Pathways for Building Fire Spread at the Wildland Urban Interface

Final Report

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FOREWORD

Fires in the WUI communities are a rapidly growing problem in the US. The last 15 years contains six of this century's top ten most damaging U.S. single fire events; all of these events occurred in WUI communities. Over 46 million homes in 70,000 communities are at risk of WUI fires (Bailey, 2013). Since 2000, over 38,000 homes have been lost to WUI fires in the U.S.

There are many potential pathways for wildland fires to ignite buildings within the WUI. These pathways (including both fire and ember exposure) depend on the characteristics of the wildland (e.g., fuels, terrain, weather, etc.), the characteristics of the community (e.g., construction materials, building designs, housing density, landscaping, etc.), and the characteristics of the interface (e.g., separation distance, physical barriers, extent of perimeter, etc.).

NFPA Standard 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire*, and NFPA 1141, *Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas*, address hazards to structures at the wildland interface and appropriate mitigation measures (NFPA, 2013; 2012). Understanding the pathways above and their contribution to fire risk will help inform future editions of these NFPA standards.

The goal of this project is to identify pathways for fire spread at the wildland urban interface and identify gaps in information to inform prevention and protection strategies.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

NFPA is a worldwide leader in fire, electrical, building, and life safety. The mission of the international nonprofit organization founded in 1896 is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. NFPA develops more than 300 codes and standards to minimize the possibility and effects of fire and other hazards. All NFPA codes and standards can be viewed at no cost at www.nfpa.org/freeaccess.

Keywords: embers, fire, firebrands, firefighting, fire risk, fire spread, ignition pathways, wildland fire, wildfire, wildland urban interface, WUI

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EXECUTIVE SUMMARY

While the Wildland-Urban Interface (WUI) is not a new concept, fires in WUI communities have rapidly expanded in frequency and severity over the past few decades. The number of structures lost per year has increased significantly, from around 900 per year in the 1990's to almost 3000 per year in the 2000's (Bailey, 2013; NIFC, 2014). This trend is the result of many factors, including increased development in rural areas, fuel management policies, and climate change, all of which are projected to increase in the future (Krawchuk et al., 2009).

Responsibility for the protection of these buildings falls between both wildland and urban fire authorities, with mixed guidance available for homeowners, code officials, etc. (IBHS, 2014; ICC, 2012; CBC, 2009; Fire Adapted Communities, 2015). The NFPA has begun to address this problem by instituting several standards, including NFPA 1141, 1142, 1143 and 1144, which aim to reduce structural ignitions and provide adequate firefighting infrastructure in WUI communities. A necessity for improvement of these standards and others is technical knowledge which can be used to understand pathways for fire spread and their statistical and/or quantitative contribution to fire risk. While the general pathways for fire spread in the WUI (flame, radiative and ember exposure) are known, the exposure conditions generated by surrounding wildland fuels, nearby structures or other system-wide factors and the subsequent response of WUI structures and communities are not well known or well understood. Several key pathways into structures, such as eaves, vents, windows, roofs and decking have received attention and limited study, but no effort has been made to compile all available data quantitatively for use in an applied, risk-informed framework.

A thorough literature review of multiple pathways to ignition and their requisite exposure conditions in WUI communities has been performed, along with a gap analysis to identify data needed to inform prevention and protection strategies. Information has been compiled from a wide array of resources, including archival publications, conference papers, research reports from academia and federal agencies, case studies and investigative reports from WUI fire incidents, existing codes and standards, and interviews with leading incident commanders and fire researchers. These studies have been compiled from local (US) resources, as well as international sources in North America, Europe, Asia and Australia who have amassed a wide variety of experience on these topics.

After reviewing the available literature, many areas related to pathways for fire spread in the WUI were found to still be in need of additional research. As part of a gap analysis, these areas were broken down into those related to quantification of risk and hazard and more practical and specific issues. Areas necessary to inform quantification of risk and hazard included pre- and post-fire data collection, improved testing of firebrands, understanding of ember and wildland fire fundamentals, and improved understanding of structural ignition mechanisms. There are also many other practical issues, which relate to specific areas of code and standard development and WUI community protection or firefighting that are in need of rapid research and development. These included understanding fuel management, defensible space, community planning, development of test standards, design of ignition-resistant materials, assessing the effectiveness of mitigation strategies, understanding the impact of wildland fires on health and the environment, improving firefighting techniques and identification of educational needs.

These categories represent a wide spectrum of subjects within possible WUI research. One of the most important gaps identified through this review is that most work to date has not *quantified* effects in a repeatable manner. While it is useful to identify vulnerabilities and best practices, protection of WUI communities cannot evolve without more quantitative analyses to optimize protection schemes, standards and risk and hazard analyses. Improved dissemination of literature, especially through more peer-reviewed studies will also enhance the technical credibility and wide dissemination of work on the field.

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Introduction

Three fundamental pathways have been identified for the spread of fire into and within WUI communities. First, radiant exposure may occur where large flames are close to exposed structural elements. The effect of radiation can often be minimized or eliminated through proper vegetation selection, location and management and defensible space around structures (the home-ignition zone, HIZ); however, the influence of other nearby structures and their impact on radiant exposure must be taken into account (e.g. conflagrations where fires spread from home to home within a community) (Calkin et al., 2014). Second, direct flame contact exposure, which occurs between flames from smaller fires and adjacent structural elements, such as litter or wood piles, can be mitigated by creating a similar defensible space around structures, entirely clear of combustible material. Third, fires may spread into and within a WUI community via the transport of firebrands (also called burning embers or brands[1]) generated either by the main fire front, nearby flammable material (e.g. vegetation) or nearby burning structures (e.g. conflagrations) (Pellegrino et al., 2013). Protection of structures must therefore incorporate all of these potential sources of ignition, as well as incorporate the cumulative effects of fires on nearby surrounding structures within the community contributing to overall fire spread. This framework has been utilized in this literature review. Part I of this report breaks down these potential pathways into research and knowledge on potential exposures to structures and the response of structures to these exposures. They deserve equal importance, particularly because recent data indicates that at least 50% of ignitions, if not more, occur due to indirect exposure, i.e. firebrands (Mell et al., 2010).

[1]The terms brand, firebrand, flaming brand, flying brand, burning brand, ember, flying ember, or burning ember are used synonymously in the literature to denote small pieces of burning vegetation or structures (whether smoldering or flaming) lofted into the fire plume and transported ahead of the fire front. The terms firebrand or burning ember are therefore used synonymously throughout this report. Similarly, an ember "storm" or firebrand "shower" denotes a large flux of small burning particles lofted through the air, whether produced by a fire front or artificially in a laboratory.

While the underlying ethos of fire spread is known, quantitative knowledge of the effectiveness of specific approaches for risk mitigation and prevention within WUI communities, especially coupled to relevant exposure conditions and homeowner maintenance, is not well known. Spearheaded by the California fire season of 1985, a joint initiative by the NFPA and the USDA Forest Service (USFS) highlighted the WUI problem and generated initial research into the problem (NFPA, 2014; Firewise, 2015). As a result, several research projects on the radiative exposure of building assemblies to large wildland fires were begun, with large-scale testing performed during the International Crown Fire Modelling Experiments from 1997-2001 (Cohen, 2004a). From these experiments, it was determined that when a clear, defensible space of 120 feet (36 m) was maintained around a structural facade, radiative exposure was insufficient to ignite wooden exterior walls from experimental crown fires, meaning that only firebrands or local combustible material (e.g. mulch) could ignite a structure. Recent analysis of the Angora fire (2007) has shown that fuel treatments that reduced the fire intensity beyond the HIZ were not effective in reducing WUI losses (Murphy et al., 2007; Safford et al., 2009). Therefore particular attention must be paid to more local, low intensity fires and the source of local ignitions (from firebrands) (Calkin et al., 2014). While different frameworks for wildfire risk assessments are available (Cohen, 2004a; Maranghides and Mell, 2013), the existing framework only allows qualitative predictions of radiative exposure. Significant assumptions are made when using many of these tools, such as ignoring firebrands and assuming that fires will occur under ordinary fuel and weather conditions, when realistically it is only the most extreme fires (high winds and low humidity) that challenge current methods of fire control (Calkin et al., 2014).

More recent efforts by the National Institute of Standards and Technology (NIST), USFS and the Insurance Institute for Business & Home Safety (IBHS) have identified clear vulnerabilities of WUI structures to low intensity fires and firebrands, including roofing components, eaves, vents, wood piles, mulch, fences, decks, etc. (Calkin et al., 2014; Mell and Maranghides, 2009; Pellegrino et al., 2013a; Quarles et al., 2012). While a significant body of work exists on the transport of embers or firebrands (Tarifa et al., 1965; Woycheese et al., 1999), limited knowledge exists on quantitative ember exposure, ignition properties or vulnerabilities of structures to embers (Hadden et al., 2010; Manzello et al. 2006a,b). The development of a testing platform, the NIST Dragon (Manzello et al., 2012a), and several detailed investigations (Cohen, 2000a; Cohen and Stratton, 2008; Maranghides et al., 2013; Mell and Maranghides, 2009; Quarles et al., 2012) have been particularly significant in developing an understanding of large-scale ember ignition. The arrangement of homes and layout of communities (land-use planning) also greatly affects the probability of ignition in WUI communities (Syphard et al., 2012). Some gaps in knowledge are being studied, so recent progress is reviewed here; these gaps include the rate of generation of embers from natural fuels and structures, the effectiveness of local fuel treatments on reducing fire intensity and, in particular, homeowner maintenance of their home and property, including the impact of community education. Many more gaps will be identified, as the effectiveness of strategies to minimize the impact of WUI fires, such as new regulations in California, have yet to be documented.

While this report will focus on fire spread in the WUI, there is no way to constrain such a review to physical factors alone. For example, appropriate planning and continued maintenance of fuel treatments on both public and private land is essential for some of these mitigation strategies to remain viable. Available knowledge on the maintenance of these efforts, specifically of defensible space by homeowners will be addressed, as will the impacts of community efforts, such as Firewise, Fire Adapted Communities, Ready Set Go!, etc.

WILDLAND-URBAN INTERFACE PROBLEM

Even though the term “wildland-urban interface” generates the perception of a problem that is determined primarily by geographic location, the WUI problem can be more simply envisioned as a *structure ignition problem* (Cohen, 2004b). If structures are safeguarded against ignition sources, property loss and costs incurred (not to mention potential loss of life) can be avoided. Changes in the location of a structure (specifically surrounding fuel and topography) can certainly affect the exposure conditions which impact any structure; however, if the pathways to ignition are fundamentally prevented via hardening structures, communities and surrounding wildland, then the WUI problem can be greatly reduced. This report will detail many of the pathways that fires can spread into and within a WUI community with the aim of preventing future WUI tragedies via informed decisions in codes, standards, future structure and component design, remodel/renovation of existing buildings and community planning.

The definition of what community areas are WUI and not often encompasses a comparison of the housing density and location of surrounding wildland (Cohen, 2008). The WUI can be defined as encompassing both interface and intermix communities, where vegetation is continuous in the intermix, except where structures are located, and less contiguous within the interface. Many studies have worked to define this interface boundary and map it (e.g. Figure 1); however, this will not be a focus of this report and can be found elsewhere (Lampin-Maillet et al., 2010; Radeloff et al., 2005; Stewart and Radeloff, 2007).

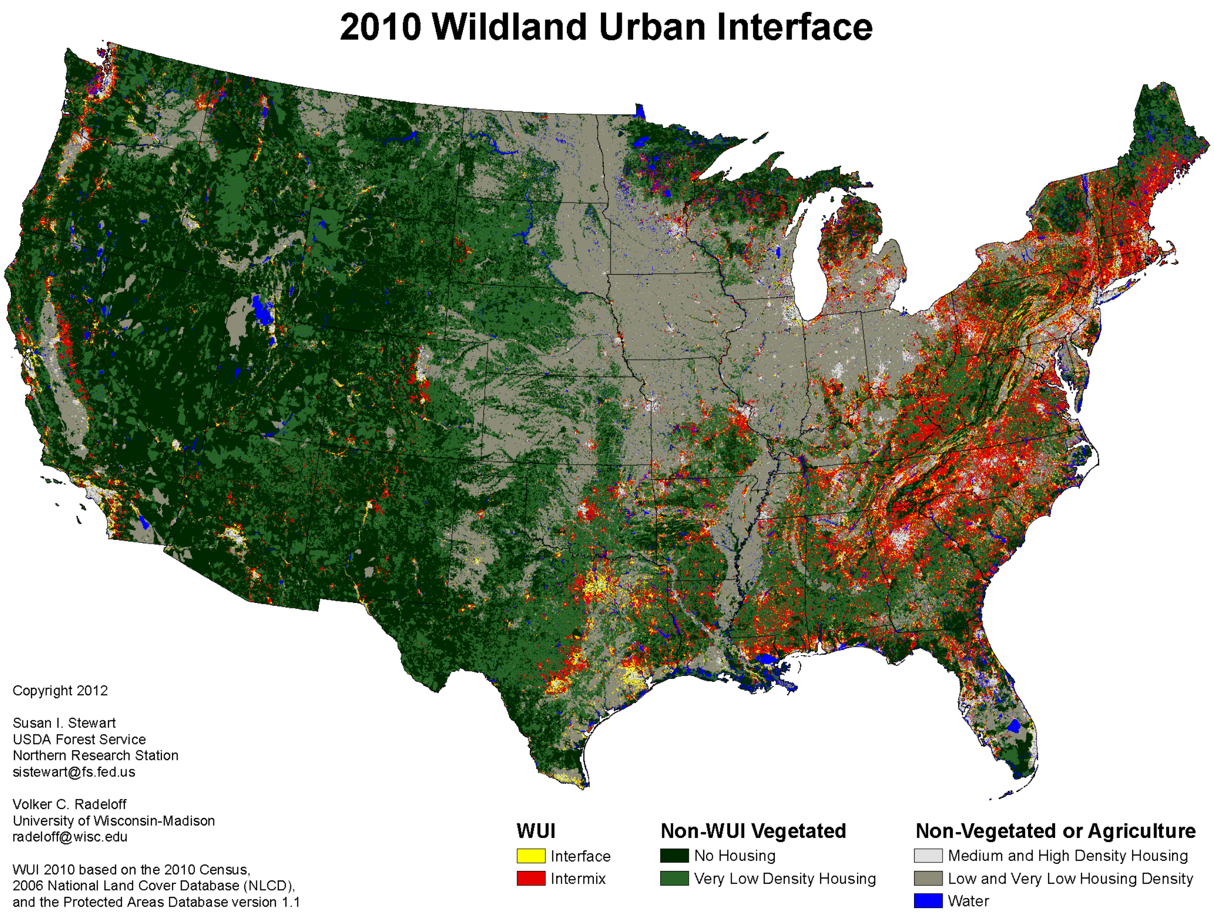

Figure 1: Map of the wildland-urban interface in 2010 (Radeloff et al., 2005 and Radeloff, 2014).

Fires in the WUI are not a new problem, but perhaps just a problem that has been more recently forgotten. During the same week as the Great Chicago Fire in 1871, the Peshtigo Fire killed between 1500 to 2500 people and burned somewhere around 1.5 million acres, completely destroying twelve communities (Brown, 2004). Comparing that to the Great Chicago Fire, which killed about 300 people and burned down only 3.3 square miles, shows the extent by which these events differed. Despite the tragic toll of the Peshtigo fire, it is rarely mentioned, while the anniversary of the Great Chicago Fire is still used as a catalyst for NFPA's Fire Prevention Week every year (NFPA, 2014a). The Peshtigo Fire and subsequent fires between 1896-1910 served as catalysts for the "fire exclusion" movement – a push for fire control and suppression of wildfires largely led by the USFS (Pyne, 2008).

Despite this long history of fire suppression in the United States, the frequency and severity of wildland fires has continued to increase, especially recently. Large WUI conflagrations such as the 1991 Oakland Hills Fire, the 2012 Waldo Canyon Fire and the 2003, 2007 and 2014 San Diego Firestorms have served as constant reminders of the threat large wildland fires pose in the WUI. Recent data show that 3% of the wildland fires in the United States are now responsible for 97% of the area burned (Short, 2014). Following decades of intense wildfire suppression policies, large areas of unburned fuels have built up in the wildland and contribute to the growing size and intensity of wildland fires. Known as the fire paradox, wildfire suppression meant to eliminate large and damaging wildfires has in turn ensured the inevitable occurrence of these fires (Arno and Allison-Bunnell, 2002). According to some studies, over 73 million acres of national forest land meet high priority for treatment of fuel buildup in WUI areas (Service & Bosworth, 2004). On top of this, a mass movement from urban residences to rural communities has increased the size of the WUI, where natural or modified wildland fuels meet traditional structures including residences, businesses and other community structures. This transition has increased the number of at-risk risk homes significantly. In 2000, WUI development was estimated to cover 465,614 km^2, an expansion of 50% from 1970 (Theobald and Romme, 2007). In the western United States, 50% of future housing development is estimated to occur in the WUI (Gude et al., 2008), highlighting a massive increase in future WUI lands. With only 14% of the interface developed, firefighting costs are now between $630 million and $1.2 billion/year. It is projected that if 50% of the interface is developed, the cost would range from $2.3 billion to $4.3 billion/year. These costs could make up nearly the entire annual budget ($4.5 billion in 2008) of the USFS, so improved land-use planning is critical (Gude et al., 2008). An illustration of this problem is presented in Figure 2, which shows a map of structures lost to wildfire in the United States from 1999-2011.

