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Modeling Potential Structure Ignitions from Flame Radiation Exposure with Implications for Wildland/Urban Interface Fire Management

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Abstract. Residential losses associated with wildland fires have become a serious international fire protection problem. The radiant heat flux from burning vegetation adjacent to a structure is a principal ignition factor. A thermal radiation and ignition model estimated structure ignition potential using designated flame characteristics (inferred from various types and densities of vegetation) and flame-to-structure distances. Model results indicate that ignitions from flame radiation are unlikely to occur from burning vegetation beyond 40 meters of a structure. Thinning vegetation within 40 meters has a significant ignition mitigation effect.

Keywords. wildland/urban interface; flame radiation: piloted ignition: vegetation management.

The Wildland/Urban Interface Fire Problem

Significant residential fire losses associated with wild-land fires have occurred worldwide in recent years. The wildland/urban interface (WUI) or intermix refers to residential areas in locations subject to wildland fire, The WUI fire problem principally addresses the loss of life and property in these areas. In recent decades, severe WUI fire losses have occurred in Parana, Brazil [1963]. Tasmania, Australia [1967], Victoria and South Australia [1983], northern China [1988], and Oakland, California [1991] (Martin and Sapsis, 1995).

Wildland/urban interface structural fire situations in the United States and other countries differ from typical residential fires. The more severe situations include the following components:

- wildland fire spread leading to large numbers of simultaneously exposed structures:
- rapid fire involvement of residential areas:
- overwhelmed fire protection capabilities resulting in large numbers of unprotected residences:
- typically the total loss of an ignited residence,

Wildland vegetation fuels initially contribute to rapid fire growth. This produces large areas of burning that can simultaneously expose numerous structures to flames and, most importantly, can rain firebrands (burning embers) on homes and adjacent vegetation over a wide area. Although advances in firefighting technology and management have produced the most effective firefighting capabilities in history, these advances have not prevented the large losses during recent WUI fires. Severe WUI fires can destroy whose neighborhoods in a few hours—much faster than the response time and capabilities of the best equipped and staffed firefighting services. Many examples of this WUI fire situation have occurred in the United States and other countries. An example from the United States occurred in 1993 during the Laguna Hills fire in southern California. Nearly all of the 366 homes lost ignited and burned in less than 5 hours. Because residential involvement occurs more rapidly than the ability to effectively protect structures, many homes do not receive fire protection/suppression during severe WUI fire situations. As a result, typical post-fire loss statistics reveal that homes either survive or are totally destroyed with relatively few structures suffering partial damage (Foote and Gilless 1996).

The WUI fire problem can be characterized as the external fire exposure (flames and firebrands) of a residence resulting in ignitions that produce widespread, extreme losses. If residential fire losses did not occur during wild-land fires, the WUI fire problem would not exist. Thus, the principal WUI fire issue becomes residential structure survival.

Structure Survival

What we observe after a V/UI fire is, in varying degrees, structure survival. The degree of survival results from a complex, interactive sequence of events involving the ignition and burning of vegetation and structures accompanied by varying fire protection efforts by homeowners and firefighters. The development of effective mitigation actions requires an explicit description of the processes involved.

Structure survival involves factors that influence ignition; and, if ignitions occur, structure survival involves factors that influence fire suppression. Thus, improving potential structure survival requires a comprehensive consideration of suppression effectiveness and structure ignitability (Cohen 1995). Figure 1 diagrams the general process leading to structure survival or loss.

As the figure illustrates, the structure survival process must "pass through" the occurrence or nonoccurrence of an ignition. The factors influencing suppression effectiveness (availability, capability, access, and the safety of organized firefighters and homeowners) greatly depend on the real-time situation. As previously stated, wildland/urban interface loss statistics generally reveal homes either surviving or having total loss. Damaged homes arc the exception. This dichtomous nature of structure loss statistics strongly suggests that expected fire suppression effectiveness is very low. Thus, improving structure survival depends on improving ignition resistance, at least initially. Improved structure ignition resistance leads to improved suppression effectiveness by homeowners and fire agencies.

WUL Ignition Processes

Three principal factors are responsible for structure ignitions:

- flame radiation,
- flame impingement—convection, and
- firebrands (burning embers).

