Wildland Firefighter Safety Zones

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In 1998 a simple rule-of-thumb was proposed as a definition of minimum separation distance between firefighters and flames to prevent burn injury. The rule stated that the safety zone must be large enough to allow the firefighter to be at least 4 flame heights in distance from the fire front. Since then safety zone research efforts have focused on obtaining measurements of energy emitted by “real” fires. These measurements are needed to evaluate the accuracy of the theoretical safety zone model. Unfortunately, such measurements are difficult to make in wildland fires. To date, measurements have been collected in fires burning through high elevation sage brush in Montana; manzanita, juniper and pinyon pine in northern Arizona; tall grass prairies in Kansas; crown fires in the boreal forest of Northern Canada; and lodge pole pine forests in eastern Oregon.

The Flame Model

Technically speaking wildland fires are composed of turbulent diffusion flames, meaning that the temperature of the flame and the energy released by the flame is a function of the rate that oxygen in the air can mix with the combustible gases released by heating of the woody fuels. This also explains why wind is the dominant environmental factor affecting fire behavior. Any firefighter who has worked on a fire has observed the strong influence that wind can play on fire intensity and size. The effect occurs in two ways: 1) increased wind causes increased mixing of the air and combustible fuels—leading to faster burning and higher temperatures; and 2) wind causes the flames to tilt forward closer to the vegetation ahead of the fire front—leading to increased energy transfer to those fuels and thus faster heating and ignition. If the temperature of the flame increases then the radiant energy emitted by the flame also increases. In fact, the radiant energy is proportional to the flame temperature raised to the power of four! For example: a change in flame temperature from 1000°F (the typical temperature of the flame tip) to 1500°F will increase the radiant energy emitted by the flame nearly **four times**!

The original safety zone research study assumed that the flame was essentially a flat plate of steel 66 feet wide with a constant temperature of 1832°F (see figure 1). This geometry was selected primarily because the mathematics for even this simple shape were relatively complex and presented a computer programming challenge. However, in reality, temperatures vary greatly in flames with the highest temperatures (as high as 2500°F) usually occurring in the lower third of the flame and the tip of the flame being roughly 1000°F. We now use a commercial software package designed specifically to model radiant energy exchange. This new tool permits us to model the flames with varying temperatures throughout (see figure 2).

Wind affects firefighter safety zones in two ways, it can increase the maximum flame temperature leading to longer and taller flames and it tilts the flames forward increasing the amount of radiant heating ahead of the flames. For example, if we calculate the minimum safe distance from a vertical flame front to a firefighter at its center as shown in figure 2, the minimum safe separation distance is between 3 and 3.5 times the flame height. If that flame is now tilted towards the firefighter as would occur if the wind were driving the flame (as shown in figure 3) then the minimum safe separation distance increases to between 3.5 and 4-times-the-flame-height. The tilted semicircular configuration is chosen for the firefighter safety zone calculations because it represents the "worst case" scenario in terms of heat impact on the firefighter.

Burn Injury Limits

The effect to the skin is the same regardless of whether the heating occurs by radiation from the fire, conduction from contact with a hot source, or convection from hot air or flames. The heating levels that cause burn injury are not easily defined; burn injury severity depends on exposure time and heating magnitude. In other words, exposure to a low level heating source like the sun for a long time would result in the same effect as exposure to a higher energy source like a fire for a short time. The type, thickness, number of layers, fit of clothing and even the rate at which the person wearing the clothing perspires also are important. The Society of Fire Protection Engineering Handbook indicates that exposure of bare skin to any type of heating greater than 0.23 Btu/ft^2-s (2.5kW/m^2) for a long period will result in burn injury. As a point of comparison the maximum energy that a person could receive by exposure to the sun is less than 0.09 Btu/ft^2-s (1kW/m^2). Exposure of unprotected skin to heating levels greater than 4.5 Btu/ft^2-s (50kW/m^2) will result in severe burn in less than 15 seconds and if the area of exposure is large enough fatality in 40 seconds. In the original safety zone study 0.6 Btu/ft^2-s (7kW/m^2) for 90 seconds was selected as the level at which a firefighter wearing Nomex clothing would receive second degree burn injury. The 0.6 Btu/ft^2-s limit is based on an experiment where Nomex cloth was located ½ inch away from the burn sensor. If the cloth is touching the skin then the time to burn injury drops to about 35 seconds. The bottom line is that severe burn injury to skin covered with one layer of Nomex from radiant heating occurs when energy flux levels exceed 0.45 to 0.72 Btu/ft^2-s (5 to 8 kW/m^2) for a minute or two. At this time there is no clear reason to change the burn injury limit (0.6 Btu/ft^2-s after exposure of 80 to 90 seconds) that is being used to define the firefighter safety zone size. As a point of comparison, while working on the Monument Fire in eastern Oregon this summer we stood about 40 feet away from flames that were 15ft wide and 50ft tall. We were receiving enough heat that it was very uncomfortable and even painful forcing us and the firefighters around us to shield our faces. Calculations assuming a rectangular flame with temperatures similar to those used for the safety zone model suggest that we were receiving about 0.3 Btu/ft^2-s (3 kW/m^2); a rate about one half that selected as the burn injury limit for safety zones.