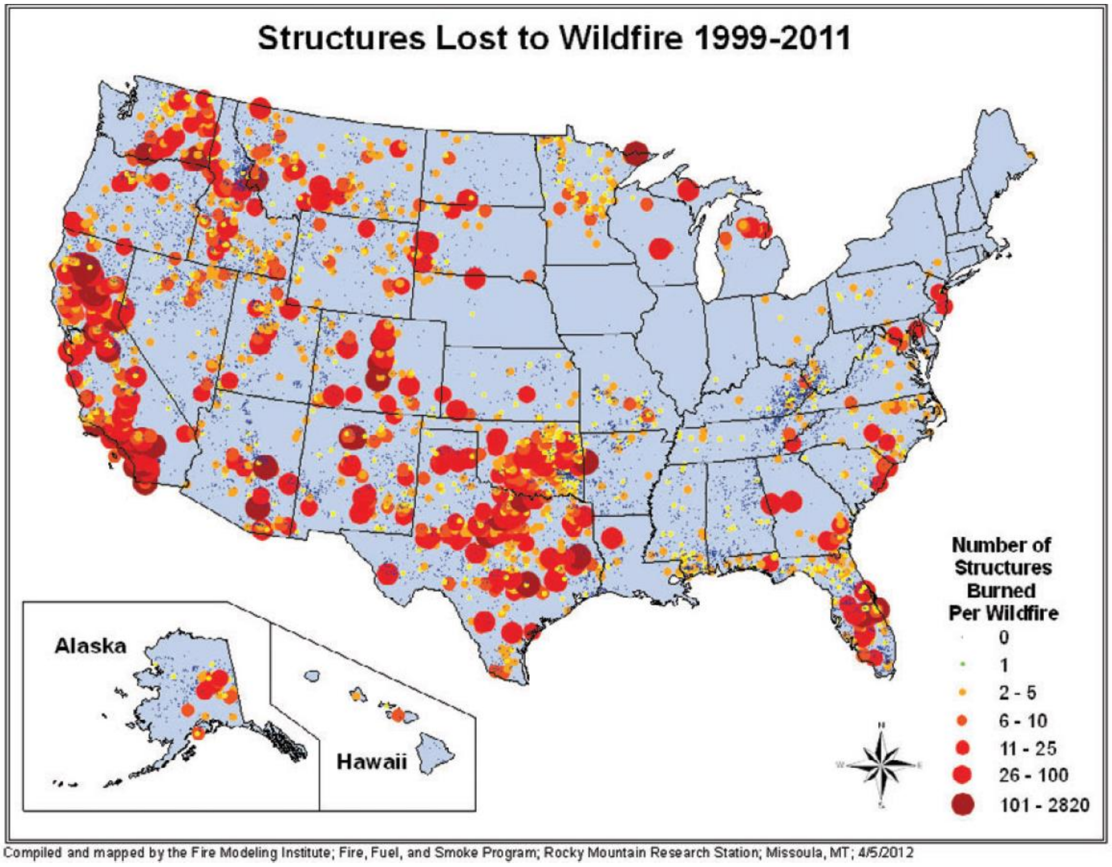

Figure 2: Map of structures lost to wildfire in the United States between 1999–2011. Data are limited to burned structures reported through the National Interagency Coordination Center database. Data source(s): Situation Report (SIT/209). Compiled and mapped by the Fire Modeling Institute, Fire, Fuel, and Smoke Program, U.S. Forest Service, Rocky Mountain Research Station, Missoula, MT, April 2012 (NIFC, 2015).

With the advent of more extreme fires becoming the norm (Figure 3), a different thought process must be taken in comparison to traditional structural firefighting techniques and risk assessments (Figure 4). In structural firefighting, the assumption for most occupancies is that the structural design of the building, passive fire protection systems and automatic fire protection systems will provide sufficient protection for the occupants to escape and for the fire department to enter the building to provide full extinguishment. In large WUI fires, many buildings burn down tens of hours after the main fire line passes through a community due to firebrand ignition. Firebrands and other smoldering debris slowly transition to flaming from innocuous sources that are difficult to identify, while the main fire front threatens new homes and communities miles away. These firebrands can also be transported several kilometers ahead of the front depending on atmospheric conditions; therefore, a large area is affected over which no firefighting crew has sufficient resources to cover (Koo et al., 2010). A different theory or approach to firefighting and structure protection must be envisioned to prevent future large scale losses. Current strategies for exterior fire protection in the WUI (e.g. homeowner checklists, mesh coverings for vents, etc.) pale in comparison to those developed for use within buildings (e.g. fire sprinklers, smoke detectors, fire retardant materials, etc.). One concept is to limit the pathways by which firebrands or other fire sources can penetrate a property or community and destroy a structure, a problem this report will shed further light on.

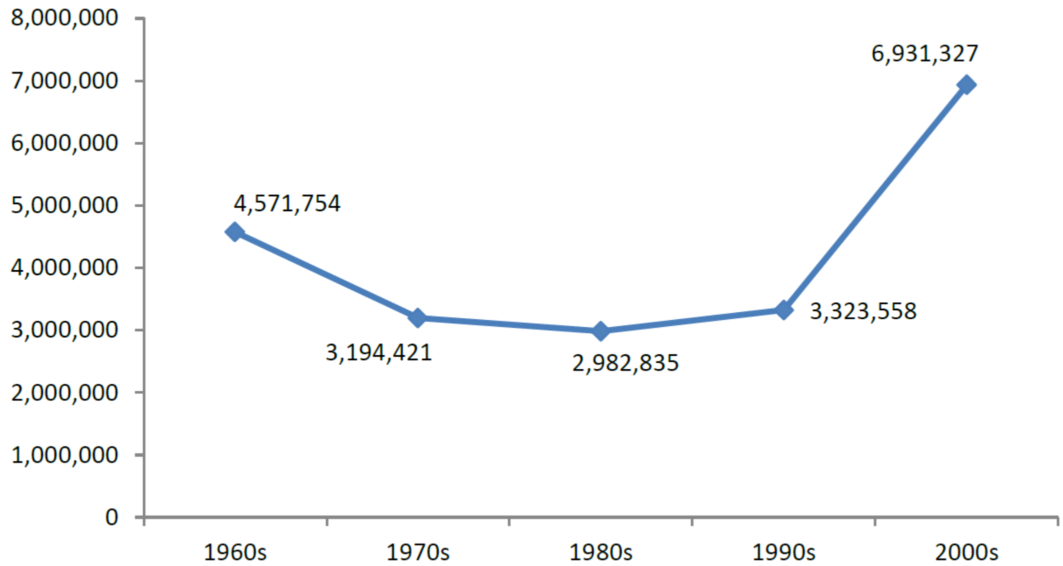

Figure 3: Average annual acres burned, by decade. Rising firefighter effectiveness and other factors steadily lowered the number of acres burned until the 1990s, when a slight rise was followed by a sharp increase in the 2000s due to fuel buildups and worsening fire weather conditions (USFS, 2013).

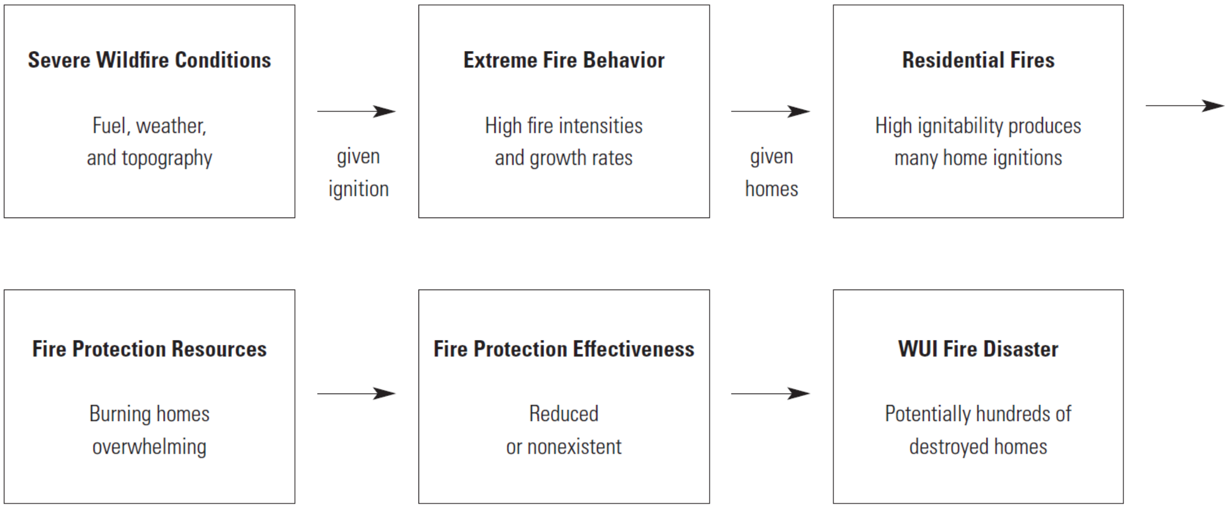

Figure 4: The WUI fire disaster context depends on exposure of vulnerable homes to uncontrollable, extreme fire behavior. If the number of burning and vulnerable homes overwhelms the fire protection capability, fire protection effectiveness is reduced, and many homes are left without protection. If homes are ignition-resistant then many homes do not ignite and fire protection is not overwhelmed by the ignitions that do occur. Thus, an extreme wildfire can occur without a WUI fire disaster (Cohen, 2008).

A higher occurrence rate of extreme fires also means that it will become important to assess incident fire severity based upon the most extreme weather conditions where high wind speed, low moisture content, etc. create challenging fire scenarios. This means that relying on historical fire and weather data will only be useful if some sense of the ecological fire regimes and drought patterns are taken into account.

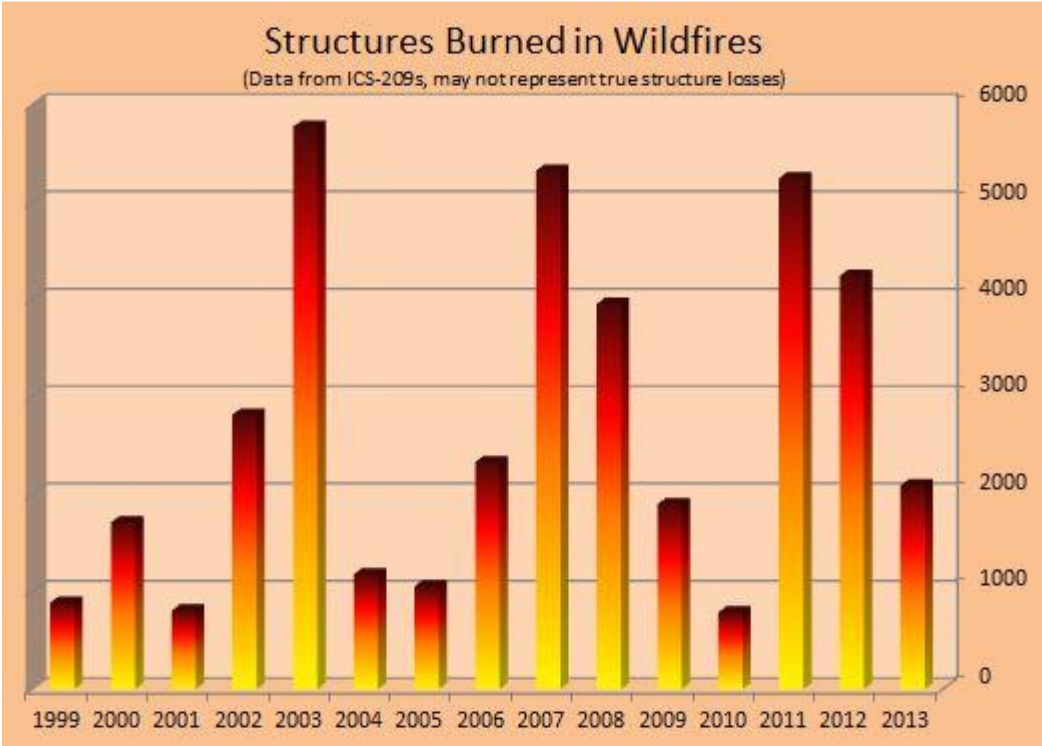

Figure 5: Historical data on structures burned in wildfires (from https://fam.nwcg.gov).

There are many means for improvement beyond direct structure protection. State laws addressing defensible space, ingress, egress, and water supply can create a safer environment for firefighters, resulting in more structures being saved (Gude et al., 2008). Many of these issues are already covered in NFPA 1141 and 1144; however, they could be improved with further knowledge including case studies and research. Data needed for quantitative risk analysis, such as wildfire exposure conditions or the reaction of components to these conditions, is severely lacking (Maranghides and Mell, 2013). Policies that address existing and future development in the WUI should be coupled with national, state, and local policies that address wildland fuel management (Gude et al., 2008).

As protection of property in the WUI has now become an increasing firefighting priority, firefighters are constantly endangered while striving to protect structures. In 2013, 97 firefighters died while on-duty. Of these, 28 of the deaths occurred at 10 separate wildland fires. An average of four wildland firefighters have died annually at wildland fires or prescribed burns in the years 2002-2012. In the most recent incident, the Yarnell Hill Fire killed nineteen members of a Hotshot wildland firefighting crew and huge media attention was focused toward the problem of safe WUI firefighting (Leblanc et al., 2014). This event was the largest single loss of life for firefighters since the September 11, 2001 terrorist attacks on the World Trade Center in New York (Manzello, 2014). Thought and planning for firefighter safety, including access to safety zones, adequate egress, etc. needs to be built into community planning (Butler, 2014).

While there still exists a large void in knowledge as to how future climate change might alter global wildland fire activity, most estimates suggest that severely altered fire regimes may increase fire activity in some regions, but reduce it in others (Krawchuk et al., 2009). Fire management policies may have to shift in the future as climate, rather than human intervention, plays a stronger role in driving fire trends than it has over the past two centuries (Pechony and Shindell, 2010). In the western U.S. in particular, a significant increasing trend in the number and size of wildland fires has been found between 1984-2011, with fires increasing by a rate of seven fires per year and 355 km^2 burned per year. These changes were most significant for southern or mountain ecoregions, with drought is a significant source of increased fire severity. (Dennison et al., 2014). While climate change may be a significant driver in making the wildland fire problem worse in some regions, proper forest management practices, such as prescribed burning, may actually help to combat the problem by both reducing the intensity of eventual fires and limiting net carbon emissions. Wiedinmyer and Hurteau (2010) estimated carbon sequestration by forest ecosystems from wildfires vs. prescribed burning, finding that 18-25% reductions in CO_2 emissions are possible in the western U.S. – with as much as 60% in specific ecosystems – by proper prescribed fire use and management practices.

EXPOSURE CONDITIONS

Fundamentally, ignition is the process by which a sustained combustion reaction is initiated. In WUI fires, a solid element is typically heated until the solid fuel releases enough flammable vapors to ignite with or without a spark (piloted or auto-ignition), releasing sufficient heat to sustain the flow of flammable pyrolysis vapors from the solid. Many times there are enough flaming sources in the vicinity of a large wildland fire to assume that piloted ignition will occur for worst-case hazard analyses. Exposure conditions are often studied to assess what thermal insult they can impart to building materials to cause them to ignite. Typically this thermal exposure is described in terms of a heat flux (rate of heat transfer, kW/m^2) and time to ignition, assuming sustained exposure to a certain heat flux.

Three primary categories can be used to describe the types of fire exposure typically imparted on structures in the WUI. The first is radiant exposure. Unlike convection heat transfer, which requires a moving fluid medium, radiation can travel relatively undeterred until impeded by a solid object, typically thought of here as the exterior of a home which may potentially ignite. As the separation distance from the home to the fire increases, the radiant exposure significantly decreases (proportional to one over the distance squared), eventually making it impossible at some distance to ignite. This analysis is often used for assessment of safe separation distances between structures and potential fuels.

Convective or conductive heating can become significant in WUI applications when heating from direct flame contact occurs. While flames of smaller sizes typically do not emit enough radiation for sufficient duration to ignite surrounding structural elements, they can cause ignition if they are close enough to impact a component for a significant duration. Due to the fact that most homes have some separation between the primary structure and a traveling fire front, direct flame contact typically occurs via secondary ignitions of smaller flammable vegetation, mulch, wood piles, forest litter, decks, plastic furniture or other flammable materials nearby or on the structure itself.

Finally, burning embers produced from vegetation or burned structures can contribute to home ignition through a variety of pathways. They can directly travel into buildings via openings such as vents, or they can ignite nearby flammable materials which proceed to ignite a home via direct flame contact or radiant exposure.

Radiant Exposure

Exposure of structural elements to radiant heating is probably the most-studied exposure condition from wildland fires. A significant body of literature is available on means of calculating radiant exposure from a fire (de Ris, 1979, 2000), and radiant ignition of a solid fuel has been understood theoretically (Liñan and Williams, 1972) and practically (Drysdale, 2011; Quintiere, 2006) for some time. Most early research on WUI therefore focused on radiant exposure to structures.

Before several initial studies in the 1980's, there was little data to support quantitative findings on the amount of radiant exposure possible from an approaching wildland fire. Initial studies utilized simplified models to determine the radiant exposure possible between an approaching wildland fire and a simulated wooden siding of a home (Cohen and Saveland, 1997; Cohen, 2004b, 1995; Cohen and Butler, 1998; Cohen, 2000b; Tran et al., 1992). Initial computational models were created to assess a worst-case separation distance, over-estimating the radiant heat flux that would come from an approaching crown fire (assumed to be a worst-case scenario) to incident wood panels (Tran et al., 1992); however, laboratory experiments showed that the model did not underestimate this distance (Cohen, 1995). These calculations estimated that approaching fires with very long flame lengths (e.g. crown fires) could ignite homes at most up to 40 m (130 ft) away. Beyond this distance, radiant ignition was deemed not possible, even from the most intense crown fire. More recent models of ignition of thermally-thick materials have also been performed, incorporating the movement of the flame front toward an exposed area over time (Reszka et al., 2012).