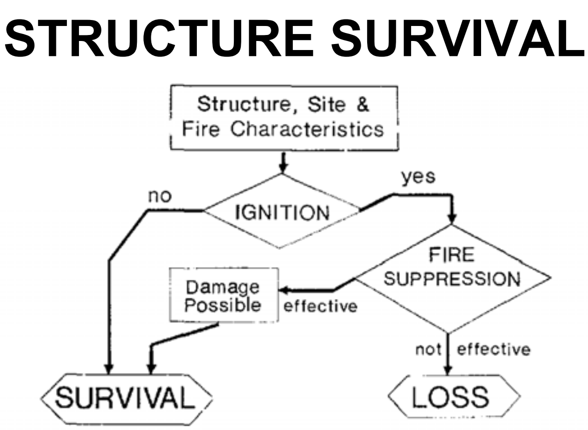

Figure 1. Structure survival depends on factors influencing ignition and factors influencing effective fire suppression. Regardless of the fire suppression effectiveness, survival initially depends on ignition resistance.

Radiation and convection involve heat transfer directly from the flame. Unlike radiation heat transfer, convection requires that the flame contact the structure. Fire-brands involve the aerial transport of burning materials to a structure from vegetation or other burning sources. Significant radiation heat transfer can cause ignitions without convection, i.e., no flame contact. Firebrands can fall on a structure and its adjacent vegetation causing ignitions from a distance such that the radiation and convection from the fire are insignificant. A structure's ignition potential increases as the radiative, convective, and fire-brand exposures increase. Thus, decreasing potential structure ignitions involves decreasing the exposure to each of the ignition factors.

Generally, fire agencies consider vegetation management as a principal approach to wildland fire hazard reduction. Specifically, the recently approved California Fire Plan includes vegetation management as a key component of prefire management for residential developments in WUI areas (California State Board of Forestry 1996). The California Fire Plan specifically identifies fuel hazard reduction near structures for the purpose of defensible space. Defensible space being defined as that area between structures and burning vegetation adequate for the safe operation of firefighters (California State Board of Forestry 1996). The newly issued 1997 Urban-Wildland Interface Code (International Fire Code Institute 1997) specifies that a vegetation management plan for the purpose of reducing fire hazard should be created for sites greater than .8 hectares (2 acres). This code includes a general association between vegetation clearance distances and fuel hazard. The California Public Resources Code specifics a 9 meter (30 feet) vegetation clearance around structures (Clark 1995). However, to our knowledge, none of these WUI fire mitigation guidelines provides specific clearance distances related to specific fire characteristics based on an analysis of the heat transfer.

We chose to analyze flame radiation of the three principal ignition factors, radiation, convection, and fire-brands. All three factors are important, but for the specific purpose of a perspective on the distances required for vegetation management, we believe an analysis of radiation should provide an appropriate indication. We reasoned that existing vegetation clearance recommendations significantly reduce or eliminate expected flame contact from most residential situations and thus, ignitions from convection. Firebrands can shower down on a structure from a fire at a distance well beyond what is practical for WUI vegetation management and where no significant radiative or convective heat transfer occurs related to direct flame ignitions—thus, our analysis of radiation.

Ignitions from Radiation

Structure ignitions (given an exposed flammable surface) from radiation heat transfer depend on two aspects of the flame: 1) the radiant heat flux incident to a surface and, 2) the duration of the radiant flux. The incident radiant heat flux refers to the rate of radiant energy per unit area that is striking the surface from the flame zone. The duration, or length of time of the radiant flux, relates to the flame source burning time, i.e., the amount of exposure time.

The radiant heat flux depends on the flame zone size, flame-structure distance, and how much the structure "sees" the flame. The larger the flame height and flame front width (the radiating flame plane) for a given distance, the greater will be the radiation transfer to the structure. Thus, a reduced flame height, and/or a smaller flame front width will reduce the thermal radiation. For a given flame length, a discontinuous flame front will also reduce the incident heat flux. For example, given the same flame lengths, individually burning tree canopies (torching trees) in a thinned stand of trees will reduce the incident heat flux as compared to a continuous line of flaming tree canopies (crown fire).

The distance between the flame and the structure also influences the radiation heat flux. For a given flame front size, the radiant flux decreases with increasing distance. However, the decrease in flux with distance cannot be generalized. The rate of decrease depends on the flame zone size. As flame zone size increases, the rate of reduction in radiant flux with distance decreases.

The incident radiant flux to a structure depends on an unobstructed view. Any obstacles between the structure and the flame zone will block part or all of the radiation and thus reduce or eliminate the incident radiation flux. Unburned vegetation, walls and terrain can effectively block radiation. For example, a structure set back from the top edge of a steep slope might not see the flame until it reaches the top of the slope. Thus, if a flame stops before reaching the level of a structure, a steep slope will shield the structure from radiation exposure in that direction. The opposite can occur on the uphill side of a structure. A steep slope uphill from a structure can possibly radiate its entire flame area. For rapidly spreading flames, a structure can be exposed to the increased radiant exposure of an extensive flaming area on its uphill side.