Given the increased heating for tilted flames and the uncertainty associated with estimating burn injury limits, flame heights, and fire intensity we recommend that the 4-times-the-flame-height rule be retained as the minimum separation distance model. We emphasize that it is a minimum and that at this separation distance under conditions where the flames are uniformly radiating from 2 or more sides of the safety zone that the firefighters will probably be subjected to heating levels that require shielding all exposed skin, they will have to breath thick smoke and will likely experience ember showers.

The math

For purposes of calculating firefighter safety zone size we propose the following geometrical configuration (figure 4) where the safety zone is a circle and the radius of the circle or total separation distance is a combination of 4-times-the-flame-height and the additional area needed for people and equipment—in other words the person closest to the fire must be 4-times-the-flame-height away. The **S**afety **Z**one **S**ize (SZS) can be calculated using equation 1.

$$SZS = 4F_H + \left[\frac{A_{FF} N_{FF} + A_E N_E}{3} \right]^{\frac{1}{2}} \tag{1}$$

SZS is total separation distance for a circular safety zone the radius of the circle. F_H is flame height or alternatively flame length, A_{FF} is area needed for each firefighter (we suggest 50 ft^2 --the space needed to deploy a fire shelter), N_{FF} is the number of personnel that will be using the safety zone, A_E is the area needed by each item of heavy equipment (e.g. a crewcab pickup would require about 200 ft^2, a D6 Caterpillar with blade and ripper attachments requires about 280 ft^2, a D8 with attachments requires about 360 ft^2). N_E is the number of pieces of heavy equipment that are expected to use the safety zone. The dividing factor of three is an approximation to the numerical constant *pi* (actual value 3.14159).

This equation is difficult to apply while working on a fire, Table 1 presents the solution to equation 1 for a range of numbers of firefighter crews and number of vehicles. The number obtained from the table should be added to 4-times-the-flame-height to get total minimum separation distance or safety zone radius. Finally a third option is to use the following approximation to equation 1:

> **The additional distance needed above the four times flame height for people and equipment (in feet) = 20 + 4 x (the number of 20 person crews) + (the number of pieces of equipment)**.

This will give an approximation to the solution of equation 1.

A fourth method is to use the 4-times-the-flame-height rule and simply estimate the area needed for people and equipment.

Table 1—Additional separation distance radius needed for crews and equipment*

		Number of pieces of equipment**			
		0	**1**	**5**	**10**
# of 20 person crews***	**1**	18	20	27	34
	5	41	42	46	50
	10	57	58	61	65

*total separation distance is 4 x flame height (in feet) + added factor from table (in feet)

**250 ft^2 per item
***50ft^2 per firefighter

The 4-times-flame-height rule represents a very rough approximation based only on radiant heating and should be taken as a minimum. It does not account for convective heating such as may occur under strong winds, in steep narrow canyons, or on slopes.

What about short flames?

There is some evidence that the 4-times-flame-height rule does not hold true for short flames (less than 5 feet in height). The primary reason for this relates to the depth or thickness of the flames. Shorter flames are less efficient radiators than taller flames and thus they give off less energy. However limited measurements in actual wildland fires indicate that as height or length of the flames increases the flames radiate more energy per unit area. Another factor is that the model is based on a uniform and continuous flame front oriented in a semicircle around the front of the firefighter (see fig. 5), very seldom is this actually the case for short flames, they usually are less uniform and continuous and do not encircle the firefighter. For these basic reasons we have not modified the 4-times-flame-height rule for short flames.

What about using water bodies as a safety zone?