Later testing as part of the International Crown Fire Modeling Experiments between 1997-2000 (Stocks et al., 2004) exposed wooden wall segments to full-scale, active spreading crown fires with deep flame zones. The wall segments experienced both radiative and convective heating, as well as short-range ignitions from firebrands (Cohen, 2004b). The derived flux-time correlation identified two primary ignition criteria for wood: a minimum critical heat flux of 13 kW/m^2 and a critical heating dosage level which accumulates over time (Cohen, 2004b). Interestingly, actual crown fires did not transfer heat sufficiently to ignite these wood panels at distances beyond 10 m. This finding was significant, as no panels at 20 m (65 ft) or beyond ever ignited, and only half of the panels at 10 m (32 ft) from the edge of the fire ignited. High radiant heat fluxes were observed at panels 10 m from the fire (as high as 150 kW/m^2 for mere seconds); however, for panels 20 m or farther away from the fire, these fluxes never reached above 20 kW/m^2, often a limiting heat flux for ignition of wood (though still enough to cause severe burns to human skin (Stoll and Chianta, 1971; Cohen, 2004b). Some of the factors contributing to this low heat flux were that the tree canopy attenuated some flame radiation and that flames were not continuous at their peak, but rather intermittent and exhibited multiple gaps in the flaming front which reduced the ultimate radiant exposure (Cohen and Butler, 1998). Although the experimental conditions were not those that are presented in extreme wildfires due to differences in weather, fuels, and topography, these experimental fires were fully-involved crown fires with significant flame lengths and radiation. In essence, this experiment signaled that unless flames or firebrands ignite close to a structure, the structure is not likely to ignite (Cohen, 2000b).

As the fires tested by Cohen et al. were under a limited set of relatively mild conditions, continuing work is being done to instrument more wildland fires in order to measure heat fluxes and imposed conditions during a fire. NIST has developed deployable instrument packages and tested them with a small shed-like structure placed within a wooded area (NJ Pine Barrens) for a prescribed fire, measuring heat fluxes of up to 100 kW/m^2 (Manzello et al., 2010b). Many other studies, primarily conducted by the USFS in large wildland fires, both prescribed and uncontrolled, have used instrument packages to measure radiant heat fluxes, among other quantities (Frankman, 2013).

For fires of many sizes, flame lengths and fire intensity can be determined using standard fire behavior modeling tools from the wildland fire community (e.g. Rothermel and Forest, 1972). These tools can be used in similar ways to studies by Cohen to determine radiant heat fluxes for different exposure conditions of fuel, topography, weather, humidity, etc. and different separation distances (Tran et al., 1992). These calculations often offer the farthest distance flammable vegetation should be located near the home. More information on material available to estimate these will be covered under direct flame contact, fire behavior.

Direct Flame Contact

Very little work is available in the literature about direct flame contact specifically applied to the WUI; however, there is a broad base of traditional wildland fire literature which describes flame lengths of vegetative fuels under various ambient conditions[2]. Direct flame contact would not typically be considered a direct source of ignition of a structure when brush and other wildland fuels are cleared away; however, it can be a secondary source from nearby burning material, including vegetation and non-vegetative combustible materials (mulch, wood pile, etc.). Heat fluxes by direct flame contact can be as high as 50-70 kW/m^2 for laminar flames (Ito and Kashiwagi, 1988) or 20-40 kW/m^2 (Quintiere et al., 1986) for turbulent flames, sufficient to ignite some components of a structure (Quintiere, 2006). While these heat fluxes are very high and can produce short ignition times, flames must directly contact building or structural materials long enough to cause ignition. Typically direct flame contact does not occur from the main fire front unless extreme conditions are present; rather ignition of combustible materials on or near a structure cause the structure to ignite and burn.

Fire Behavior

The steady rate of spread (ROS) is an especially relevant parameter for WUI purposes, both because it signals the rate at which a fire will spread toward a community through wildland fuels, and also because the ROS can be related to the fireline intensity and flame length of the fire at the moment of arrival. The fireline intensity (kW/m), comparable to the heat-release rate per unit length used in fire protection engineering, can be determined from the steady ROS via Byram's correlation. This quantity is simply derived by multiplying the ROS by the heat content of the fuel and the fuel load consumed in the flaming front (Byram, 1959). This quantity can then be related to the flame length via correlations by Byram for surface fuels (Byram, 1959) and Thomas for crown fuels (Thomas, 1963). Flame lengths can be useful in estimation of radiant heat fluxes from approaching fires to ignite structural components (Cohen, 1995). It should be noted that it is difficult to interpret flame length values for deep fuel beds.

[2] Some codes and standards, such as the California State Fire Marshal standards associated with the California Building code Chapter 7A, have a flame contact exposure component (CBC, 2009).

Several numerical modeling tools are also available to calculate these parameters. Based upon these same quantities, BEHAVE Plus can calculate one dimensional fire properties such as ROS, fireline intensity and flame length (Andrews et al., 2003). FLAMMAP is available to spatially calculate these values over a geolocated map (Finney, 2006b). FarSITE can then calculate these parameters temporally to provide predictions of fire spread (Finney, 2004). All of these tools are available through the USFS at http://www.firelab.org/.

Other tools are available in other countries. In Canada, most models utilize the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al., 1989), which is based on significant fundamental work by Van Wagner (Van Wagner, 1977). In Australia, models are based on McArthur (1966a,b) for grasslands and McArthur (1967) for eucalypt forests in their fire rating danger system. These models mainly consist of purely empirical correlations of observed fire behavior at field scale, with data augmented by well documented wildfires. Cheney and Sullivan more recently replaced MacArthur grassland FDRS as the preferred tool for grassland fires (Cheney and Sullivan, 2008). Reviews of available models worldwide, including physical and quasi-physical models (Sullivan, 2009a), empirical and quasi-empirical models (Sullivan, 2009b) and simulation tools (Sullivan, 2009c) have been prepared.

When performing predictions of future fire behavior, it is important to follow proper protocols when estimating the extreme wind and weather conditions that could be expected, as well as the fuel loads around structures and communities. Fuel loading and terrain features are especially important for predicting fire behavior and explaining post-fire effects for any fuels treatment meant to decrease fire severity (Hood and Wu, 2006). A how-to guide for using models in the United States is available (Scott, 2012).

While the rate at which a fire spreads is generally determined from correlations, a special effect in steep terrain with canyon walls, sometimes called eruptive fire behavior, has also been documented in the literature (Viegas and Simeoni, 2010). This effect, similar to the trench effect found in urban fires (particularly the 1987 King's Cross fire in London), can extend flame lengths significantly, cause flames to attach to the surface and drastically increase rates of flame spread. While several models are available to describe this effect (Viegas, 2004), these models are designed for firefighter safety, rather than WUI design. Nonetheless community designers should keep this effect in mind when designing placement of structures or escapes, as large inclined canyons with significant fuel loads could cause enhanced flame lengths and rates of spread that are not properly accounted for in other models. This situation could not only endanger structures and occupants, but also be a safety hazard for responding firefighters.

Despite a wide availability of literature on the fire behavior of traditional vegetation under a range of conditions, these models are almost all semi- or fully-empirical approximations of observed phenomena fitted to specific fire conditions. Without a firm physical basis of fundamental heat transfer and combustion processes that drive spread, these models may break down under untested conditions, in particular under extreme fire conditions (Finney et al., 2013). For safety reasons, these extreme conditions cannot be tested during large experiments, such as prescribed burns, despite the fact that extreme fires (high winds, high fuel loads and low moisture contents) are responsible for the majority of devastating wildland and WUI fires. Models also seem to be unable to predict thresholds of fire spread, such as the initiation, acceleration or cessation of fire spread (Finney et al., 2010), which becomes significant when modeling potential effects of firebreaks. Spyphard et al. has indicated it would be useful to have a fire model which accurately determines effectiveness or size of needed fuel break, but such models are unavailable (Syphard et al., 2011a). Finney and co-workers have highlighted these and many other problems with current models (Finney et al., 2013) and recently implemented some work toward resolving these discrepancies (Finney et al., 2010; Finney et al., 2013; Gorham et al., 2014); however, until the results of this and other work are finished, current models should be used with the understanding that their results are not 100% accurate, but provide the best estimates of fire behavior available today. It is important to also remember that these models have been developed for steadily-spreading wildland fires, not for fires spreading through WUI communities. In WUI communities, there are various structures that contribute to the fuel load and may affect spread parameters, although investigation by NIST has indicated that rates of spread in the WUI are lower than in surrounding vegetative fuels (Maranghides et al., 2013).

Firebrands

Firebrands, also called burning embers, are now thought to be one of the primary sources of ignition in the wildland-urban interface. They present hazards because they can either directly ignite components of vulnerable structures or can ignite nearby vegetation and other combustibles which can subsequently ignite the structure via radiant heating or direct flame contact (Quarles, 2012). There does not appear to be a consensus on the percentage of ignitions caused by embers, primarily because it is difficult to determine after-the-fact what caused each individual home or structure to burn down during a fire. There are "hints" though in structures that burned down. IBHS suggests that the majority of buildings in WUI fires are ignited through embers (IBHS, 2014). In many fires, such as the Witch Creek and Guejito fires, firebrands are a major threat to homes; ignition from these firebrands may depend upon the conditions of the fire. Examples of clear ember ignition of homes during the Angora fire are shown in Figure 6 and Figure 7, where spot fires independent of the main fire front were observed to ignite a home and small vegetation fire, respectively. Later sections of the report will review specific vulnerabilities of structures to firebrand ignition, but existing knowledge on the generation, transport and physical mechanisms of transition to flaming will be reviewed here.

There are questions as to how much detailed knowledge of firebrand production, transport and ignition will assist future prevention efforts. Model building, perhaps statistically, is a prominent idea. In the end, worst-case scenarios must become the focus of all risk modeling efforts as the most extreme fires are the ones causing WUI problems. Characterizing this worst case firebrand flux—how far embers can travel and their likelihood of igniting different materials — is needed to inform these risk modeling efforts.

Firebrands by firebrands is most often a chance event, making it difficult to represent using traditional fire models. Still, a probabilistic approach to the problem is possible. Reviews by Babrauskas (Babrauskas, 2003), Koo (Koo et al., 2010) and Manzello (Manzello, 2014) should be referenced for further information beyond relevant details provided here.

Figure 6: A destroyed home following fire spread from the Angora fire. Note the intact, unburned vegetation surrounding the structure. Murphy et al. notes that this house was ignited by wind-blown firebrands, not by surface fire spread or radiant heating (Murphy et al., 2007).

Figure 7: A small spot fire produced by firebrands next to a burning house during the Angora Fire from (Murphy et al., 2007).

Firebrand Production

It is important to understand the size, distribution and flux of firebrands to burning buildings, in order to potentially help in the prediction of spotting or home ignition distances. In models of firebrand transport, there is often an assumption of the size and shape of burning brands, which might not be representative to the type of firebrands actually experienced/received.

Waterman was among the first to study firebrand generation, focusing on generation by burning roof constructions on complete homes (Waterman, 1969). Brands were collected via a screen trap and quenching pools under conditions which varied the wind and heights of buildings. The firebrands collected tended to primarily be disc-shaped, a shape later used in several studies of firebrand transport (Pagni, 1999).

Figure 8: Digital photographs showing samples of the firebrands collected as a function of tree size and moisture content. (left) Douglas-fir with tree height 5.2 m, moisture content 20%. From (Manzello et al., 2007). *(right) 4 m Korean Pine with moisture content 13%* (Manzello et al., 2009).

For vegetative fuels, laboratory tests have been performed to collect firebrands off 2.6 to 5.2 m tall Douglas-fir trees at NIST. The average firebrand size for the 2.6 m Douglas-fir trees was 3 mm in diameter and 40 mm in length. The average size for the 5.2 m tree was 4 mm in diameter with a length of 53 mm. Firebrands with masses up to 3.5 to 3.7 g were observed for the 5.2 m tall tree. The trees did not produce firebrands without wind if the moisture content was greater than 30%. All firebrands were cylindrical in shape and the surface area was directly related to the mass of the brands, as shown in Figure 8 (Manzello et al., 2007).

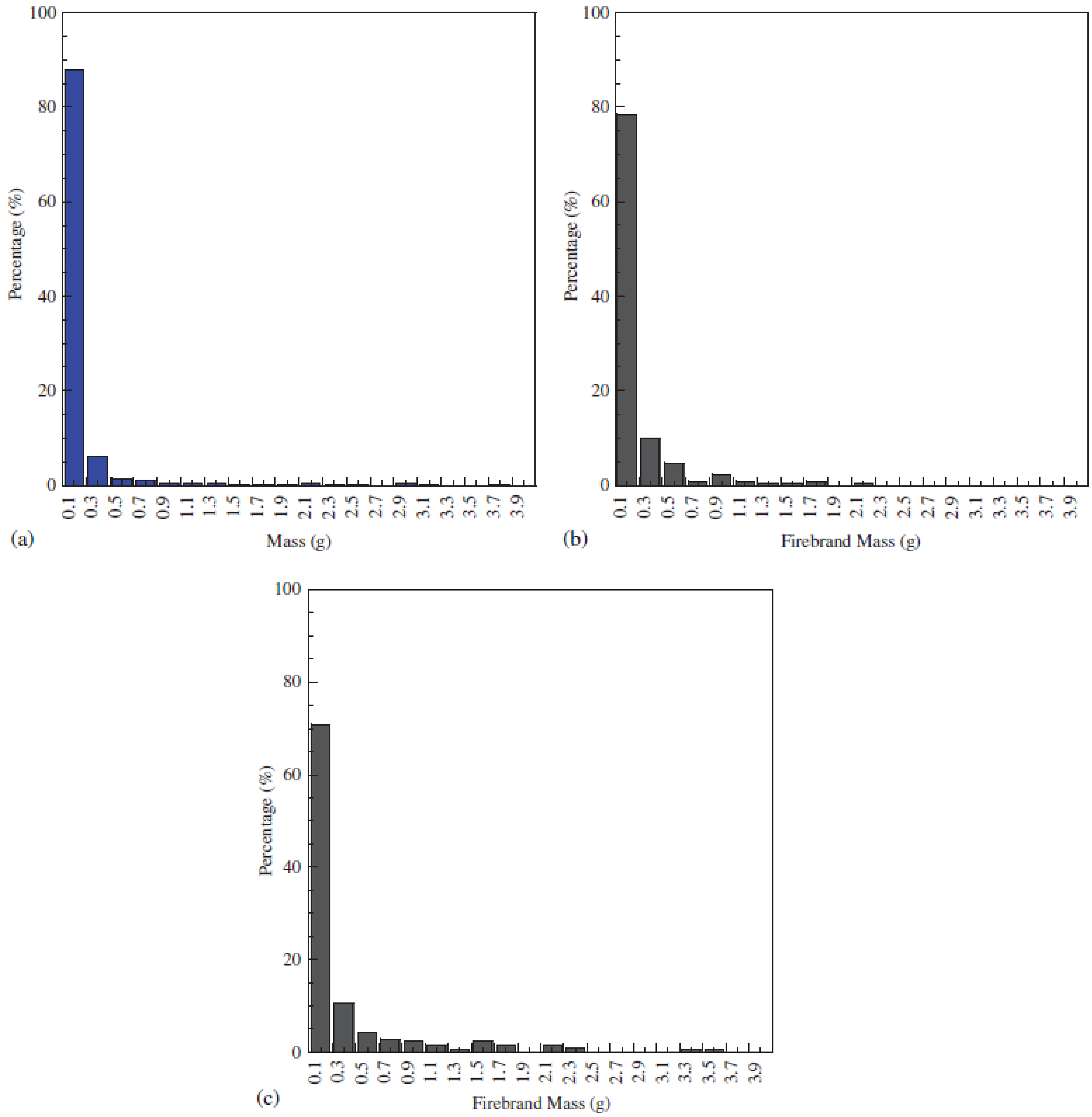

Figure 9: The mass distribution of collected firebrands from (a) 4 m tall Korean pine trees (Manzello et al., 2009) *and (b) 2.6 m tall Douglas-fir and (c) 5.2 m Douglas-fir trees from* (Manzello et al., 2007).

Later experiments performed by Manzello et al. (2009) at the Building Research Institute (BRI) in Japan investigated Korean Pine under varying wind and moisture conditionsTrees were all 4 m tall and moisture content was varied between 10 to 100% on a dry-mass basis. Collected firebrands were cylindrical in shape, similar to experiments on Douglas-fir (Manzello et al., 2007). The average firebrand size was 5 mm in diameter and 40 mm in length. A summary of the mass data collected is provided in Manzello et al. (2007) and Figure 9.

Experiments have been performed to measure the mass and size distribution of firebrands produced downwind from a burning structure as well. It is thought that structures may contribute firebrands of different mass and size distributions than burning vegetation. The earliest documented studies are by Vodvarka, who measured firebrand size and transport distances following five full-scale experimental building fires (Vodvarka, 1970, 1969). Similar to more recent studies, small firebrands dominated the distribution with 89% of the firebrands smaller than 0.23 cm^2. In two of the building fires, a majority of the firebrands deposited were located at a single location downstream, with one sheet used to measure the firebrand distribution receiving over 97% of all deposited brands.

Yoshioka et al. performed experiments in a large wind tunnel where a crib fire ignited a burning house and firebrands from the two fires were collected at the outlet of the wind tunnel in trays with and without water (Yoshioka et al., 2004). A later test was performed by Suzuki et al. (2012) on a controlled burn of a structure in California. They found that the majority of firebrands were produced from the structure during burning, not during application of water to the structure. In this test, 95% of the firebrands were collected about 18 m from the structure and 96% of those collected from about 4 m from the structure had less than a 10 cm^2 projected area[3]. The results from Suzuki et al. (2012) are compared to previous studies by Vodvarka (1970, 1969) and Yoshioka et al. (2004) in Figure 10.

[3] The results of Suzkuki et al. (2012) does not provide explicit description of the “hose stream” applied to the house during burning, however it appears from photographs in the article that straight stream was applied over the house so as to wet it but not directly impact the structure.