The duration of the radiant heat flux also influences ignition. For any radiant heat transfer rate above the minimum required for ignition, a time to ignition depends on the magnitude of the radiant flux. As the radiant heat transfer rate to a surface increases, the time required for ignition decreases. Generally for wildland vegetative fuels, flame zone burning time depends on the fuel particle size. Grasses, twigs, leaves and conifer needles represent fine fuels that have flame durations of approximately one minute or less. By contrast, a firewood pile or a neighboring structure might support a significant flame zone for tens of minutes.

Modeling Ignitions From Radiation

Modeling ignitions requires an understanding of the rate that energy arrives at the material and the required exposure for the type of ignition. For our modeling purposes, we described the incident radiant heat flux to a flat surface and the required thermal exposure for piloted ignition of wood *(Pseudotsuga menziesii),* Douglas-fir.

Incident Radiant Heat Flux

Our radiation heat transfer model simplifies the actual fire-structure situation, but we have attempted to make our assumptions so the error produces greater heat transfer. Figure 2 illustrates these assumptions. We represent the flame as a rectangular radiator at the constant, uniform temperature of 1200 degrees Kelvin with a black-body emissivity dependent on flame depth (but for our analysis we assumed an emissivity of 1). The flame-wall configuration is represented by centered parallel plates. We calculate the average incident radiation at the center of the wall where the maximum heat flux occurs. Equation 1 calculates the incident radiation per unit area to the receiver (wall) consistent with the model assumptions.

$$\dot{q}''_w = F_{t,W} (\varepsilon) \sigma T_f^4$$

where:

$\dot{q}''_w$ = incident heat flux (kW/m^2)
$F_{f,W}$ = view factor of the flame to the wall
ε_f = flame emissivity
σ = Stefan-Boltzman constant (kW/m^2/K^4)
T_f = flame temperature (K)

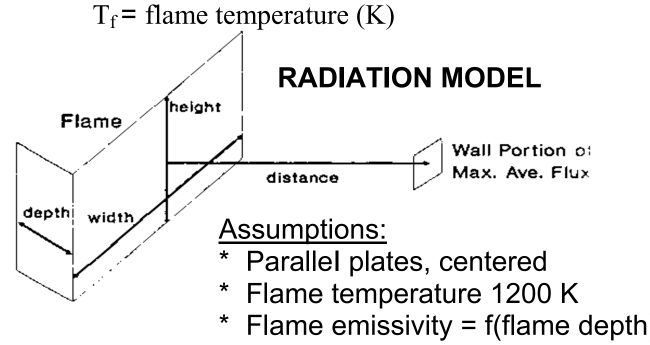

Figure 2. The radiation model simplifies the flame-wall configuration, radiative temperature and flame emissivity. These model assumptions bias the calculations toward increased incident radiation—a worse-case analysis.

Piloted Wood Ignition

The ignition model relates the radiant exposure over time with the minimum required radiant exposure for piloted ignition of wood, Based on the work of Tran and others (1992), the model uses an experimental correlation relating the time to piloted ignition and the incident radiant heat flux. The modcl assumes a flat wood surface and a pilot ignition. Equation 2 calculates the incident heat flux exposure necessary for piloted ignition and determines whether that exposure is sufficient for ignition.

$$\int_{t_o}^{t_f} \pm (\dot{q}''_w - \dot{q}''_{cr})^{1.828}\, dt \geq FTP_{ig} \qquad (2)$$

where:

$\dot{q}''_w$ = incident heat flux (kW/m^2)
$\dot{q}''_{cr}$ = minimum incident heat flux for ignition (=13.1 kW/m^2)
$\pm$ = 0, for: ($\dot{q}''_w < \dot{q}''_{cr}$)
$\pm$ = 1, for: ($\dot{q}''_w \geq \dot{q}''_{cr}$)
t_0 = time exposure begins
t_l = time exposure ends
FTP_{ig} = minimum FTP for ignition (=11501)

The flux-time equation in its most general case accounts for a continuously varying radiant exposure and the sufficiency for piloted ignition. However, given a constant radiant exposure, equation 2 can be solved for the minimum time required for ignition. Equation 3 represents the minimum ignition time (t_{ig}) form of the ignition model.

$$\int_{t_o}^{t_f} dt = t_{ig};$$

$$t_{ig} = FTP_{ig}\, (\pm (\dot{q}''_w - \dot{q}''_{cr}))^{-1.828}$$

for:

$$(\dot{q}''_w \geq \dot{q}''_{cr}),\ \pm = 1$$

$$(\dot{q}''_w < \dot{q}''_{cr}),\ \pm 0,\ t_{ig} = \text{undfined, no ignition}$$

$$(\dot{q}''_w = \dot{q}''_{cr})\ t_{ig} = \text{undefined, infinite time}$$

Figure 3 relates the incident radiant heat flux to the minimum time to achieve piloted ignition. For perspective, Table 1 lists various radiant exposures and their effects. With respect to the incident radiation, Figure 3 and Table 1 provide a comparison of human sensitivity to the required exposures for piloted wood ignition.

