function of flame height and the distance between the firefighter and the flame. The flame was approximated as flat surface of given height and width with uniform temperature and emissivity. The firefighter was approximated as another flat surface 1.85 m tall and 0.5 m wide. Gray diffuse radiant exchange was assumed. The flame and surroundings were assigned an effective emissivity of unity. Figure 1 is a schematic of the geometry.

Siegel and Howell (1981) define the radiant view factor between the flame and firefighter ($F_{1\text{-}2}$) as the fraction of radiant energy leaving surface 1 (the flame) that arrives at surface 2 (the firefighter). Mathematically it is expressed as:

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

Where μ_1, μ_2, A_1, A_2 and S are defined as shown in Figure 1.

Equation 1 was solved by numerical integration and the radiant energy exchange between the flame and firefighter calculated by solving an energy balance on the firefighter as defined in Incropera and Dewitt (1985), where the net radiant flux on surface i is q_i (see equation 2) with emissivity ε_i and emissive power $E_{bi}=\sigma T_i^4$. Other variables were σ the Stephan-Boltzman constant and T_i the absolute temperature of surface i.

$$q_i = \sum_{j=1}^{n} A_i F_{ij} (J_i - J_j) \qquad (2)$$

Where radiosity J_i from surface i, is defined as

$$J_i = \varepsilon_i E_{bi} + (1 - \varepsilon_i) G_i \qquad (3)$$

and irradiation G_i incident on surface i is

$$G_i = \sum_{j=1}^{n} F_{ij} J_i \qquad (4)$$

Equations 1 through 4 were solved for a range of flame heights and distances between the flame and firefighter. Laboratory and field measurements suggest that a flame radiative temperature of 1000°C and emissivity of 1 are appropriate. The firefighter was assigned a surface temperature of 45°C and an emissivity of 0.8 (Incropera and Dewitt, 1985). The surroundings were assigned a temperature 20°C and emissivity of 1.

Discussion

Some results of the heat transfer calculation are shown as a contour plot in Figure 2. Calculations by Tassios and Packham (1973) and Fogarty (1994) produced similar results, but they are not directly related to flame height. It is clear that the incident heat flux is highly dependent on distance from the flame and flame height. Others have shown that bare human skin cannot safely tolerate sustained heat fluxes greater than 2 kW/m^2 and that clothing results in an increase by three and a half times this number. Thus, we have assigned an incident heat flux level of 7 kW/m^2 as the maximum level tolerable by firefighters wearing Nomex® clothing, and head and neck protective equipment.

Examination of Figure 2 quickly leads to the conclusion that for most cases safety zones must be relatively large to reduce the incident heat fluxes to tolerable levels.

A comparison was made between the predicted required separation distances and those reported on four wildland fires that occurred in the United States: 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 three survived. The incident occurred in an open stand of scattered mature (60 to 100+ year old) ponderosa pine with a grass understory. Flame heights of 3 to 12 meters were estimated to have occurred at the time of the entrapment. The data shown in Figure 2 suggest that a safety zone large enough to provide 40 meters between the firefighter and flames was needed. Rothermel (1993) indicates that Dodge's escape fire burned about 90 meters before the main fire overran it. Assuming an elliptical shape for the burned area wherein the width was approximately half the length, the safety zone created by Dodge's escape fire was probably 40 to 60 meters across. According to the data shown in Figure 2 this would have resulted in a marginally survivable safety zone.

The Battlement Creek Fire occurred in western Colorado during July, 1976 (anon, 1976). The fire burned on steep slopes covered with a growth of 2 to 4 meter high Gambel oak. A significant frost kill had occurred the previous month resulting in a large amount of dead material in the brush canopy. Flames were estimated at 7 to 10 meters above canopy. Four firefighters were cutoff from