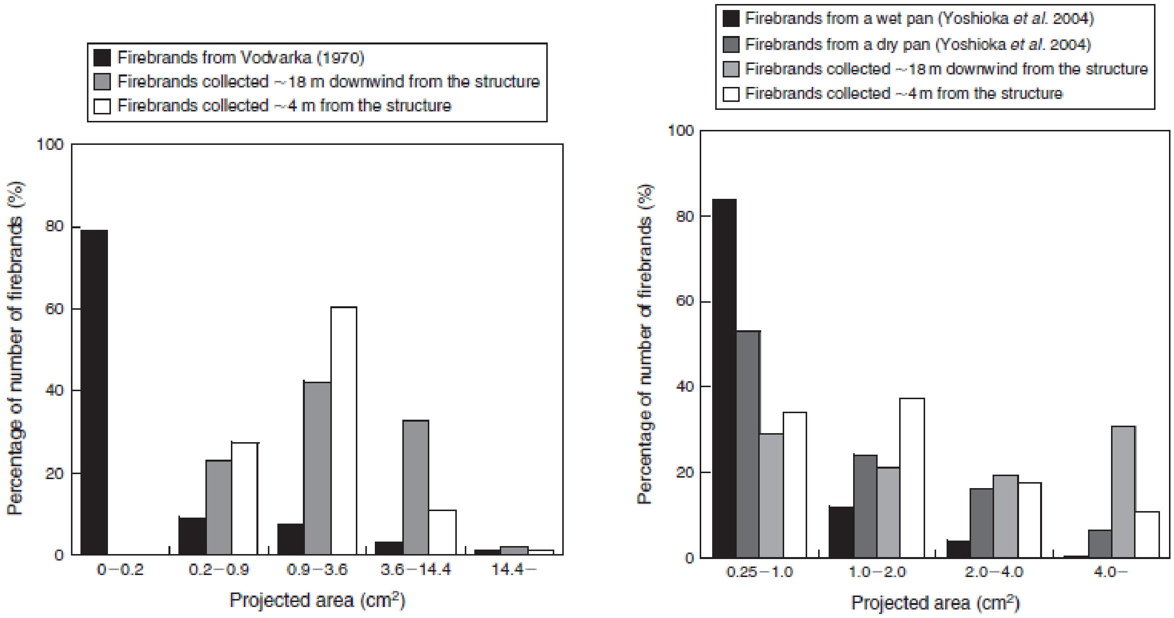

Figure 10: A comparison of the mass distributions of firebrands from (left) Vodvarka (Vodvarka, 1970) versus two collection distances from Suzuki et al. (Suzuki et al., 2012) and (right) mass distributions from Yoshioka et al. (Yoshioka et al., 2004) vs. two collection distances from Suzuki et al (Suzuki et al., 2012).

In a more recent study, Suzuki et al. burned full-scale structures at the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF) in Japan with a 6 m/s wind (Suzuki et al., 2014). More than 90% of the generated firebrands weighed less than 1 g and 56% weighed less than 0.1 g. The mass distribution was similar to previous studies; however, different firebrand collection strategies were shown to induce some small differences between this study and previous studies, as shown in Figure 12. The relationship between a firebrand's projected area and mass was also very well supported in this laboratory study (Figure 11), confirming previous observations form burning vegetation and structures. Another study by Suzuki et al. also tested the ability of isolated building sidings both perpendicular to imposed wind and in a re-entrant corner configuration to produce firebrands, developing mass distribution results very similar to full-scale structure experiments (Suzuki et al., 2013).

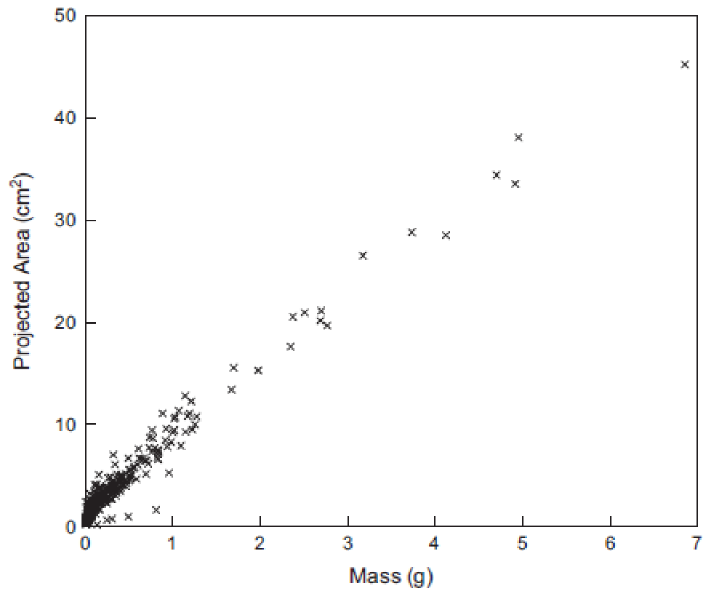

Figure 11: Correlation between the projected area of collected firebrands versus the mass of the brands under controlled laboratory conditions from a burning structure from (Suzuki et al., 2014).

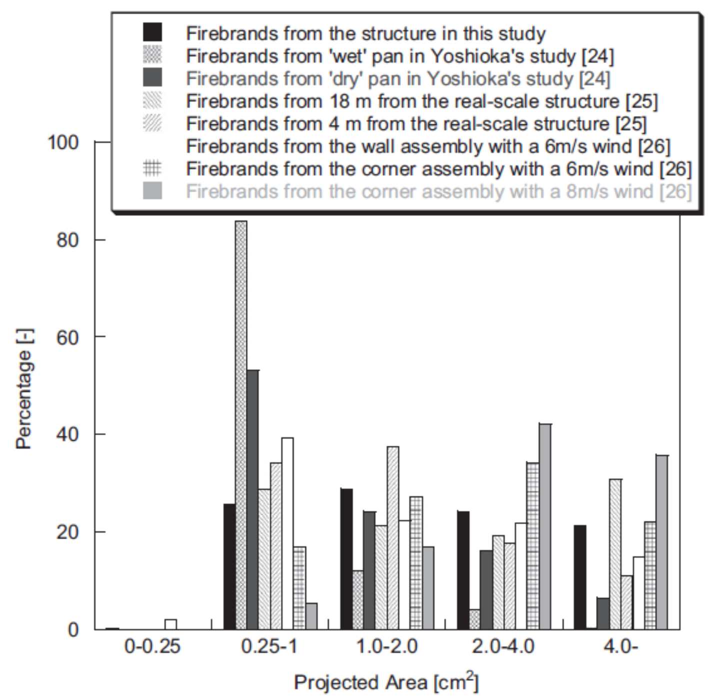

Figure 12: Firebrand size distributions from a structure in a well-controlled wind tunnel from (Suzuki et al., 2014) compared to previous studies by others (Suzuki et al., 2013, 2012; Yoshioka et al., 2004).

Foote et al. (2011) examined the size distribution of firebrands during the Angora Fire, a severe WUI fire in California in 2007 (Foote et al., 2011). Nearby fuel mostly consisted of White Fir and Jeffrey Pine with a heavy understory surface fuel loading[4]. Some shaded fuel breaks were present nearby collection locations. In the study, a trampoline, which was exposed to wind-driven firebrands during the fire, experienced melted “burn holes” from firebrands and served as a representative source for observation of firebrand size and density over an area throughout passage of the fire. The trampoline had an area of 1.5 m^2 with over 1800 burn holes analyzed by digital photographs. The largest hole in the trampoline had a 10.3 cm^2 burned area, while more than 85% of the burned areas were from firebrands less than 0.5 cm^2 and more than 95% were from firebrands with an area of less than 1.0 cm^2. In addition to the trampoline data, burn patterns were observed on building materials and plastic outdoor furniture at 212 individual locations on or near numerous Angora Fire buildings. A large majority of these firebrand indicators were less than 0.40 cm^2, with the largest being 2.02 cm^2.

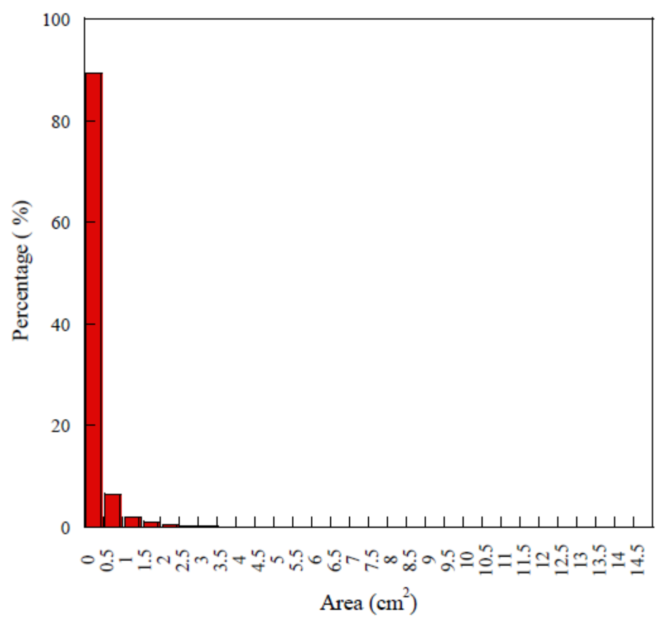

Figure 13: Distributions of the area burned measured from holes in a trampoline following the Angora fire from (Foote et al., 2011).

Limited data is available on the production of firebrands from structures within real wildland fires. Firebrands were observed coming off of a test structure during experiments by NIST and the USFS at a prescribed burn in the New Jersey Pine Barrens, but no quantitative measurements were made (they were observed to be produced via video) (Manzello et al., 2010b). Future tests

[4] See Murphy et al. (2007) for more information on fuel loading.

in the Pine Barrens by groups at the USFS and the University of Edinburgh are ongoing and should be released in the future, but have not been made publicly available yet (Simeoni et al., 2014).

The NIST Firebrand Generator (NIST Dragon) has been instrumental in the testing of many building components, as it is able to continuously produce constant size distributions of wind-driven firebrand showers consistent with previous studies reviewed above (Manzello and Foote, 2014; Manzello et al., 2009; Manzello et al., 2007). The majority of firebrands produced in the apparatus are less than 0.5 cm^2, in close correlation to results from vegetative and building firebrand studies (Manzello and Foote, 2014; Manzello et al., 2009; Manzello et al., 2007). The NIST firebrand generator has been used in Japan at the BRI FRWTF, where experiments can be performed with wind speeds up to 10 m/s in a wind tunnel with a cross section of 4 m by 5 m and a test section length of 15 m (Manzello, 2014). Versions of this apparatus have been produced at IBHS, Underwriters Laboratories (UL) in the United States and at Association for the Development of Industrial Aerodynamic (ADAI) in Portugal.

Figure 14: A typical experiment with the NIST Dragon in BRI's FRWTF (Manzello, 2014).

In Richburg, SC, the IBHS research center uses a larger-scale, modified version of the apparatus. Mulch burning equipment creates firebrands similar to the NIST Dragon but significantly scaled up in size. The combination of the large scale, higher winds and the ability to rotate a building during testing make the facility unique in its ability to represent the characteristics of natural winds and firebrands occurring during wildfire conditions. The firebrand generating equipment developed for the IBHS Research Center has been used in several tests which will be presented within this report (IBHS, 2014).

Figure 15: Ember storm produced in the IBHS research facility (IBHS, 2014).

Firebrand Transport

A large body of work is available in the literature on firebrand transport. While it is well known that brands can be transported some distance and ignite new spot fires or structures in WUI communities, it can be surprising just how far these brands can transport. In a NIST report on a community outside San Diego affected by the 2007 Witch Creek and Guejito, firebrands were found to arrive one hour before the flame front, traveling up to 9 km (Maranghides et al., 2013). These firebrands subsequently ignited properties over the following 9 hours.

Tarifa et al. were among the first to study burning brands of woody fuels, examining their burning properties, flight paths, and lifetimes through an innovative wind-tunnel apparatus

(Tarifa et al., 1965b). They studied cylindrical and spherical samples of pine, oak, aspen, spruce, and balsa wood with initial spherical diameters ranging from 10 to 50 mm, and initial cylindrical dimensions ranging from 6 to 15 mm and 18 to 36 mm in diameter and length, respectively. Wind was used as a variable from 0 to 40 m/s, and it was found that brands did not drastically change their shape during burning, nor did moisture content of the brand exert much influence on the brand flight path (Tarifa et al., 1965b).

A variety of models for firebrand transport were later developed based on Albini's 1979 model for the distance a spot fire could ignite from a single burning tree (Albini, 1979). Albini's predictive model calculated the maximum spot fire distance when firebrands are lofted by the burning of tree crowns. Variables included were the quantity and surface/volume ratio of foliage in the burning tree(s), height of the tree(s), the wind field that transports the firebrands, and the firebrand burning rate. No validation data is available; however, later work (Albini, 1983, 1981, 1983; Chase, 1981; Morris, 1987) has incorporated Albini's model into multiple numerical simulations, including FarSITE (Finney, 2004) and HIGRAD/FIRETEC (Koo et al., 2012).

Pagni and Woycheese (2000) significantly expanded on Tarifa's work to develop several models of brand propagation, lofting and burning. Information was found through a series of tests and by utilizing brand momentum conservation with spherical wooden, artificial brands lofted above a symmetric pool fire in a constant horizontal wind. Variations to these conditions were not considered. The dimensionless regression rate of brands depends inversely on both the dimensionless burning parameter and the dimensionless diameter. It was found that the diameter decreases faster in larger brands than the smaller diameter brands. It was also found that for sufficiently large brands, the acceleration during lofting was dominated by the drag and gravity (Woycheese, 1999).

Pagni and Woycheese also expanded their work to study combustion of brands of spherical, cylindrical and disk shapes (Pagni and Woycheese, 2000). Their experiments identified two stages to combustion of brands: flaming combustion and surface (glowing) combustion. It was found that denser wood samples (oak and Douglas-fir) produced flaming combustion for a longer duration than other fuels, but were less likely to transition to glowing surface combustion. Complete combustion of any brand rarely occurred without significant, persistent surface combustion on the upwind face of the brand. Wood with a lower density, such as cedar and balsa wood, more readily transitioned from flaming to surface glowing combustion, with flaming combustion ending relatively early in the brand’s lifetime. Also noted throughout the examination of the results is the effect of the wood grain orientation; they found that an end grain faced the end velocity vector (Pagni and Woycheese, 2000).

Pagni later reviewed eight combustion models for burning brands, including an averaged stagnation-point burning model via the use of wood's chemical properties (Pagni, 1999). A Baum and McCaffrey model (Baum and McCaffrey, 1989) was used for the plume and a constant horizontal velocity, driving downwind propagation was approximated. Pagni and Woycheese then applied their own combustion model to determine the maximum propagation distance for disk-shaped brands, which they found to be most common in their studies. Analytic equations for brand thickness and propagation height lofted from large, single fire plumes were determined as a function of time for different heat release rates, wind speeds, and brand properties (Woycheese et al., 1999; Woycheese, 1999). Using their model, they found that brands released from greater heights will typically be smaller in size and thus completely combust in air, whereas brands released from lower elevations will typically be larger, but will result in shorter propagation distances (Pagni, 1999).

Other models, such as those by Wang, have integrated previous models and observations for brand production, lofting and ignition into a statistical form which can be used when modeling (Wang, 2009). Baum and Atreya also recently developed a new model for firebrand combustion, used to determine the duration of burning and thus the ultimate transport distance during lofting. They considered several different shapes and determined an analytical solution for quasi-steady burning (Baum and Atreya, 2014).

Numerical studies of the distribution of firebrands from burning line fires (Sardoy et al., 2008) and burning trees (Sardoy et al., 2007) have also been performed. In the numerical study of line fires, several correlations for the distribution of firebrands were found based upon firebrand initial conditions and the wind. There was also a dual distribution of embers found, with most embers falling close to the fire still in a state of flaming combustion and those further away in a glowing state of combustion. Nondimensional correlations for these distances are presented in both works.

Firebrand Ignition of Fuel

Many variables contribute to the process of target fuel ignition, including the physical dimensions of the firebrand, properties of the material and ambient weather conditions, making firebrand ignition one of the most difficult aspects of the recipient fuel ignition process to describe (Babrauskas, 2003; Pagni, 1999b). Depending on these variables, an ignited recipient fuel may start glowing combustion and then die out, just smolder or transition from smoldering to flaming and grow into a larger fire. Understanding the effects of each of the above variables on the ignition process is important in order to develop a physical model for firebrand ignition.

Because most firebrands cease flaming combustion before landing on recipient fuels (Manzello et al., 2006a; Tarifa et al., 1965), they often land in a state of smoldering combustion (sustained glowing combustion). Modeling, therefore, must incorporate a hot object landing with some initial thermal inertia onto a bed of flammable material. As firebrands are often still smoldering upon landing, they continue to generate heat through chemical reactions while resting on the recipient fuel surface. It has been suggested that the summation of energy stored in a brand (including stored heat or both stored heat and chemical energy for a smoldering brand) is a possible means of correlating and/or modeling the phenomena of ignition (Stokes, 1990). Recent work with heated particles (Hadden et al., 2010) though has found a poor correlation between particle thermal energy (joules) and time to ignition. A possible approach to modeling the problem is that of a "hot spot" ignition theory such as that proposed by Gol'dshleger et al. (Gol'dshleger et al., 1973; Thomas, 1964). This theory neglects the energy of the fuel particle but takes into account a 1-step Arrhenius reaction of the recipient fuel. This approach may be useful because it can take into account the different sizes of heated particles. Qualitative agreement between this approach and ignition of a cellulose-powder fuel bed by hot particles has been achieved (Hadden et al., 2010), illustrating the connection between spherical particle diameters and ignition, not thermal energy. The theory has some limitations, as it does not take into account ongoing reactions in firebrands, the moisture content of fuels, radiative feedback, external radiation, etc., and the theory is still quantitatively different from experimental observations. Continued improvement of theories is ongoing, and includes ideas such as taking into account different thermal properties of materials into Gol'dshleger's original theory (Jones, 1995).

Viegas et al. (2012) has also studied firebrand ignition of fuel beds of varying vegetative materials under different moisture contents with no wind. The results of this study showed that fuel bed properties were more influential in the ignition process than brand characteristics. Spot fires are typically divided into three phases: formations, propagation and ignition; however, Viegas et al. divided them into five different phases : firebrand release, transport of firebrand by fire plume and ambient winds, firebrand combustion, firebrands landing in a fuel bed, and consequent ignition of a new fuel bed. Ignition was much more likely in a fuel bed that received a glowing firebrand with airflow, confirming results from previous studies. Manzello et al. (2006b) has also performed significant work producing realistic firebrands and firebrand showers and using them to ignite fuel beds and building components. One significant insight from this work is that multiple firebrands must contact a fuel source (mulch or building component) for ignition to occur, as no single glowing fire brands could ignite most tested fuel beds.