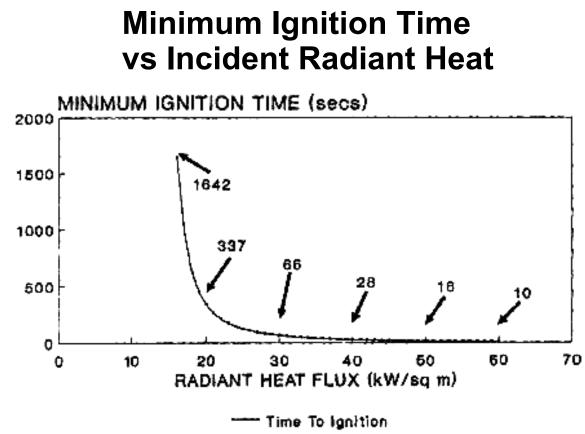

Figure 3. The minimum time for piloted wood ignition depends on the incident radiation heat flux (given as a constant) that is greater than the critical heat flux of 13.1 kW/m^2.

Model Analysis

The fundamental questions:

- How much vegetation management must be done to significantly reduce residential ignitions from radiation exposure?
- How much vegetation management must he done to provide defensible space?

The significant difference between the effects of radiant exposure on wood and humans as seen in Table 1 suggests that the vegetation management required to decrease structure ignitions may he significantly less than that required for human tolerance. i.e.. defensible space.

Figure 4 presents the incident radiant heat flux as a function of the flame-wall distance for a variety of flame sizes. We associated the flame sizes to a vegetation type. For example, at a distance of 6 meters for a flame of 5 meters wide by 2 meters high (possibly low shrub landscaping), the model estimates a heat flux of approximately 7 kW/m^2. At the same distance, for the next larger flame

Table 1. The effects of radiant exposure on human skin and wood indicate that humans are greatly more sensitive than wood during a WUI fire.

Heat Flux (kW/m^2)	**Effect of Exposure**
6.4	Pain on exposed skin after 8 secs. (Drysdale 1985).
7.0	Maximum estimated exposure for a firefighter wearing wildland firefighting clothing and head and neck protection over a period of approximately 90 secs, (Butler and Cohen 1997).
10.4	Pain on exposed skin after 3 sees. (Drysdale 1985)
16.0	Blistering of exposed skin after 5 secs. (Stoll 1969).
20.0	Piloted wood ignition after more than 5.5 minutes (ignition model).

size (5x6 m, larger shrubs), the model estimates a heat flux of approximately 22 kW/m^2. Examination of the minimum ignition time (reference fig. 3 or calculate from eqn. 3) indicates that 7 kW/m^2 is not sufficient for ignition for any duration of exposure and 22 kW/m^2 has an ignition time of approximately 3.5 minutes (211 seconds). Although the smaller flame will not produce an ignition, the exposure will not accomodate the sustained presence of wildland firefighting personnel, i.e., by definition, it is not defensible space. The larger flame definitely does not afford defensible space and may not produce an ignition if the radiation duration is less than the time to ignition. As discussed previously (IGNITIONS FROM RADIATION section), the flame residence time is a critical consideration for ignition.

Recognizing that the spreading flame zone has a residence time of 1 to 2 minutes. We nevertheless decided on a longer exposure duration for judging vegetation modification requirements. We chose an incident radiation heat flux of 20 kW/rn^2 or an ignition time of approximately 5.5 minutes. This produces a conservative, severe-case criteria, but the reader should feel free to use their own judgement. Examination of figure 4 indicates that at a flame-wall distance of 15 meters, all exposures drop to 20 kW/m^2 or below for all but the largest flame front. Further examination of figure 4 reveals that all vegetation does not require removal to 15 meters. Vegetation producing smaller flames can be placed at distances closer than 15 meters.

Coniferous tree crowns and some broadleaf species (e.g., *Eucalyptus spp.)* can produce very large flame heights. Clearing trees for fire hazard reduction potentially results in significant changes in the aesthetics of a residential site and thus, is often resisted. Tree thinning offers an effective alternative to total clearance.