There are historical accounts of firefighters and others successfully using water as a safety zone. Two different cases can be distinguished. The first case is when firefighters are *on* the water, for example in a boat. For this case, the standard 4-times-the-flame-height minimum separation distance rule applies. Common sense dictates that all personnel on the water should have a personal floatation device. The second case is when firefighters are *in* the water (i.e. swimming, floating, wading, etc). For this case the separation distance model we have developed does not apply. The reason is because the water (assuming typical stream and lake temperatures) cools the skin more effectively than air does. This suggests that the firefighter could be closer than 4 times the flame height and not be burned from radiant heat. However, there are other factors that should be considered in this case such as the risk of drowning and hypothermia. Also being closer to the flames could expose the firefighter to convective heating which could lead to burning of the airways. In general water should not be considered as a safety zone except as a last resort, when escape routes have been cut off and a deployment situation is imminent. Such action should include use of the fire shelter as a heat shield while in the water.

Conclusion

In conclusion, further modeling and field measurements support the 4-times-flame-height rule of thumb for minimum safety zone size. It is important to realize that this should be considered a minimum—meaning that in all cases larger is better. It is also important to remember that the rule of thumb is based on radiant heating and firefighters should always be cognizant of situations that may lead to convective heating. Future work will focus on characterizing the parameters that influence convective heating. Upto-date summaries of firefighter safety zone information can be found at www.firelab.org/fbp/reshome.htm

Example calculation of safety zone size:

Situation:

You are a member of a crew of 20 firefighters that has just arrived at a fire burning south of Ely, Nevada. You arrived the previous night. The morning briefing is scheduled for 20 minutes from now and your crew boss asks you to provide him with some estimates of minimum safety zone sizes that will be needed for the morning and afternoon. He expects that you will be assigned to build and maintain fireline on the southeast flank of the fire. You may have one D4 dozer assigned to work with you.

Solution:

Information needed is:

1) F_h--flame height or length for both the morning and afternoon.
2) N_{ff}--number of persons that will be using the safety zone.
3) N_E--number of vehicles and/or heavy equipment that may need to use the safety zone.

Procedure:

You are unfamiliar with the area and fire behavior, so you go to the fire behavior analyst (FBAN) and ask for estimates of flame lengths given expected weather and fuels in the area you will be working. He says that flames have been 15 to 20 ft in the mornings and 20 to 25 ft in the afternoon. But today a dry cold front is expected to pass through about 1430, it will result in higher westerly winds then previous days. The FBAN is predicting flame lengths of 28 to 35 ft during the cold front passage. The FBAN predictions correspond with observations from the previous day's burning (during initial attack, an FBAN may not be available, but in most cases, other firefighters that have observed fire in similar fuels and under similar conditions can provide estimates of flame height). With this information you now can calculate the minimum safety zone size assuming a circular safety zone.

F_h = 20 in the morning and 35 in the afternoon
N_{ff} = 20 plus 2 (crew plus dozer operator and dozer boss)
N_E = 4 (2 crew rigs, a dozer boss rig and a D4 dozer)

<u>Using Equation 1:</u>

Safety zone radius $= 4 \times \text{flame height} + [(N_{ff} \times 50 + N_E \times 200)/3]^{1/2}$

Safety zone radius $= 4 \times 20 + [(22 \times 50 + 4 \times 200)/3]^{1/2}$
$= 80 + [(1100 + 800)/3]^{1/2}$
$= 80 + [633]^{1/2}$
$= 80 + 25$

= 105 ft for the morning period and (140+25 due to the expected taller flames) or 165 ft in the afternoon.

<u>Using Table 1:</u>

Safety zone radius = 4 x flame height + (# from table for 1 crew and 4 pieces of equipment)

Safety zone radius = 4 x 20 + 24
= 80 + 24
= 104
= 104 ft for the morning period and (140+24 due to the expected taller flames) or 164 ft in the afternoon.

<u>Using the simplified equation:</u>

Safety zone radius = 4 x flame height + 20 + 4 x (# crews) + (# of pieces of equipment)

Safety zone radius = 4 x 20 +20 + 4 x 1 + 4
= 80 + 20 + 4 + 4

= 108 ft for the morning and 168 ft (140 + 28) during the afternoon.

You can now tell your crew boss that the safety zones need to be big enough to allow the firefighters to be more than 100 ft from the flames in the morning and more than 160 ft from the flames in the afternoon. For a circular safety zone these distances would be the circle’s radius.