Weir looked at data from several prescribed fires performed in Oklahoma to observe the probability of spotting downwind of the main fire front as a function of moisture content (Weir, 2004) and found a strong correlation (Figure 16). Whether this threshold has anything to do with ignition on materials in a home is unknown, but maintaining a high moisture content on any vegetation nearby a home will ensure it is less likely to ignite.

Manzello et al. (2009) also performed experiments on common building materials to determine the range of conditions under which glowing firebrands might ignite these materials. Materials tested included oriented strand board (OSB) and plywood, which were oriented in a v-shaped pattern at varying angles to determine how angle, wind speed and number of firebrands would influence the material's contact with glowing firebrands and its subsequent ignition. It was found that single firebrands were unable to ignite the materials used, even after applying various airflows; however, multiple firebrands were able to ignite some materials. It was concluded that the critical angle of interest for ignition was between 60° and 135° for any tested airflow. No ignitions were found below 1.3 m/s for any conditions, signaling that the combined effect of a mass of glowing firebrands and sufficient incident wind are necessary for ignition.

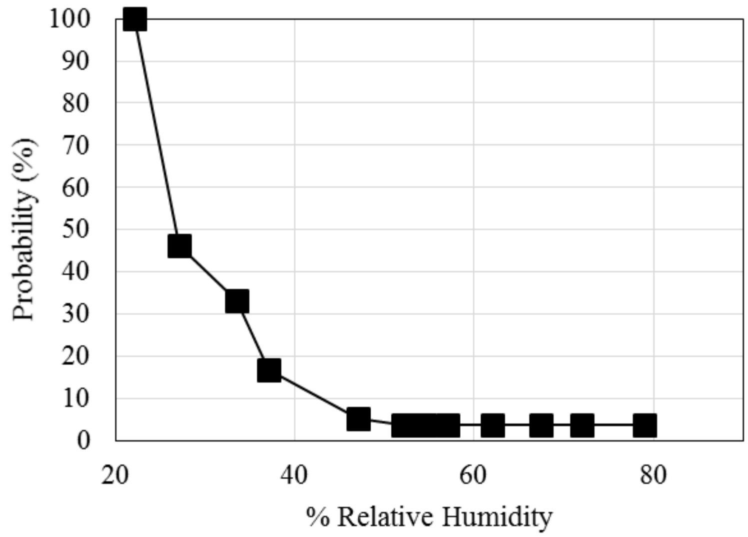

Figure 16: The probability of spot fires as a function of relative humidity, based on 99 prescribed fires conducted across Oklahoma from 1996 to 2002 (Weir, 2004).

Large-scale testing of ignition of building features by firebrand showers has been conducted at the IBHS Research Center (Quarles, 2012; IBHS, 2014). Tests have looked at ignition characteristics of roof gutters, debris on the roof, bark mulch, vegetation on the ground., siding, etc.

RESPONSE OF COMPONENTS AND SYSTEMS

As a structure in the WUI is exposed to radiation, flame contact and firebrands, specific components on the structure will first smolder, then ignite. This section reviews many different components found to be vulnerable to these exposure conditions. This breakdown follows the framework suggested by NIST (Maranghides and Mell, 2013), where information available in each area is reviewed below and reference to quantifiable information for risk-informed planning cited.

Roofing

Flammable roofing on WUI-exposed structures, especially wooden shingles, has been found in several studies to be the most susceptible building component to firebrand attack and ultimately the single most effective predictor of a home burning down. In a study of the 1990 Santa Barbara Paint Fire, 70% of houses with nonflammable roofs survived, while only 19% of houses with flammable roofs survived (Foote, 1994). Later, in an investigation of the 2007 Witch Creek and Guejito fires, it was found that all houses with wood shake roofs were destroyed while only 33% of structures with an approved roof type (Class A) were destroyed or damaged (Maranghides et al., 2013). Of roofs with exposed Spanish tile, 24% were destroyed (Figure 17). In an investigation of the 2012 Waldo Canyon fire it was also found that wood shake roofs and other roof designs that were vulnerable to firebrand accumulation greatly enhanced the chance of home destruction (Quarles et al., 2012).

Fire ratings of roofs are typically governed by the American Society for Testing and Materials (ASTM) Standard E-108 (ASTM, 2011), Underwriters Laboratory (UL) Standard 790 (UL, 2014) and the National Fire Protection Association (NFPA) Standard 276 (NFPA, 2011). These tests are essentially the same test and are designed to evaluate three fire-related characteristics of a roof assembly: its ability to resist the spread of fire into the attic, resist flame spread onto the roof covering, and finally to resist generating burning firebrands. Roofs are ranked into three classes, Class A, B and C, where Class A is considered effective against severe fire testing exposures. Tests include an air flow over an inclined roof which is subjected both to flames and burning “brands”, a wood crib made of Douglas-fir sticks[5]. If flames resulting from the burning “brands” penetrate the roofing assembly, the sample has “failed” the test and will not gain a Class A rating. Codes such as Chapter 7A of the California Building Code require a Class A rated roof in very high fire severity zones[6] (CBC, 2009).

	Sample Population	Destroyed Structures Wood Shake Roofs	Destroyed Structures Spanish Tile Roofs	Typical Comparisons	
Typical (only destroyed homes)	74	12	37	**16% of destroyed** homes had wood shake roofs	**50% of destroyed** homes has Spanish tile roofs
Complete (all structures within fire line)	242	12	154		
Technically Valid Comparisons		**100% of exposed** wood shake roofs destroyed	**24% of exposed** Spanish tile roofs destroyed		

Figure 17: Comparison of influence of roofing material on destruction of structure following the Wttch and Gueijto fires (Maranghides et al., 2013).

Although the current standards include a test of roofing decks exposed to firebrands, it is argued that placing a wood crib on top of the assembly with an applied airflow does not correctly simulate the dynamic process of numerous firebrands landing under roofing tiles or gaps (Manzello, 2014). Embers generated by the “brand” are blown off the roof and therefore do not serve as a realistic simulation of firebrand attack because they cannot accumulate. Recent full-scale research performed at the IBHS Research Center showed ignition to occur both in the field of the roof (i.e., away from the roof edge or roof to wall intersection) for untreated wood shake roofs and at the roof-to-siding intersection via wind-blown firebrand ignition of accumulated

[5] Note that Class C brands are made from non-resinous white pine.

[6] Note that the California Building Code, Chapter 7A defers to Chapter 15 of the International Building Code for fire rating requirements.

vegetative debris, even when roofs were properly rated[7] (Quarles, 2012).Tile roofing assemblies have also been found to be vulnerable to firebrand attack (Manzello et al., 2010a). Experiments by Manzello et al. were performed using the NIST Firebrand Generator (6 minute duration) in a wind tunnel with a constant velocity of 9 m/s. Tiles were installed with and without tar paper (to simulate "weathering" or other worst-case damage that may occur over time, e.g degradation of the tar paper layer), with and without bird stops, and finally perfectly aligned and slightly off-aligned to simulate gaps that may form with aged roofs. When bird stops were not installed at the base of tiles without tar paper, firebrands collected within the exposed space, first smoldering and finally transitioning to flaming ignition through the oriented strand board (OSB), which could eventually involve a structure (Manzello et al., 2010a). Some smoldering ignitions as a result of firebrand penetration between the tile and bird stops were also found when bird stops were properly installed, but none transitioned to flaming. The presence of needles and dead leaves placed in gaps when bird stops were not installed enhanced the ignitability of roof assemblies with tiles so that all configurations tested transitioned to flaming under firebrand exposure.

Manzello (2013) later extended these roofing studies by investigating the response of concrete and terracotta tiled roof assemblies to wind-driven firebrand showers with an average mass flux of 10 g/m^2s under a 9 m/s constant wind. It was found that concrete tile roofing assemblies (both flat and profiled), as well as terracotta tile (flat and profiled), could allow firebrand penetration through the tile assembly and melting of the underlayment or sarking (sheathing material in the form of a layer of aluminum foil laminate bonded with a fire retardant adhesive to a polymer fabric). The flat tile terracotta roofing assembly performed best, most likely due to its interlocking design. Firebrands were observed to become trapped within the interlocking sections of the tiles and, as a result, the firebrands did not penetrate past the tiles towards the sarking material. Manzello (2013) indicated a potential cost-effective mitigation strategy would be to use a continuous underlayment of firebrand-resistant sarking. The effect of roof slope angle on ignition under wind-driven firebrand attack was also studied by Manzello et al. (2012a). They

[7] Specifically, a Class A fire rated asphalt fiberglass composition shingle roof covering (Quarles, 2012). Note that a smoldering front penetrated through the untreated wood shingle assembly to potentially ignite the attic, but not fully through the Class A rated asphalt composition (fiberglass roof covering).

studied angled crevices made of asphalt shingle roofing assemblies (oriented strand board (OSB), tar paper and asphalt shingles) and OSB alone, which might be exposed if other layers are removed through weathering or damage[8]. Firebrands were able to ignite the inclined samples with only OSB exposed with flaming ignition at a 60° crevice inclination and with smoldering ignition at 90°. As the angle was increased to 135°, ignition no longer occurred. For asphalt shingle roofing assemblies firebrands were seen to accumulate at the seams of shingles, at 60° and 90°; however, they only melted some of the roofing shingles and did not ignite the roof (Manzello et al., 2012a).

Some building codes require wooden roof shingles to be pressure-impregnated with fire retardants to pass test standards, however wood exposed to the elements will weather extensively and may affect fire performance. Several studies on the effectiveness of fire retardants after significant weathering have been conducted by the Forest Products Laboratory (FPL) in Madison, Wisconsin. The first set of studies by Holmes (1971) evaluated various fire retardant treatment systems for western red cedar wood shingles and shakes for their fire performance and durability. An 8-foot tunnel test (ASTM E286-69), a modified Schlyter Test simulating vertical flame spread (Holmes 1973) and a modified class C burning-brand test ASTM E-108-58) were used. Accelerated weathering was simulated with a 28-day exposure with daily water spray and natural rainfall totaling 30 inches, followed by sunlamp radiation at 150°F (65°C). They were then re-tested with the Schlyter and burning brand methods. Four vacuum-pressure impregnations were seen to be viable as Class-C rated woods (ASTM E-108-58). A fire retardant paint was also somewhat successful, but failed the Schlyter test indicating it was lacking in resistance to flaming ignition[9].

Studies were then continued and updated at 2 and 5-years of outdoor exposure Holmes and Knispel (1981) and finally after 10 years of exposure (LeVan and Holmes, 1986). After ten years of exposure, the authors found that, of all treatments evaluated, the commercial treatment NCX (a commercial formulation by Koppers) performed best in fire tests. UDPF (urea-dicyandiamide-formaldehyde-phosphoric acid) and DP (dicyandiamide-phosphoric acid) performed well in the

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[8] However removal of these layers would result in significant leakage that may be observable.

[9] Note CBC Chapter 7A specifically includes coatings, such as this.

burning brand test after exposure, but unacceptably in the modified Schlyter flame spread test. They also correlated the accelerated weathering test of 1,000 hours of light coupled with daily water spray to approximately 2 years of outdoor exposure. Even though the equivalent of 34 years of average rainfall were applied, there was probably not enough UV light exposure. Photodegredation by UV light, resulting in erosion of wood fibers and associated fire retardant chemical and biological degradation was thought to be just as important in maintaining retardancy in treated shingles. Copious amounts of water-repellant re-sealers provided some promise in extended leach resistance, however they would have to be applied periodically and no general results were presented.

Based on past research, untreated wood shakes and shingles are known to be readily ignited by firebrands and pose a significant threat, however some pressure impregnated wood shakes and shingles have a higher fire resistance (LeVan and Holmes, 1986). Still, their rating of Class B or C fire resistance (ASTM E108) rather than Class A remains a worrying factor in their use. Some tests described above have demonstrated the potential for Class-A rated roofs populated with typical debris (pine needles, etc.) to achieve smoldering ignition[10] under wind-driven firebrand attack, therefore without further research indicating pressure-treated wood's ability to resist ignition by firebrands our opinion is that they should not be used on vulnerable buildings. Whether this applies to wood products other than shingles, such as those used on fences or decks is not known either.

More recent research on wood fire retardants by Marney et al. (2008) have incorporated wood fire retardants with wood preservatives that, when tested under a radiant cone heater (cone calorimeter) reduced the rate of fire growth (heat-release rate) by 40%. Its effectiveness after weathering or firebrand exposure was not tested. Marney and Russell (2008) also reviewed the literature on impregnation of wood with chemical systems for resistance to both fire and degradation for outdoor uses. They found that typically boron-based compounds are still used. The review highlighted a lack of consistency in terms of fire performance and wood preservation

[10] Although during limited testing, smoldering ignition was observed only on flammable members of the assembly, not penetrating into the attic area.

testing. The recommend a more uniform approach using the same fire and preservative testing regime between different studies.

Gutters

Gutters can be significant sources of ignition of a home, primarily because debris collected in the gutter can be ignited by firebrands. Pine litter collected in gutters was found to be a significant cause of ignitions in the Grass Valley Fire near Lake Arrowhead, California (Cohen and Stratton, 2008).

Flat roofing assemblies were tested with a polyvinyl chloride (PVC) gutter attached to the front (Manzello et al., 2008). When flammable materials, such as pine needles, were placed in the gutter, the firebrands deposited in the gutter produced smoldering ignition which transitioned into flaming. The asphalt shingles then melted but did not fully ignite under the conditions tested.

Figure 18: Ignition of pine needles in a gutter after transitioning to flame spread from (Manzello et al., 2008). *This fire did not actually ignite the roof assembly, but there is potential for ignition of the roof assembly depending on the gutter, roof and flammable material inside the gutter.*

IBHS also performed tests on full single-story homes with gutters and observed ignition of gutters with flammable materials such as pine needles and other litter inside. When the debris in a vinyl gutter caught on fire, the gutters disconnected from the house and fell to the ground (IBHS, 2013). In similar tests with a gutter made of metal, the debris can catch the house on fire[11]. Despite potential concerns with metal gutters, vinyl gutters are not necessarily recommended because the roof could still ignite or the falling gutter could ignite debris on the ground which could later ignite the siding of the home. In general, there is a significant body of literature recommending removal of fuels from gutters but very little detailing quantifiable risks.

Mulch and Debris

Mulch, such as bark and rubber, woody vegetation, wood piles and other flammable debris are not recommended to be stored or allowed to accumulate near a structure as a measure to minimize the chance of ignition from subsequent radiant heat and flame exposure (Quarles et al., 2012). Several experimental tests have been performed on mulch and other dead vegetative debris that may be located near homes. Tests performed at the IBHS Research Center (IBHS, 2014), demonstrated that flammable debris on the ground ignited and caused rapid upward flame spread on the side of the house (Quarles, 2012). More fundamental work that quantifies ignition of debris and fuel beds in terms of moisture content and other variables in a statistical form (reviewed under the Firebrands Section) may be useful in risk assessment methodologies (Zak et al., 2014).

Manzello et al. (2006b) performed experiments on several mulches including shredded hardwood and pine straw, both commonly used in the USA, as well as dried cut grass. During experiments, smoldering or flaming ignition were not observed in any of the fuel beds with only one single *glowing* firebrand. With flaming firebrands, all fuel beds were observed to achieve either glowing or flaming ignition with the exception of shredded hardwood mulch fuel beds held at 11% moisture content. Multiple glowing firebrands were also unable to ignite cut grass fuel beds and shredded hardwood mulch fuel beds held at 11% moisture content. Under the mass flux of embers used, the ability for fuel beds to ignite was increased when multiple glowing or flaming

[11] In these tests, the metal gutter remains in place, so that direct flame contact to the fascia and roof sheathing occurs (IBHS, 2013).

firebrands were introduced, thereby stressing the importance of understanding the flux of firebrands.

Steward (2003) performed experiments on 13 different mulches to measure their relative ease of ignition. Plots were left to sit for 2 weeks before a lit cigarette, match or propane torch was placed on the bed, and monitored for 20 minutes to see if it ignited. Ignition was found in the tests to be a variable process, with ground, recycled pallets and composted yard waste igniting every time when ignited by cigarettes, shredded pine park 3 out of 4 times, oat straw and shredded cypress bark 2 out of 4 times, pine bark nuggets once during tests and decorative ground rubber, pine straw needles, shredded hardwood bark, cocoa shells, bluegrass sod and brick chips never igniting. When igniting with a torch, all mulches eventually ignited, but with ground rubber and pine needles igniting significantly faster than other mulches. The results, unfortunately did not include further quantitative measures on the flammability of these mulches or their behavior under different environmental conditions.

Quarles and Smith (2004) measured some relative flammability properties for 8 mulches in 8 foot (2.5 m) diameter plots. Mulches were exposed to over two and a half months of hot, dry weather exposure in Nevada, presenting normal conditions for Nevada. They were burned under fan-produced winds of 10-15 miles per hour (4.5 - 6.7 m/s) and the resulting flame height, rate of spread across the bed and temperatures above the bed were measured. With the exception of the composted wood chips, all of the mulch demonstrated active flaming combustion. The composted wood chips[12] produced only incidental flaming with smoldering as the primary form of combustion. It is not known if the performance of the composted wood chips was specific to the brand and type purchased for their project, or if composted wood chips from other sources would perform in a similar manner.

Based on the three combustion characteristics measured, shredded rubber, pine needles and shredded western red cedar demonstrated the most hazardous fire behavior. The least hazardous fire behavior was observed for composted wood chips and a single layer of Tahoe chips. The shredded rubber mulch produced the highest temperatures above the bed and greatest flame

[12]Which had a relatively high ask content compared to other materials.

heights for a prolonged period, with pine needles representing the second most-hazardous mulch material based on combustion characteristics. A summary of results for the 8 mulches tested is shown in Figure 19, where relative values of combustion characteristics were determined by normalizing the shown quantities by the highest value in each category. It's important to note these experiments were repeated three times for each bed, producing useful relative information but not quantitative results capable of being applied to WUI risk modeling.