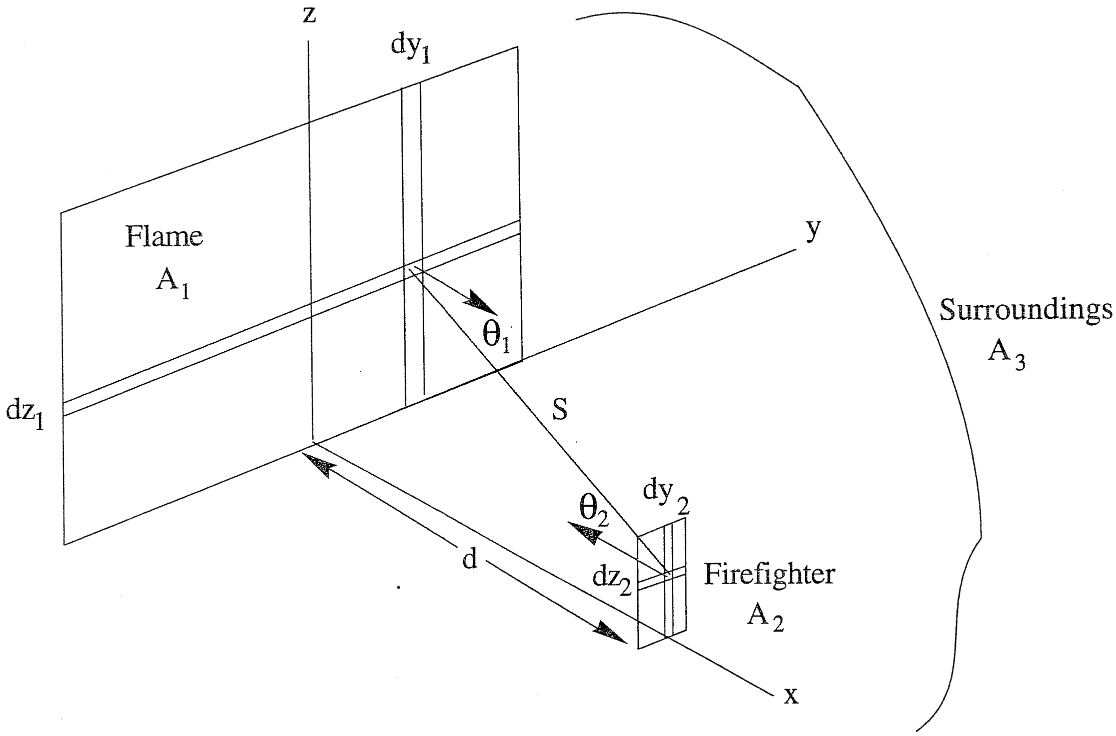

Figure 1 Schematic of mathematical model.

access to their designated safety zone and laid face down without fire shelters on the ground in a slight depression near the top of a ridge. The area was approximately 8 meters across. Tragically only one of the four survived, and he suffered severe burns over most of his body. Figure 2 suggests that for this fire a minimum safety zone size is 25 meters, with 50 meters being preferable.

Flame heights were reported to be 60 to 100 meters high on the Butte Fire. It was burning on steep slopes covered with lodgepole pine and douglas fir during August of 1985 (Mutch and Rothermel, 1986). Examination of Figure 2 indicates that a cleared area greater than 400 meters across would be needed to reduce the incident heat flux on the exposed firefighters standing in its center to less than 7 kW/m^2. In fact, safety zones 90 to 125 meters 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.

The South Canyon Fire was located in western Colorado, it displayed rapid fire spread in Gambel oak on the afternoon of July 6, 1994 (USDA/USDI, 1994). Eyewitness accounts and estimates based on fire behavior models place flame heights in the range of 15 to 30 meters, possibly higher. While fourteen firefighters were overrun by the fire and died, eight smokejumpers deployed in fire shelters in a burned out area approximately 45 meters in diameter. They remained in their shelters while three separate fire runs occurred approximately 160 meters away from them. None were injured. Air temperatures inside the shelters were estimated to have reached 43°C and the occupants remembered smoke and glowing embers entering the fire shelters during the most intense burning periods. Survivors felt that the separation distance was sufficient that survival with minor injuries would have been possible without the protection of a fire shelter (Petrilli, 1996). In fact, one firefighter who did not deploy in a shelter, but remained on a narrow ridge below the eight smokejumpers during the "blowup" experienced no injuries (USDI/USDA, 1994). Figure 2 suggests that in this situation the safety zone must be large enough to allow 120 to 150 meters separationbetween the firefighters and flames.

In cases where the fire could burn completely around the safety zone it would be necessary to make the diameter of the safety zone twice the value indicated in Figure 2. Such a situation occurred on the Butte Fire where firefighters had to crawl to opposite sides of their "safety zone" while inside their shelters. This was due to the changes in the heat incident on them as the fire burned from one side of the safety zone to the other.