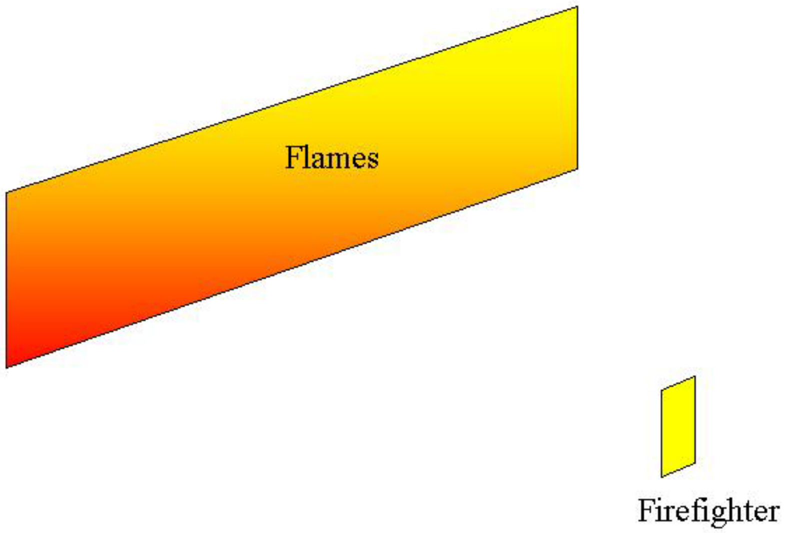

Figure 1—Flat plate fire front.

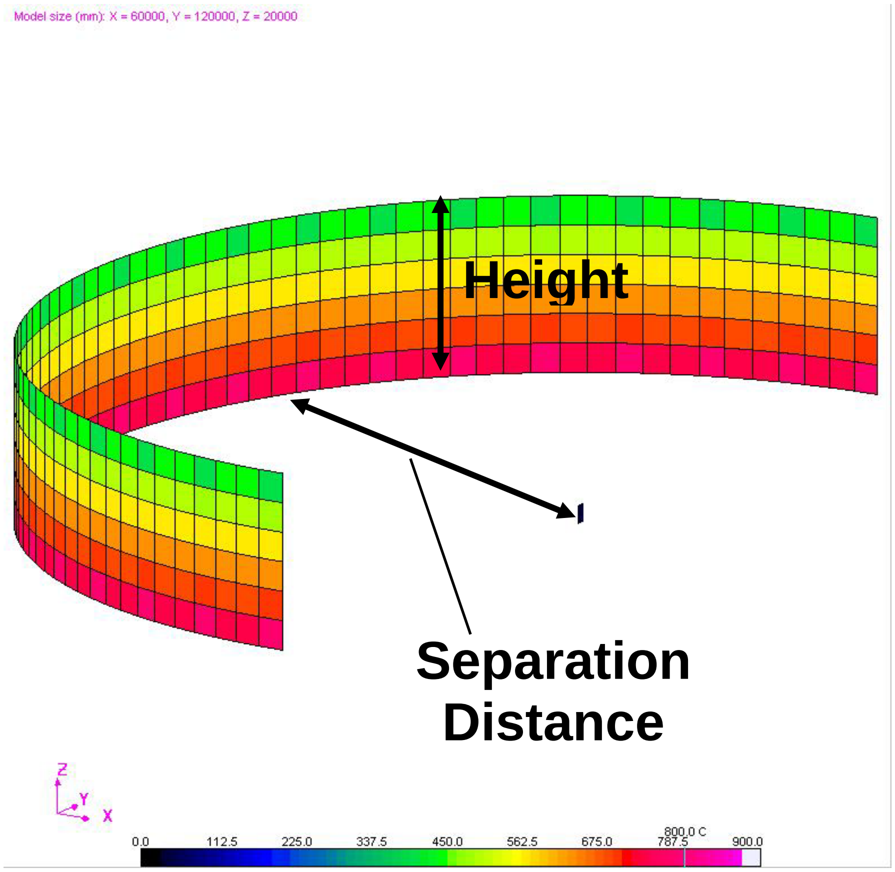

Figure 2—Semicircular flame model with vertically varying temperature.