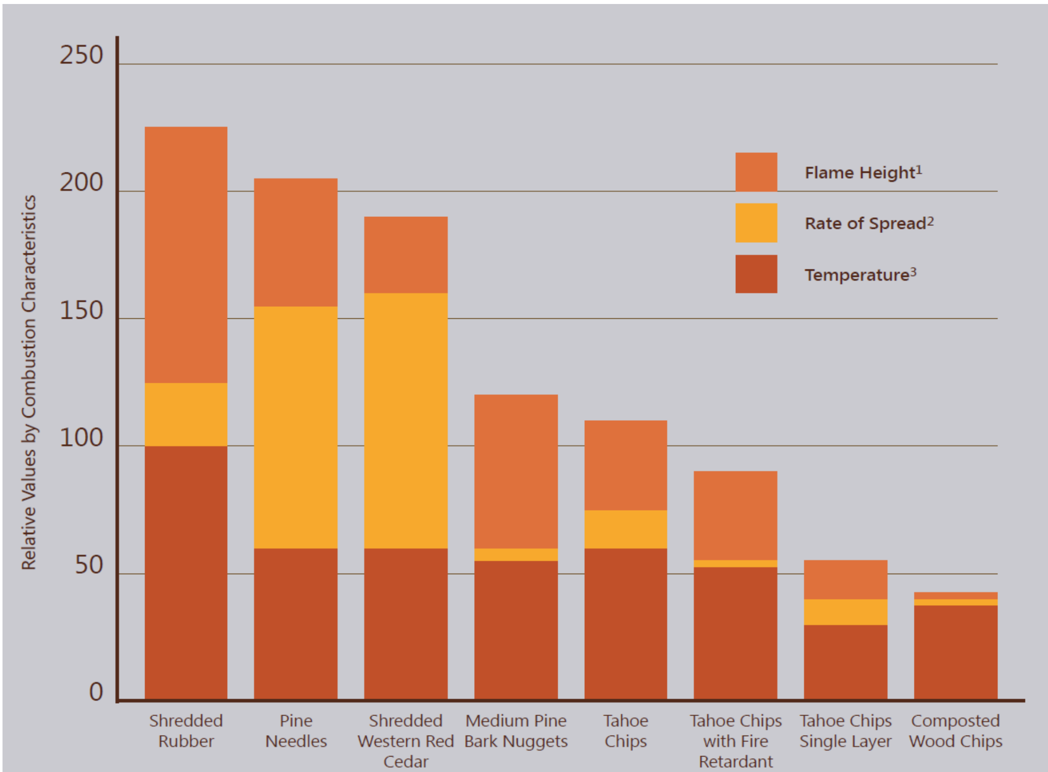

Figure 19: The relative flammability of dried mulches tested in Quarles and Smith (2004). Flame height, rate of spread and temperature shown for each mulch sample are normalized based upon the maximum value measured.

Manzello et al. (2014) performed later experiments exposing shredded hardwood mulch beds with a moisture content of 0 – 25% to continuous firebrand showers using the NIST Dragon apparatus. The mulch was placed at the base of a re-entrant corner, thought to be a worst-case scenario due to a stagnation region, which contributed to a significant accumulation of firebrands, and the fact that a corner fire represents the most rapid rate of fire growth upon ignition (Drysdale, 2011). The mulch was shown to quickly achieve smoldering ignition and later transition to flaming under both 6 and 8 m/s conditions. Full results of the experiments are not available yet; however, design guidelines espousing all flammable materials staying at least 5 feet away from structures appears to be a clear safety decision (IBHS, 2013). Several other experiments are detailed in the Sidings, Windows and Glazing section below, all of which demonstrate easy ignition of building siding from very little impetus on the side of structures. Therefore it is vital to keep the fuel load directly next to structures (typically espoused to be ~5 ft) free of all flammable materials.

Figure 20: Mulch bed tests from Beyler et al. (2012) showing ¼, ½ and full-size Class C brand ignition sources from the ASTM E-108 test.

Recently a test protocol has been proposed to more quantitatively evaluate ignition and flame spread of different mulch beds (Beyler et al., 2014). This test method was based on the ASTM E-108 test "brand" (essentially a wood crib) which was used to test its ability to ignite a 0.6 m square mulch bed (ASTM, 2011). Characteristics such as mulch depth, moisture conditioning, bed dimensions, ignition properties, slope and wind speed were varied during development to provide a test protocol that is capable of ranking different mulches flammability properties.

While the test is able to evaluate one mulch vs. another quantitatively, it does not intend to provide worst-case conditions.

Eaves and Vents

Eaves and vents have been recognized to be significant sources of ignition for homes in the WUI. Vents provide an opening through which burning brands may penetrate the interior of a structure, often the attics. Most homes have these vents both for thermal efficiency and to minimize the chance of moisture buildup, shown schematically in Figure 21. Meshes used on these vents were traditionally designed to stop entry of rodents, etc. into attic and crawl spaces; therefore considerations of vent size for wildland fire is a recent addition.

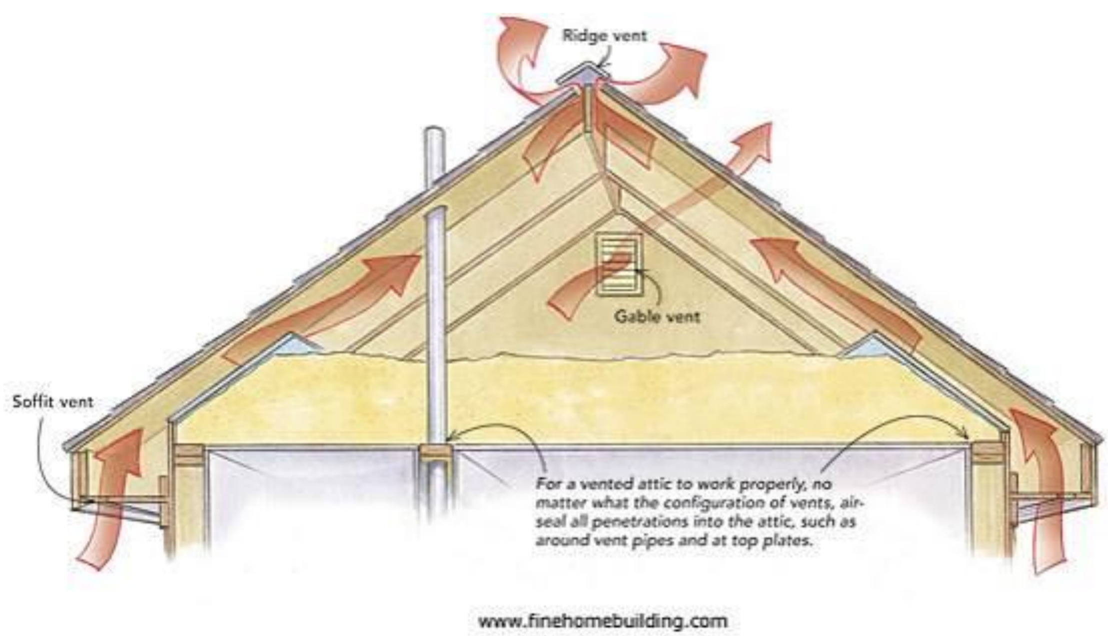

Figure 21: A schematic of vents used to ventilate an attic space from www.finehombuilding.com. It is common to have at least one outlet vent type, for example gable, ridge or soffit.

As shown in Figure 21, three types of vents are typically used for household attic spaces: a soffit vent placed under an eave, gable vents on the exterior wall of a house or ridge vents placed at the top of a roof. The 2007 California Building Code of Regulations, Title 24, Part 2, Chapter 7A first required building vents have a metal mesh of 6 mm placed on all vents to mitigate firebrand penetration (CBC, 2009). Because these regulations were not based on any testing, Manzello et al. (2012a) used the firebrand generator to test the effectiveness of different gable vent opening mesh sizes.

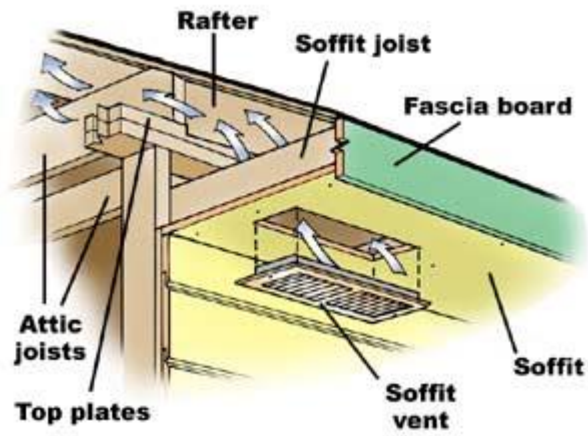

Figure 22: Illustration of a soffit vent and airflow pattern to ventilate an attic space (http://www.cornerhardware.com/howto/ht076.html).

Initial testing was performed on gable vents with mesh sizes of 6, 3 and 1.5 mm. The results of the tests showed that firebrands were not quenched by the presence of the mesh, but rather would continue to burn until small enough to pass through the mesh. All mesh sizes tested resulted in ignition of shredded paper behind the vent; however, larger mesh sizes (6 mm) ignited the paper more quickly.

Later investigations on six mesh sizes (5.72 mm to 1.04 mm), as well as using three different types of ignitable materials (shredded paper, cotton and wood crevices) inside the structure, were used to generate a database of firebrand behavior through a simulated gable vent (Manzello et al., 2012a).

These tests confirmed the fact that firebrands were not quenched by the presence of the mesh and would continue to burn until they were small enough to pass through the mesh, even with an opening as small as 1.04 mm. Reduced mesh sizes were observed to reduce the ignition potential in some configurations, such as small wood crevices, perhaps because the thermal inertia of the smaller brands was reduced, making it harder to ignite denser material, as illustrated in Figure 23. It presented the penetration ratio, defined as the number of firebrands, leaving the mesh over the number of firebrands arriving at the mesh during the sample period (Manzello et al., 2011).

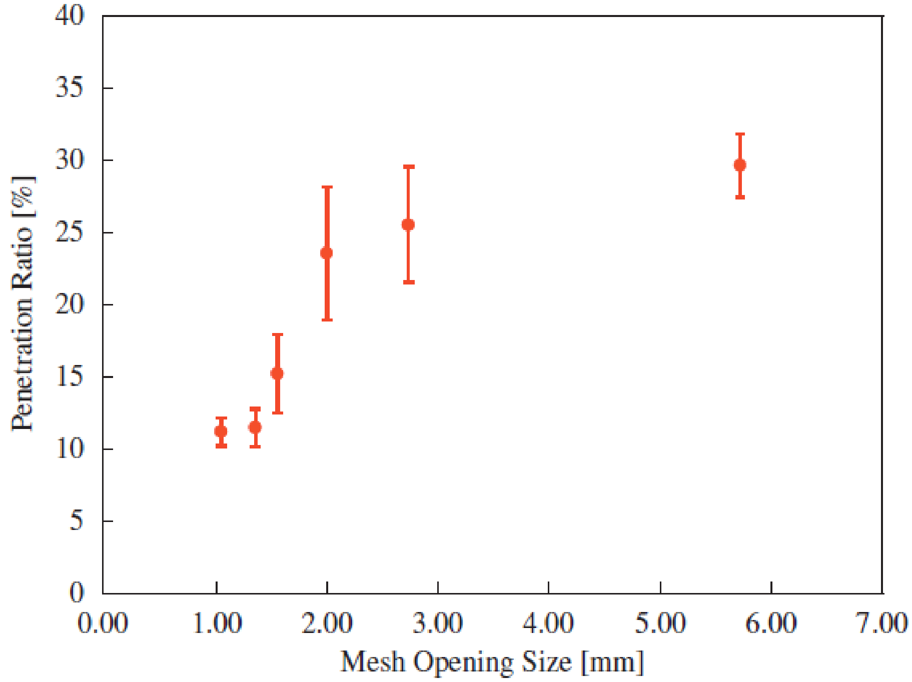

Figure 23: Firebrand penetration ratio as a function of mesh opening size from (Manzello et al., 2011).

A new standard has been developed by the ASTM E05.14 External Fire Exposure subcommittee: ASTM E2886. ASTM E2886, the Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement, is designed to evaluate the ability of exterior vents to resist the entry of burning embers and flame penetration (ASTM, 2014a). The test includes both an ember exclusion/intrusion test and a flame intrusion test. The ember intrusion test is different than previous tests performed with the NIST Dragon, as it produces embers which fall through a vertical shaft and through a vent onto a cotton target, while the NIST Dragon tests were performed horizontally in a large-scale fire wind tunnel. Even though the horizontal wind-driven test is more realistic, the vertical apparatus was considered to be a worst-case scenario and is therefore used in the test standard (Manzello et al., 2010c).

Manzello et al. also used the NIST Dragon at BRI's FRWTF to study open eave construction (where the roof rafter tails extend beyond the exterior wall and are readily visible), as it is often cited as the most severe eave configuration (Manzello et al., 2012b). They used a 61 cm eave overhang with exposed OSB sheathing which was not dried, as the wall was meant to show whether firebrands would accumulate. During tests at 7 and 9 m/s, no accumulation was found at the open eave without vents; however, 11 and 28 firebrands were observed at the 7 and 9 m/s tests with open vents, respectively. These openings had 50 mm holes drilled into blocking material with an 8 x 8 mesh (2.75 mm opening) installed as per the 2009 California WUI code (CBC, 2009).

During the above eave and vent tests, a severe accumulation of firebrands was found at the base of the wall. The 9 m/s firebrand shower exposure was sufficiently severe to cause the wall to ignite from this accumulation. No other combustibles were present at the base of the wall (Manzello et al., 2012b). The wall assembly tested was also modeled using the Fire Dynamics Simulator (FDS) which showed the presence of a large stagnation zone that formed in front of the wall assembly perpendicular to the flow direction and generally increased with increasing airflows. Under the eave there was little to no flow velocity, which would be responsible for driving firebrands into the joints between the eave and wall assembly, supporting conclusions observed in the experiments. Manzello's experiments show that eave vents have less accumulation than gable or foundation vents at this scale, because the horizontal vent structure created recirculating flow that does not carry firebrands as well.

Fences

In an investigation of the 2007 Witch Creek and Guejito fires, it was found that 45% of homes with attached wood fences were destroyed (Maranghides et al., 2013). In most cases, there was evidence that flames came dangerously close to homes by igniting entire wooden fences or sections of them, the ignition of which led flames to surrounding houses. Wooden trellises and other yard structures were also burned (IBHS, 2008).

Post-fire studies conducted by NIST on the Waldo Canyon Fire in Colorado that occurred in 2012 determined that wood fences were vulnerable to ignition from firebrand showers in WUI fires but there has never been any experimental verification of this ignition mechanism (Manzello, 2014). As a result of these observations, a series of experiments were conducted to expose cedar and redwood fencing assemblies to wind-driven firebrand showers by NIST; however, full results have not been released yet (Manzello, 2014).

Decks, Porches and Patios

During the 2007 Witch Creek and Guejito fires, decks were observed to be one of the most significant sources of ignition. Of 16 damaged homes, the ignition location was most often a detached structure or decking (Mell and Maranghides, 2009). Similar observations were made during the Waldo Canyon fire, where wooded slopes with overhanging decks created a large hazard (Quarles et al., 2012). Most of these ignitions were thought to originate from firebrands or local flame contact. One issue is that deck material is tested for flame spread properties and some ignition potential from direct flame contact, but not firebrands or the potential radiant energy production from the deck to ignite the adjacent structure (Wheeler, 2004; CBC 2012). Many houses in the Angora fire had attached decks with combustible material stored under the deck. In some cases, direct flame impingement from a low intensity surface fire ignited these combustibles which eventually ignited the deck and, ultimately, the house. Aerial evidence showed that most of the vegetation between homes did not burn or burned only with a low intensity surface fire (Murphy et al., 2007).

Wheeler performed 6 (non-repeated) tests on various wood and Trex (a wood-plastic composite) decking materials. First, hot embers were placed on the wood members to see if the decking material ignited. Decking material smoldered, but did not transition to flaming. The lack of transition to flaming is likely due to the fact that no wind was applied, because wind is often necessary to initiate a transition to flaming (Manzello et al., 2006c). In another test, a pile of pine needles (debris) was lit underneath each deck and a 5-8 mph wind was applied. All decks ignited; however, wood ignited last and self-extinguished. Composite materials ignited quickly and produced large, severe fires. The slowest composite to ignite was Trex, which self-extinguished once pine needle fuel was consumed by fire. The authors recommend keeping the underside of decks clear of debris (Wheeler, 2004).

Manzello and Suzuki have performed tests on 1.2 x 1.2 m sections of wood decks in a reentrant corner assembly exposed to a continuous firebrand shower from the NIST Dragon under a 6 m/s wind. Decks were built out of western redcedar, douglas-fir and redwood, then exposed to a total firebrand mass flux of 17.1 g/m^{2}s. The deck boards were oriented perpendicularly to the airflow direction. Firebrands accumulated on the deck surface and every assembly was observed to ignite by flaming ignition. Average times for ignition were 437 s for Cedar, 934 s for Douglas-fir and 756 s for redwood. About 20% of the glowing firebrands ejected from the NIST Dragon accumulated on the top of the decks. There appeared to be a correlation between the firebrand mass required for sustained flaming ignition and the density of wood base boards; however, more information will be required to confirm this relationship in the future. (Manzello and Suzuki, 2014).

Sidings, Windows and Glazing

The ignition of materials on the exterior walls of structures is a major concern in WUI fires. Siding materials often ignite due to either direct flame contact or radiant heat exposure. Without proper clearance around the base of a structure, firebrand accumulation can lead to ignition of nearby vegetation or other fuels (e.g. mulch, wood piles, etc.), which can in turn lead to direct flame contact and radiant heat exposure on the exterior walls (IBHS, 2013). Under wind-driven conditions, re-entrant corners lead to the formation of a small recirculation zone which can attach the flame close to a wall (essentially mimicking a fire whirl) and lead to a higher vulnerability to ignition. Since such a configuration is also the worst-case situation for upward flame spread due to resulting air entrainment patterns (Drysdale, 2011) re-entrant corners are a significant hazard that are now thought to be a worst-case scenario for siding ignitions.