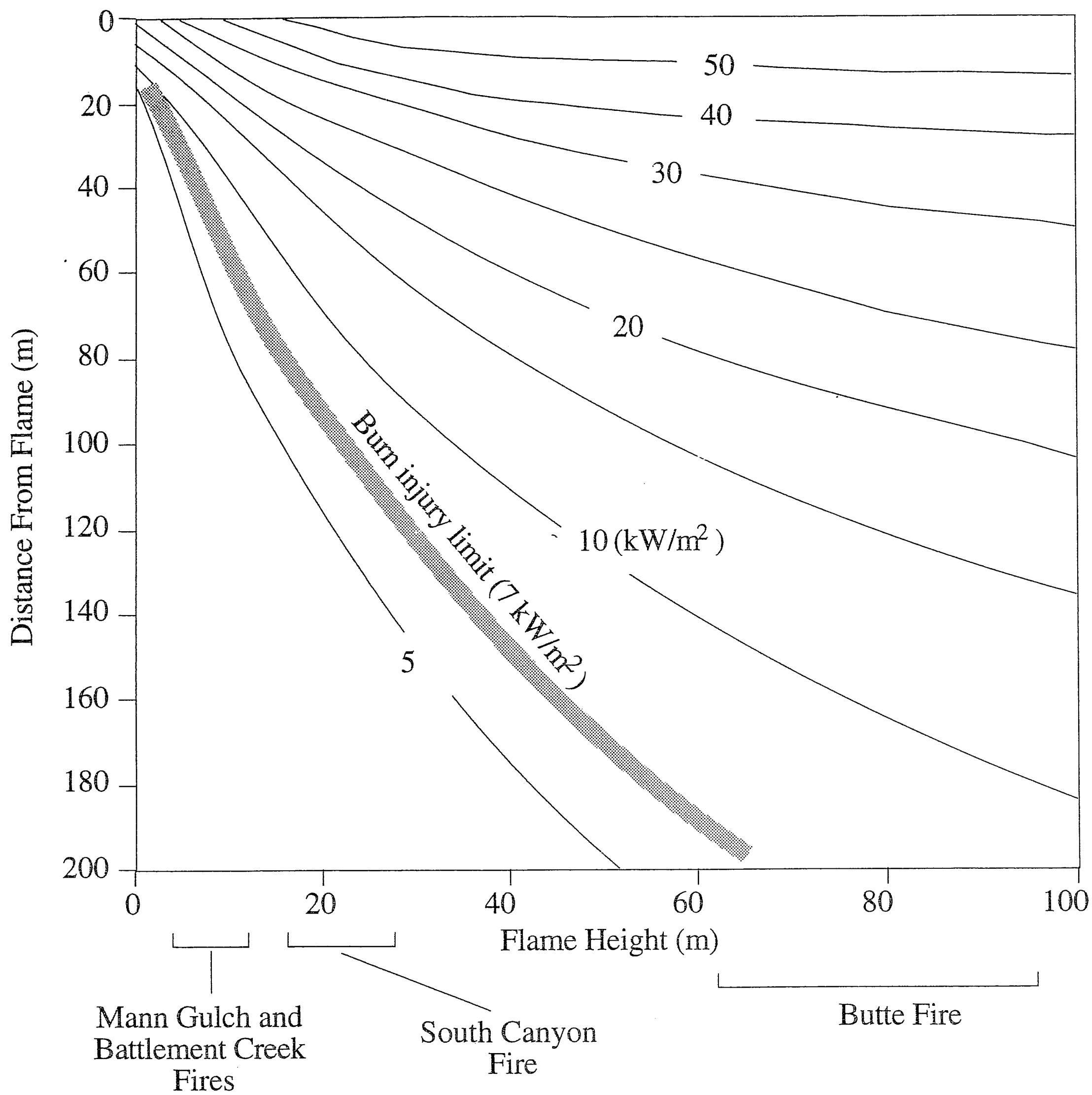

Figure 2. Predicted net heat flux to firefighter as a function of flame height and distance from flame. It is assumed that the firefighter is wearing fire retardant clothing and appropriate head and neck protective equipment.