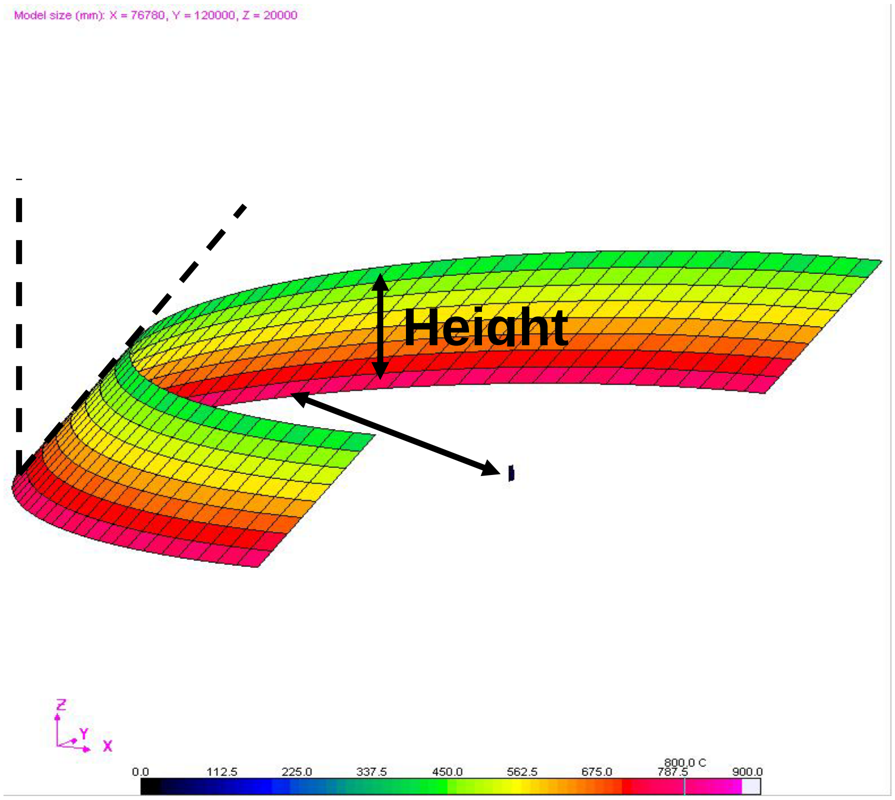

Figure 3—Semicircular tilted flame front with vertically decreasing temperature.

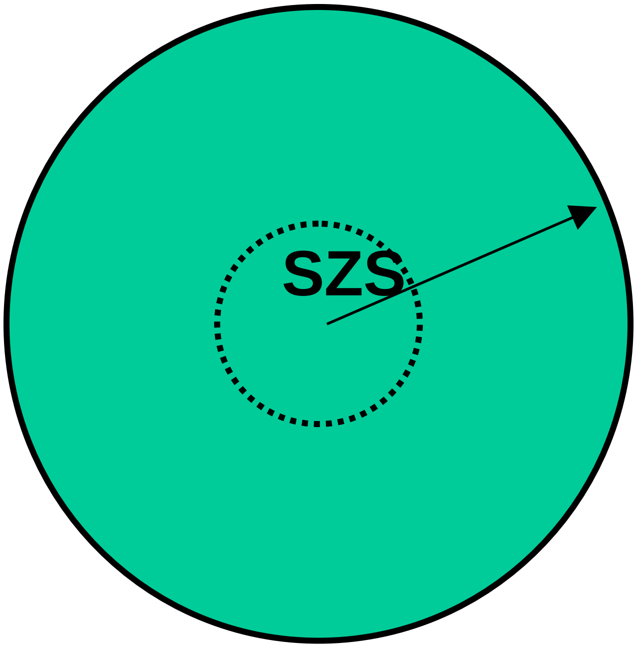

Figure 4—Safety zone configuration. SDR is the radius of the safety zone and is determined by the flame height or length and the number of firefighters and equipment that will be using the area.

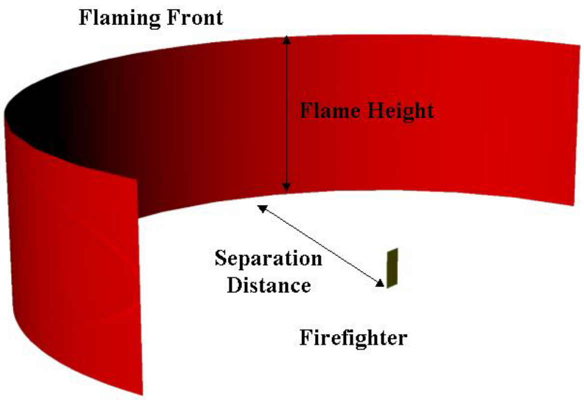

Figure 5—Semicircular fire front.