Manzello et al. used the NIST Dragon at BRI's FRWTF to study siding treatments (siding material on top of a layer of housewrap and OSB) in a re-entrant corner configuration under wind-driven conditions of 7 and 9 m/s (Manzello et al., 2012b). For experiments with vinyl siding, firebrands were observed to melt through the siding material to the point where holes were visibly observable through the material. Ignition of the OSB sheathing underneath the vinyl and Tyvek was only observed for vinyl siding with 9 m/s of wind applied and OSB that was oven-dried. During this ignition, the OSB burned through completely, eventually igniting the structural wood members underneath. Although polypropylene vinyl siding melted, it did not form holes and no ignition occurred. In an actual wildland fire, winds can be above 20 m/s, so this representative test illustrates some potential hazards in this configuration (Manzello et al., 2012b). A severe accumulation of firebrands was also found at the base of an OSB wall during eave experiments which can quickly lead to ignition of a structure (Manzello et al., 2012b).

Figure 24: High-exposure time photograph showing firebrand accumulation in front of an obstacle from (Manzello et al., 2012a).

Firebrand accumulation around glazing assemblies surrounding windows has also been noted as a possible mechanism for window breakage which can contribute to fire penetration into a structure. Manzello et al. tested both horizontally and vertically sliding window assemblies. They were both double hung, as it was thought that this configuration might present the worst-case scenario for ember accumulation and ignition (Manzello et al., 2012b). Their experiments showed that embers could accumulate in the framing of the assembly, more so in the vertical wall assembly, but none sustained sufficient damage to break the glass or penetrate the structure.

Windows have also been tested for radiant exposure. In one test, a 50 by 63 inch (127 by 160 cm) panel with a radiant heat flux of 35 kw/m^2 was used to expose various window and wall assemblies (previous 1997 International Crown Fire Modeling Experiments in Canada showed that this heat flux is rarely achieved for more than 1 min) (Cohen, 2000b). These tests found that glass is the most vulnerable part of window – if it breaks, embers can directly enter a house; however, dual-pane tempered glass did not fail even with a 25 min exposure, showing that dual-pane glass is unlikely to fail due to radiative heating in a wildfire scenario. This conclusion supports code, such as NFPA 1144 5.7.2 which requires the use of tempered or other fire-resistant glass (NFPA, 2013). Screens were also shown in their tests to absorb radiant heat. Painted siding generally ignited more quickly than windows broke with times for all siding ignition ranging from 4 to 16 minutes. When vegetation is cleared at least 30 ft (9 m) from a building it does not appear that radiant heat fluxes could ignite siding within the short times a spreading vegetative fire will burn. A nearby detached garage, outbuilding or neighbor's house, however could provide a sustained source of radiation capable of igniting siding that should be carefully considered (Quarles et al., 2012). Assessment of siding ignition times from the preliminary results in the Northwest Territories proposed two story structures should be spaced about 39 feet apart based on expected radiant heat fluxes (Cohen, 1995). It is important to note these studies are based on a limited study, particularly, of siding materials and Quarles et al. (2012) does not have published, peer-reviewed data available on the tests.

Maranghides and Johnsson (2008) performed large-scale experiments at NIST where they compared a building clad with combustible materials against one with non-combustible underlying materials (such as fire-rated gypsum wallboard) and measured the time for fire to spread from one ignited assempy to another. They found that even with a 6-ft (1.8 m) separation between buildings, fire spread could be slowed down with a 1-hour fire rated assembly that incorporated gypsum wallboard. Flame spread resulting from penetrations at windows, whether from flames exiting from burning structures or entering/heating broken windows on an unignited assembly was most significant. Flames exiting the burning compartment contributed to total heat fluxes measured on the recipient wall (6 ft (1.8 m) from the burning compartment) that peaked between 60 - 110 kW/m^2 at the top of the wall. Around 20 kW/m^2 reached the window on the recipient wall. As a result, a one-hour fire-rated wall could increase the protection for closely spaced homes, but complete hardening of a home would require other protection methods (Quarles et al., 2012). Window assemblies appropriately protected for a presumed fire expsoure, such as double-paned windows with tempered glass, would also increase protection as a higher heat flux is required to break them.

While some literature highlights skylights as a point of entry for wind-blown embers or flames to penetrate a structure, no data seems to be available to back up the assessment (IBHS, 2013). Ignition of roofing or siding near skylights does seem feasible as accumulation of debris on the roof can cause glass to be broken by ignition around the window. Additionally, flammable plastic skylights can themselves ignite. Still no data in the literature shows them to be of particular hazard in the past.

Community Planning and Adjacent Structure Interactions

The location and arrangement of homes contributes to the overall fire risk within a community. For example, in the Waldo Canyon fire in Colorado, in areas where home-to-home ignition occurred, spacing between homes was typically only 12 feet to 20 feet (3 to 6 m) (Quarles et al., 2012). The spacing between homes — the housing density — and that interaction with surrounding vegetation has been reviewed by several authors below that all point to a significant impact on community-wide fire resilience simply by the arrangement and density of structures. A study of the implementation of Firewise zones around homes was also conducted in a study of the Witch Creek and Guejito fires which showed a clear correlation between the lack of vegetation near a home and the resulting number of structures destroyed. Spread within the community studied was primarily governed by structure-to-structure spread, the results of which are presented under the mitigation strategies section (Maranghides et al., 2013).

Spyratos et al. used a simplistic percolation-theory based fire model along with housing and vegetation data to show that fire risk can be strongly modified by the density and flammability of homes within the WUI (Spyratos et al., 2007). In particular, they found that there was a sharp increase in the probability of a greater fire size with the introduction of combustible housing into their models; this probability also increased when the typical landscape vegetation flammability found in most of the U.S. WUI was used. On the basis of their results, the authors suggest that homes should be additionally hardened against ignition from wildland fires, that nearby vegetation be similarly modified to reduce its flammability (i.e. landscape with lower flammability plants) and that the density and spacing of housing be taken into account when assessing fire risk in the WUI (Spyratos et al., 2007)

Syphard et al. (2012) has done a variety of work studying past fires and the effect of land use planning in the Southern California area. They focused on communities in California by using previous fire perimeter data compiled by the California Department of Forestry and Fire Protection (CAL FIRE) Fire and Resource Assessment Program (FRAP). For the study, Syphard et al. created a continuous raster map representing the number of times an area had burned from the beginning of record-keeping, 1878, until 2001. They focused on properties that had been lost in two Southern California regions prone to wildfires. Their work found that structures in areas with low to intermediate structure density in isolated clusters (with separation of 100 m or more separating clusters) were more likely to burn, rather than the highest density housing. Structures located at the edge of developments or in housing clusters on steep slopes, were also more susceptible. This result suggests that the interaction of both densely populated structures and wildland surrounding and within the community play a role in ignition and spread of fire between structures in the WUI. Arrangement of structures and their location also strongly affected their susceptibility to wildfire. The most important location-dependent variable found in the Santa Monica Mountains was historical fire frequency, which corresponded with wind corridors. Given that property surrounded by wildland vegetation, rather than urban areas were also more likely to burn hints at potential exposure conditions being a very pertinent variable. This relationship has impacts both for future housing planning and zoning as well as risk mapping – identifying regions of certain densities where mitigation strategies such as hardening structures may be most effective in reducing losses.

CASE STUDIES AND INVESTIGATIONS

Reviewed here are a series of WUI fire events (where post-fire reports are available) that have contributed to our understanding or framing of the WUI problem within the United States. There are many events not included in this listing; however, those events mentioned have shaped some of the discussion within this report, summarized in Table 1. Existing mitigation strategies deployed worldwide rely on both quantitative and anecdotal evidence of effectiveness, which in many cases has been compiled as a result of the investigations covered here.

Post-fire investigation remains a significant challenge, as reports of all fires described below reference deficiencies in available knowledge post-fire. Several workshops have been held to try and fulfill this need, including one specifically devoted to the topic hosted by the USFS (WFDRI, 2012) and a general NIST workshop on the WUI that also covered tools for post-fire evaluation (Pellegrino et al., 2013).

The USFS workshop was held to discuss the differing fire data reporting systems at the Federal, State, and local levels. The goal was to discover ways to improve fire data by making sure it is as accurate as possible. There was an information sharing session where different speakers discussed current systems and newer systems that are a work in progress. From these discussions, participants agreed that fire data is mostly inaccurate because of lack of clarity in terms of what defines a wildland fire, lack of reporting in general, and duplicate reports. One issue is that there is a Fire Module and a Wildland Fire Module in federal reporting systems, the latter of which is optional and has different data elements and definitions than the Fire Module. The issues discussed were categorized in the following categories: data and terminology standardization, analysis standardization, and data quality and completeness (WFDRI, 2012).

The data and terminology standardization group had two main focuses: creating a national definition of wildland fire, so everyone knows what events should be reported, and determining the minimum data element requirements for reporting (element definitions will be given to ensure clarity). The analysis standardization group focused on how to develop accurate statistical reports by creating a national estimates approach, producing historical data that contains no duplicate reports, and developing a system from current databases without incorporating all current databases in a new database. The data quality and completeness group was focused on improving incidents of non-reporting, improving the quality of what is reported, and training the entities responsible for reporting (WFDRI, 2012).

Table 1 A list of WUI fires under extreme conditions taking place after 1990. Unless otherwise indicated, reference taken from (Cohen, 2008).

Year	Incident	Location	Structure Loss	Investigations
1990	Painted Cave	Santa Barbara, CA	479	(Foote, 1994)
1991	Spokane “Firestorm”	Spokane, WA	108	
1991	Tunnel/Oakland	Oakland, CA	2900	(Trelles and Pagni, 1997)
1993	Laguna Hills	Old Topanga Laguna and Malibu, CA	634	
1996	Millers Reach	Big Lake, AK	344	
1998	Florida Fires	Flagler and Volusia counties, FL	300	
2000	Cerro Grande	Los Alamos, NM	235	(Cohen, 2000a)
2002	Hayman	Lake George, CO	132	
2002	Rodeo-Chediski	Heber Overgaard, AZ	426	
2003	Aspen	Summerhaven, AZ	340	
2003	Old, Cedar, etc.	Southern CA	3640	
2006	Texas-Oklahoma Fires	Texas and Oklahoma	723	
2007	Angora	Lake Tahoe, CA	245	(Manzello and Foote, 2014; Safford et al., 2009)
2007	Witch, Slide, Grass Valley, etc	Southern CA	2180	(Maranghides et al., 2013; Mell and Maranghides, 2009; IBHS, 2008; Cohen and Stratton, 2008)
2012	Waldo Canyon	Colorado Springs, CO	346	(Quarles et al., 2012)
2014	San Diego and Basilone Complex	San Diego County, CA	65+	(County of San Diego, 2014)

During the NIST symposium, the need to improve tools for post-fire evaluation was highlighted. Both NIST (Maranghides et al., 2013; Mell and Maranghides, 2009) and IBHS (Quarles et al., 2012) have examples of detailed post-response reports available in the literature; however, even these reports cite significant improvements that could be made. At the conclusion of the NIST workshop, it was recommended that more software and hardware training along with consistent standard operating procedures be available for post-fire methodologies and that consistent methodologies for post-fire mitigation be developed. Items such as characterizing firefighting or homeowner suppression efforts during the fire are particularly important and difficult to capture; nonetheless, both are essential for accurate post-fire analyses (Pellegrino et al., 2013).

Santa Barbara Paint Fire (1990)

On June 27, 1990 during a very hot and dry day in California, a fire broke out in the Painted Cave area and formed the “Paint” fire, which subsequently burned 5,000 acres, 440 houses and 28 apartment complexes. An investigation by Foote provided important information on the flammability of roofing. After the fire, 70% of houses with nonflammable roofs were found to have survived, while only 19% of houses with flammable roofs survived (Foote, 1994). Similar conclusions on the effect of flammable roofing on WUI fire spread were found after the 1923 Berkeley Hills fire (National Board of Fire Underwriters, 1923).

Oakland Hills/Tunnel Fire (1991)

The October 1991 Oakland Hills Fire (or Oakland Firestorm) was a significant WUI event that killed 25 people and injured 150 others. While only 1,520 acres were burned, over 3,354 homes and one apartment complex (about 5 buildings) were destroyed, resulting in a net loss of nearly 1.5 billion dollars (Pagni, 1993; Steckler et al., 1991). At the time, the fire was the worst fire loss from a wildland fire in California. Hot and dry Diablo winds contributed to rapid fire spread which trapped firefighters and residents as they tried to escape through narrow, winding roads.

Following the Oakland Hills Fire, several extensive studies were conducted at the University of California, Berkeley, including a study on fire-induced winds including the influence of mass fire effects (Trelles and Pagni, 1997) and studies on firebrand propagation (Pagni and Woycheese, 2000).

Cerro Grande Fire (2000)

There were approximately 200 structures that were completely destroyed or irreparably damaged during the May 2000 Cerro Grande Fire near Los Alamos, New Mexico. Although the fire was an intense crown fire, there were areas within several hundred yards or more of residential communities that burned as a surface fire. The occurrence of the transition to surface fire was discovered because tree canopies leading up to destroyed homes were not burned. Many of the homes burned due to home-to-home fire spread. Another important factor in this fire was an abundance of pine needles, dead leaves, cured vegetation, flammable shrubs, woods piles, etc. adjacent to or on homes, which were ignited by small surface fires or wind-blown firebrands. In several cases, a scratch line, such as the raking of pine needles from the base of a wood wall, prevented a house from igniting (Cohen, 2000b).

Grass Valley Fire (2007)

The 2007 Grass Valley Fire in the Lake Arrowhead area of California destroyed or damaged a total of 199 homes. The wildland fire started at 5:08 pm and transitioned to an urban conflagration after it started burning overlapping home ignition zones (HIZ) at 10:30 pm. From that point forward, homes were primarily ignited by flames and firebrands from other burning structures. The steep terrain of the area added to the intensity of the fire behavior. Most of the destroyed homes had unconsumed vegetation surrounding them, which suggests that homes ignited due to firebrands (Cohen and Stratton, 2008).

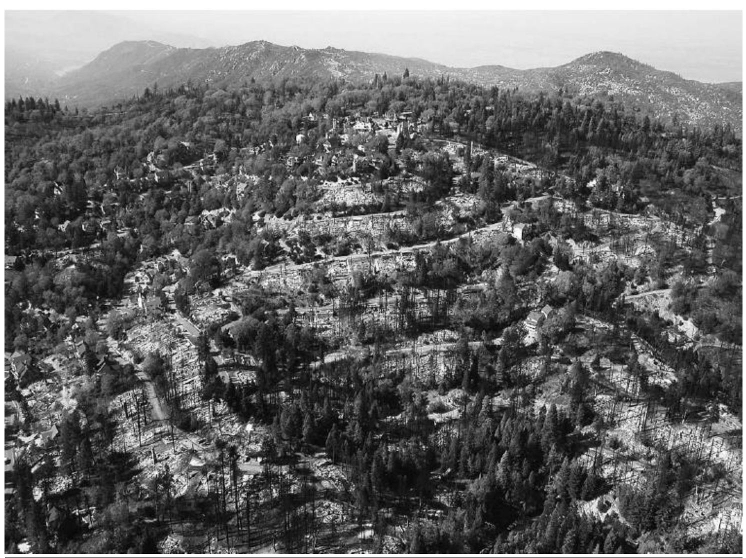

Figure 25: These homes near Lake Arrowhead, California, were destroyed on October 22, 2007, as part of the Grass Valley Fire, and serve as a WUI fire disaster example. Although the homes initially ignited from the wildfire, structures continued to ignite and burn after the wildfire had largely ceased its high-intensity spread. Taken from (Cohen, 2008).

For all but six homes, the advancing high intensity wildfire was not the direct cause of home ignitions (Cohen and Stratton, 2008). Instead, the structure ignition was the result of fire spread from surface fuels within the residential area in contact with homes, the result of firebrands generated by burning vegetation or thermal exposure directly related to burning residences.

Witch Creek and Guejito Fires (2007)

Among a complex of fires in California occurring in October 2007 were the Witch Creek and Guejito fires in San Diego County, California. As a result of the fires there were over 2000 structures lost, over 1 million persons evacuated (the largest in California history) and, through federal assistance, over 6,000 firefighters fought the blazes, including the United States Armed Forces and National Guard. Exacerbated by recent drought and low humidity, high wind Santa Ana conditions contributed to rapid fire spread.

A significant number of studies investigated isolated communities as well as whole regional areas to learn from these fires. Evidence determined that many homes were ignited via firebrands (IBHS, 2008). Overhanging trees played a large factor in the burning of homes, particularly due to built-up dead vegetative material. Two major implications from these fires were the importance of land use planning and the critical need for science-based data and research (Keeley, 2013).

An initial investigation into the Witch Creek and Guejito fires showed that ignitions due directly or indirectly to embers totaled 55 of 74 destroyed homes in the Trails community studied (Mell and Maranghides, 2009). Specific study of the Trails community showed embers from the wildland fire were reported in the community about 80 minutes before the fire front arrived. Through observations and discussions with home owners, it was determined that there was significant surface litter present on and around structures. The degree of damage was often dependent on surrounding structural and vegetative fuels, which varied with location. As new structures ignited in the community, the presence of embers also increased. Of the 16 damaged homes in the Trails community, the ignition location was most often a detached structure or decking (Mell and Maranghides, 2009).

Further investigation by NIST researchers found that a majority of defensive suppression activities by responding fire departments in the Trails community were very effective and that other defensive activities, such as those advocated by Firewise, were somewhat effective and that the level of effectiveness was correlated to fire and ember exposure. Defensive actions were also more than twice as effective at saving structures in low-exposure sections of the community in comparison to high-risk areas (Maranghides et al., 2013).