Conclusions

The model predicts safety zone sizes consistent with the data from these four fires, thus lending credibility to the predictions. However, it is emphasized that this study represents a mathematical evaluation of the radiant heat transfer from wildland fires, it does not include any convective energy transfer. Convective effects can be very significant, for example, firefighters caught in the Butte and South Canyon Fires recall intense turbulent gusts and loud noise associated with the passage of the fire front. 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.

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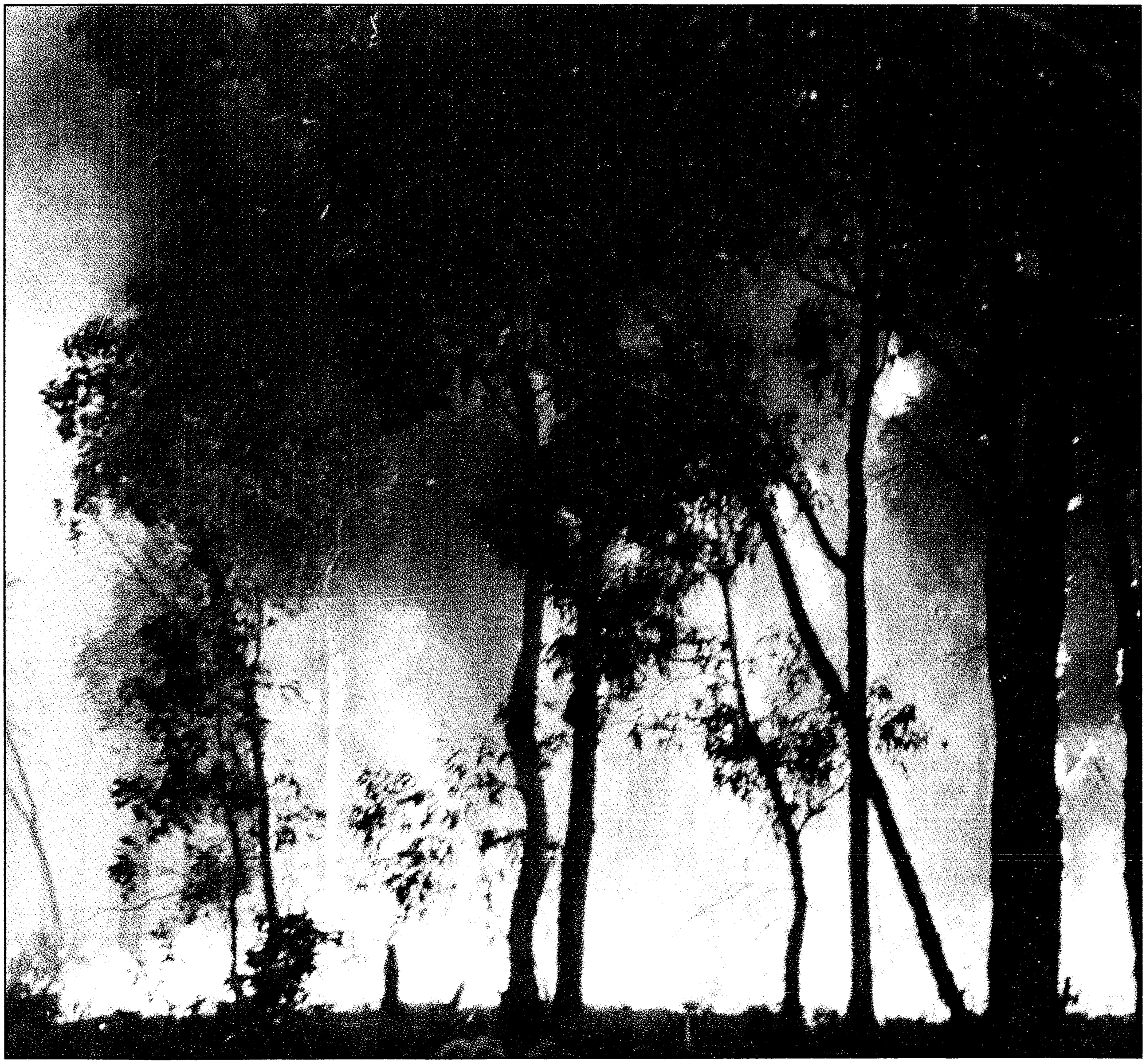

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