Figure 5 illustrates the effect of tree density on incident radiation exposure. Without any consideration for decreasing crown lire potential due to a decrease in tree

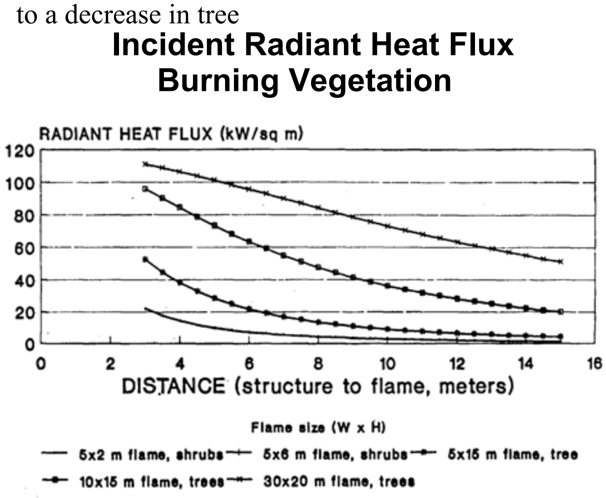

Figure 4. Given a constant flame size, the incident radiation heat flux depends on the flame-wall distance and the flame size (associated vegetation type).

canopy continuity, figure 5 indicates that complete tree removal is not necessary to achieve a radiation exposure below the 20 kW/m^2 criteria. For example, thinning to a 4 meter spacing reduces the exposure to 20 kW/m^2 at a flame-wall distance of approximately 16 meters. Figure 5 also illustrates how progressive thinning might be used as a function of distance from a residence. By following the 20 kW/m^2 line (or any heat flux of choice) across the graph, the tree spacing varies to maintain that exposure level. This is illustrated by the intersections with the heat flux/tree spacing curves presented.

Figure 5 also indicates the maximum distance for fuel hazard modification for the vegetation type shown (trees). Using the 20 kW/m^2 criteria, our analysis indicates that fuel management beyond 40 meters does not reduce radiation produced ignitions.

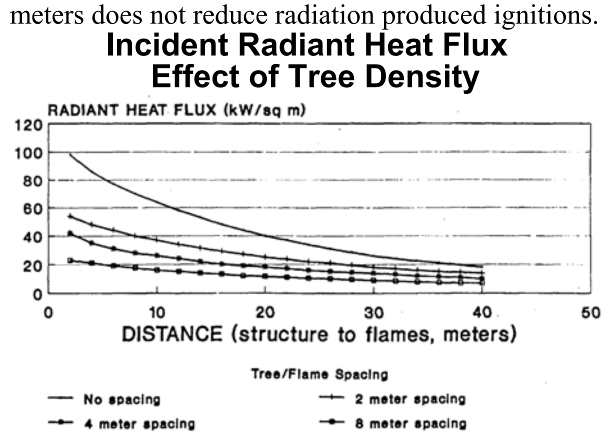

Figure 5. Given a constant flame size, the flame/trees are 2.5 meters wide, 20 meters high, and extend along a 50 meter flame front. The incident radiation heat flux depends on the flame-wall distance and the flame/tree spacing.

Our analysis only examined piloted wood ignition due to radiation exposure. The analysis did not examine radiation effects on various other exterior structural materials such as plastics, nor did we consider thermal fracturing of window glass. These are considerations for future examination.

We specifically examined structure ignitions in the context of vegetation fuels; we did not consider neighboring structures. An important difference between burning vegetation and burning structures concerns the flaming residence time. Although burning structures may not produce flames as large as some vegetation, the expected residence time is longer, perhaps 10 times longer. Thus, for a given flame size and distance, a burning structure might produce ignitions on an adjacent structure where burning vegetation does not.

Conclusions

- Defensible space and the flame-wall distance at which ignitions occur depend on the flame size and the flame duration, i.e., the flame front width, flame height and flaming residence time.
- A wildland firefighter's maximum radiant exposure is well below exposures necessary for piloted wood ignition. Our analysis indicates that defensible space requires more vegetation fuel hazard reduction than fuel reductions required for preventing piloted wood ignition.
- Vegetation management to prevent ignitions from radiation does not require extensive vegetation removal hundreds of meters from a structure. Our analysis indicated that 40 meters was sufficient for a 20 meter flame height.
- Our analysis indicates that thinning trees to produce gaps in the flame front significantly reduces the radiant exposure.
- Neighboring structures potentially burn with much longer flaming residence times and thus may be a greater ignition threat than vegetation.

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