Waldo Canyon Fire (2012)

In investigation of the Waldo Canyon fire, there were multiple risks that contributed to home loss. Wooded slopes with overhanging decks created a large hazard. Windows were another hazard, as they allowed firebrands to enter the house. Home-to-home spacing where houses were destroyed was usually 12 to 20 feet (3.6 – 6 m). In high density situations, fire-rated wall construction could be helpful. Other hazards included near home combustibles, buildup of embers at the base of exterior walls, wood shake roofs and roof and exterior wall designs that were vulnerable to ember accumulation (Quarles et al., 2012).

Quarles et al. (2012) also found that fuel treatment efforts in Solitude Park near the Cedar Heights neighborhood were successful, particularly in assisting firefighting efforts in the neighborhood. However, there was evidence of potentially vulnerable conditions that may not have performed as well if conditions had changed. While the mitigation work conducted in the high risk areas of the community was credited with helping the fire department achieve an 82 percent save rate, further investigation particularly focusing on exposure conditions vs. the vulnerabilities of homes is necessary to help refine these conclusions. Reports on some of these ongoing investigations, particularly performed by NIST should be released soon.

MITIGATION STRATEGIES

The history of aggressive fire suppression has brought about changes to species and vegetation that have resulted in the high intensity wildfires of the present. During WUI fires, the necessities for combustion can be met through flames (radiation and convection heating) and firebrand ignitions. Models and testing have shown that large flames must be within 100-200 feet of the structure (the home ignition zone) in order to ignite it. Because this distance is rarely met for sufficient duration, small flames or firebrands ignite most homes (Cohen, 2008). In order to prevent disaster, WUI fires need to be thought of in terms of the potential for home ignition. Many approaches to minimize home ignition are possible, including regulation, community education programs, fire service intervention and fuel treatments. These tools may be applied at different scales, from the community, to the neighborhood or subdivision, individual lot or applying to components of an individual building (Figure 26). Fuel treatments themselves do not necessarily make homes less ignitable; rather, they facilitate successful suppression. The goal of decreasing home ignitability places much responsibility on the homeowner (Cohen, 2008). Post-fire analyses have shown that some mitigation strategies are effective in decreasing fire damage; these strategies will be reviewed throughout this section.

Figure 26: Different scales at which mitigation strategies can be applied from Duerkson et al. (2011).

Codes and Standards

Codes and standards are useful guidelines for regulatory bodies to adopt in order to help mitigate potential WUI home ignitions. A number of relevant codes and standards exist for the WUI. Regulatory standards specifically for the WUI include:

- NFPA 1141: Standard for fire protection infrastructure for land development in wildland, rural, and suburban areas (NFPA, 2012)

- NFPA 1142: Standard on water supplies for suburban and rual firefighting (NFPA, 2012b)
- NFPA 1144: Standard for reducing structure ignition hazards from wildland fire (NFPA 2013)
- NFPA 1143: Standard for wildland fire management (NFPA, 2014)
- ICC International Wildland-Urban Interface Code (ICC, 2012)
- California Building Code Chapter 7A: Materials and Construction Methods for Exterior Wildfire Exposure (CBC, 2009)

The standards set by NFPA 1141 - 1144, the ICC WUI code and CA CBC Chp. 7A can partially be used by AHJ's, planners, developers, and communities. NFPA 1141 primarily addresses means of access, building access and separation, fire protection, water supply, community safety, emergency preparedness and fire protection during construction. NFPA 1142 regulates water supplies required in rural areas which may include the WUI. NFPA 1143 applies to wildland fire management. NFPA 1144 applies more to home or property owners in the WUI, as it includes means of assessing fire hazards in the structure ignition zone (or HIZ), building design, location and construction and fuel loads around the defensible space around a home.

Section 701A of the 2009 California Building Code addresses topics in order to protect against WUI fires, including protection against intrusion of embers under roof coverings or into attics through attic ventilation, ignition-resistant exterior construction, use of tempered glass windows, and multiple decking requirements (CBC, 2009). In the aftermath of the 2007 San Diego fires, investigation showed that houses built between 2001 to 2004 following CA Building Code standards were much less likely to burn, with 2-3% of those houses exposed to WUI fires burning, as opposed to 13-17% of exposed homes built before 2001 burning (IBHS, 2008).

Many other standards are directly related to the above, primarily for the testing of materials referenced for use on components of structures in WUI communities such as:

- ASTM E108 - Standard Test Methods for Fire Tests of Roof Coverings (ASTM, 2011)
- ASTM E84 - Standard Test Method for Surface Burning Characteristics of Building Materials (ASTM, 2014b)

- ASTM E2726 – Standard Test Method for Evaluating the Fire-Test-Response of Deck Structures to Burning Brands (ASTM, 2012)
- ASTM D2898 – Standard Practice for Accelerated Weathering of Fire-Retardant-Treated Wood for Fire Testing (ASTM, 2010)
- UL 790 - Standard Test Methods for Fire Tests of Roof Coverings (UL, 2014)
- Testing Standards CA SFM 12.7A-1, Exterior Wall Siding and Sheathing (CBC, 2009)
- Testing Standards CA SFM 12.7A-2, Exterior Windows (CBC, 2009)
- Testing Standards CA SFM 12.7A-3, Under Eaves (CBC, 2009)
- Testing Standards CA SFM 12.7A-4, Decking (CBC, 2009)

In a Fire Protection Research Foundation (FPRF) review of WUI regulatory practices, Duerksen et al. outlined four levels of WUI Regulatory rules: community scale, neighborhood/subdivision scale, individual lot scale, and structure protection (Duerksen et al., 2011). In reviewing these rules and standards, Duerksen interviewed twelve WUI communities spread across the United States and asked nine questions to determine how the available tools are actually being used. Based on responses from the interview questions, several important lessons were learned, which are summarized below:

- Most communities were happy with the technical aspects of standards available to them
- Enforcement requires coordination between multiple departments.
- The greatest deficiencies found among the communities were a lack of coverage for existing development and a lack of enforcement of maintenance. The reason for the second problem is that *enforcing long-term maintenance of defensible space is labor and cost intensive*.
- Flexibility in administration of WUI regulations is critical.

The study suggested that new technical codes are probably not needed, but that the reorganization of the material to reflect their actual use would be beneficial. This recommendation is given because the authors found that many communities “cherry-pick” what is most useful to them. A WUI Best Practices Guide for local governments was also a suggestion for communities that do not want to fully adopt a set of standards (Duerksen et al., 2011).

Through the evaluation of 12 independent variables, including vegetation density, area of defensible space, adjacency of a parcel to public lands, proximity of a house to the nearest fire station, road width, road type, parcel size, subdivision morphology, assessed value, elevation, slope and aspect, Bhandary and Muller (2009) evaluated risk factors that influence the probability that a house will burn from a wildfire. Logistic regression was used to study data gathered from pre and post-fire IKONOS images as well as other geo-referenced data. Both the Healthy Forests Restoration Act (HFRA) and NFPA 1144 standard and policy variables were tested over the test area located in Colorado with elevations ranging from 6000 to 8000 feet. It was found that 8 of the 12 variables were statistically significant. These 8 variables included: vegetation density, area of defensible space, adjacency of parcel to federal land, road width, and subdivision morphology, proximity of a house to a fire station, assessed value, and parcel slope. They also stated that both the full and reduced models presented in this paper lend general support to the standard risk mitigation strategy represented by the NFPA 1144 guidelines and the results of the full model also support use of landscape treatments as a mitigation strategy both on private lots and surrounding undeveloped lands (Bhandary and Muller, 2009).

Other programs, such as Firewise, provide checklists and guidelines for communities and homeowners to perform preventative procedures to prevent WUI disasters. These programs are outlined in a following section.

Vegetation, Separation, Defensible Space and Fuel Treatments

Extensive work by Cohen et al. (2000b), including experiments with large crown fires in the Northwest Territories has, confirmed that separating homes from surrounding vegetation by at least ~120 ft will almost always prevent radiant ignition of the home. If radiant ignition is prevented, other sources of ignition around a home become more significant. The propagation of small flames through local vegetation can ignite small debris and other flammable material near a home, such as wood piles or collected dead vegetation, to cause radiant or direct flame contact ignition of the home. Firewise, NFPA 1141 and the ICC WUI Code all define the home ignition zone within the first 200 feet of a home. Some details on how this zone is defined in each specific code is listed in the appendix; however, details from Firewise will be presented here, as that is the only program which has been quantitatively assessed in the aftermath of a WUI fire.

Zone Concept

As part of an appropriate scheme for structure protection, fuel modification in zones around a structure in the WUI is advised by educational programs such as Firewise, as well as by standards such as NFPA 1141 and the ICC WUI Code[13]. Firewise specifically calls for limiting the amount of flammable vegetation and materials surrounding the home and increasing the moisture content of remaining vegetation. The home itself and everything around it up to 100 – 200 feet is known as the 'home ignition zone' (HIZ), as described by Cohen (2008). The HIZ is typically divided into three zones, shown illustratively in Figure 27 (NFPA, 2014b).

Figure 27: Diagram of three zones recommended by Firewise (Firewise, 2015b).

The **first zone** encircles the structure and all its attachments (wooden decks, fences, and boardwalks) for at least 30 feet on all sides. Within this area, Firewise recommends to:

- Mow the lawn regularly. Prune trees up 6-10 ft from the ground.
- Space conifer trees 30 ft between crowns. Trim back trees with overhanging branches within ten feet of the roof.

[13] Note that these zones are clearly designed to mitigate ignitions by radiation or direct flame contact as firebrands are known to travel up to several miles and cannot be stopped by breaks in vegetation.

- Create a 'noncombustible zone within 5 feet of the home, using non-flammable landscaping materials and/or high-moisture-content annuals and perennials [14].
- Remove dead vegetation from under deck and within 10 ft of house.
- Consider fire-resistant material for patio furniture, swing sets, etc.
- Remove firewood stacks and propane tanks; they should not be located in this zone.
- Water plants, trees and mulch regularly.
- Consider xeriscaping if you are affected by water-use restrictions.

The **second zone** is 30 to 100 feet from the home, and plants in this zone should be low-growing, well irrigated and not very flammable. In this area it is recommended to:

- Leave 30 feet between clusters of two to three trees, or 20 feet between individual trees.
- Encourage a mixture of deciduous and coniferous trees.
- Create 'fuel breaks', like driveways, gravel walkways and lawns.
- Prune trees up six to ten feet from the ground.

The **third zone** is 100 to 200 feet from the home, and this area should be thinned, although less spacing between trees is required than in Zone 2. NOTE: Because of other factors such as topography, the recommended distances to mitigate for radiant heat exposure actually extend between 100 to 200 feet from the home – on a site-specific basis. In this area:

- Remove smaller conifers that are growing between taller trees. Remove heavy accumulation of woody debris.
- Reduce the density of tall trees so canopies are not touching.

Similar guidelines are espoused in NFPA 1141, such as recommendation of three zones from the home between 100 – 200 ft. The standard also recommends spacing between tree crowns (preventing crown fires and reducing potential fire severity and radiant exposure), as shown in Figure 28. Implementing mitigation strategies to further distances is sometimes recommended

[14] Note the closest area near the home in this diagram is not a "fire-free" area.

depending on the fuel loading and potential fire severity that might be encountered (which varies as a function of fuel, weather, and terrain).

Table A.6.2.5 Recommended Tree Crown Spacing to Prevent Structural Ignition from Wildland Fire Radiant Heat

Zone	Distance from Structure	Recommended Tree Crown Spacing
1	0–30 ft (0–9 m)	18 ft (5.5 m)
2	30–60 ft (9–18 m)	12 ft (3.7 m)
3	60–100 ft (18–30 m)	6 ft (1.8 m)
4	Beyond 100 ft (30 m)	No restrictions

Figure 28: Recommended spacing between tree crowns from NFPA 1141.

Some confirmation of the effectiveness of these treatments has been provided in surveys following the NIST investigation of the Witch Creek and Guejito Fires. As shown in Figure 29, the percent of structures destroyed with wildland vegetation within zone 1 (0 – 30 ft from the structure) increased drastically to 67%, compared to only 32% of structure losses for homes without wildland vegetation (modified) in that zone (Maranghides et al., 2013). Similar results were found in zone 3 (100 – 200 ft from the structure) and even extended beyond this to other area surrounding the home (zone 4). Another issue associated with buffer zones that was observed is that some homeowners pushed fuel piles away from their homes to try and achieve the 100 ft separation but in the process, they pushed the fuel closer to their neighbor's home. The zone concept is most effective when the fuel is physically removed from the area, not just pushed to the edge of one's property and perhaps near someone else's structure. More data from this study is presented in a review of Firewise effectiveness in the following section.

Zone	With Wildland Vegetation	Without Wildland Vegetation
1	67%	32%
2	59%	27%
3	54%	27%
4	64%	17

Figure 29: Percent structure destroyed with and without wildland vegetation for Firewise zones 1 through 4 following the Witch Creek and Guejito Fires from Maranghides et al. (2013).

Defensible Space

Recent analysis of pre and post-fire imagery by Syphard et al. (2014) of 1000 structures burned between 2001 to 2010 in San Diego County, CA showed that structures were more likely to survive a fire with defensible space immediately adjacent to them. The most effective treatment distance was between 5 and 20 m (16-66 ft) from the structure, but distances larger than 30 m (100 ft) did not reduce the probability of burning, even when structures were located on steep slopes. The most effective action found was to reduce woody cover up to 40% immediately adjacent to structures and to ensure no vegetation was overhanging or touching the structure. While this recent analysis report is promising for current zoning and defensible space practices, information is missing in the model such as the specific types of construction, other mitigation undertaken, suppression efforts, etc. Only with more detailed pre and post-fire investigations could these questions be answered, as some effects may be associate with one another, such as firefighters choosing to perform suppression only on homes that already had defensible space, but this new technique may be able to provide data on a larger scale to supplement more intensive investigative efforts.

Fuel Treatments

Fuel treatments involve physically altering vegetation (e.g. removing, thinning, pruning, mastication, etc.) on natural wildland with the intent of reducing the probability of extreme fire behavior, including reducing a potential fire's intensity, flame lengths and rates of spread (Hudak et al., 2011). Mechanical treatments often involve removing ladder fuels, reducing surface fuels or removing densely spaced trees to reduce the probability of transition to a crown fire in the tree canopy. Mechanical treatments can be accomplished by hand or machine and may include chipping or pile burning of removed fuels. Grazing is another option for smaller-vegetation; in this case, goats or other animals can reduce the fuel loading (Hood and Wu, 2006). When performed in accordance with local ecological fire regimes, prescribed burning is an important option for reducing fuel loads and thus the intensity of a potential wildland fire (Wiedinmyer and Hurteau, 2010). Continued maintenance is important in order to retain fuel treatment effectiveness. The reduction of intensity is sometimes designed along with protection of WUI communities; however, it can be used to reduce the intensity of fire behavior regardless of the presence of a community.

For fuel treatments to be successful, site-specific fuel treatments are necessary. Agee and Skinner suggest four guidelines to develop fire resilient stands in dry forests. These recommendations include reducing surface fuels, increasing the ground to canopy height, decreasing crown density, and retaining big trees of fire resistant species (Agee and Skinner, 2005). Despite the benefits of fuel treatments, caution must be exercised in regards to the amount of thinning, because too much thinning can increase surface wind speed, cause drier surface fuels, and increase the flammability of fuels over time. All of these factors result in increased surface fire behavior. An understanding of the changes to fuel models, and their effects on the fire behavior of the specific landscape, must be accomplished before conducting a fuel treatment plan. Treating fuels is an ongoing venture that will be costly; however, biomass from fuel treatments can serve as a resource that can increase local economic development and help to cover the cost of fuel treatments (Reinhardt et al., 2008). The strategy of using fuel treatments near WUI communities and collecting the discarded biomass has been effective in some communities such as Flagstaff, AZ. There they have observed improved access for fire fighters and apparatus, easier location and suppression of spot fires and overall improved public safety (Farnsworth et al., 2003).

Most research on fuel treatments has focused on fuel treatments in the wild rather than in the WUI; therefore, current assessments do not include their effectiveness in reducing structure ignition potential. There is general consensus (Hudak et al., 2011) that fuel treatments are effective in lowering fire severity in both forests and rangelands, where effectiveness is determined by whether the treatments reduced fire behavior to improve firefighter safety, protect people and property and whether they mitigated severe fire effects important to vegetation and soil resources. In almost all cases, Hudak et al. (2011) found that fires with appropriate fuel treatments reduced fire behavior from a crown fire to a surface fire in forest stands. Prescribed burns were found to vary in effectiveness. The treatments became less effective over time without maintenance. Topography and wind also affected treatment effectiveness (i.e., resulting fire intensity) in Hudak's study.

Syphard et al. (2011a) studied the effectiveness of fuel breaks in Southern California, the main approach used in the region to mitigate wildfire risk. They referred to two studies, one done over a 28 year period by the USGS and the other conducted over a 30 year period by the Conservation Biology Institute. Both studies concluded that fuel breaks were only effective in stopping fire spread through wildland when they provided firefighter access. Among the forests studied, only 22% to 47% of fires stopped at fuel breaks, even when firefighters were present (Syphard et al., 2011b). The authors believed that it would be useful to have a fire model which accurately determines the effectiveness or size of a needed fuel break; however, such models are not yet available (Syphard et al., 2011a).

In an assessment of the 2007 Angora fire which burned under extreme conditions in the forests surrounding South Lake Tahoe, California, investigators found that area fuel treatments were effective in reducing fire behavior from a crown fire to a surface fire (Murphy et al., 2007). For example, Figure 30 shows the effect of fuel treatments around a single lot which locally reduced a crown fire into a surface fire. Fuel treatments located adjacent to subdivisions provided important safety zones for firefighters, increasing suppression effectiveness which saved structures. Urban lot treatments were also qualitatively shown to reduce ember production and reduce heat and smoke, allowing firefighters to be more effective at suppression efforts. Still, a large number of houses were observed to burn from firebrands generated from other burning structures, rather than from wildland fuels (Murphy et al., 2007). Fuel treatments on steep slopes burned at higher intensity than those on flat ground, both because they were adjacent to untreated units and because fire severity is increased with increasing slope. Therefore, the authors recommend further study as to appropriate fuel treatments on steep slopes and the balance between runoff management and fire severity (Murphy et al., 2007; Safford et al., 2009).

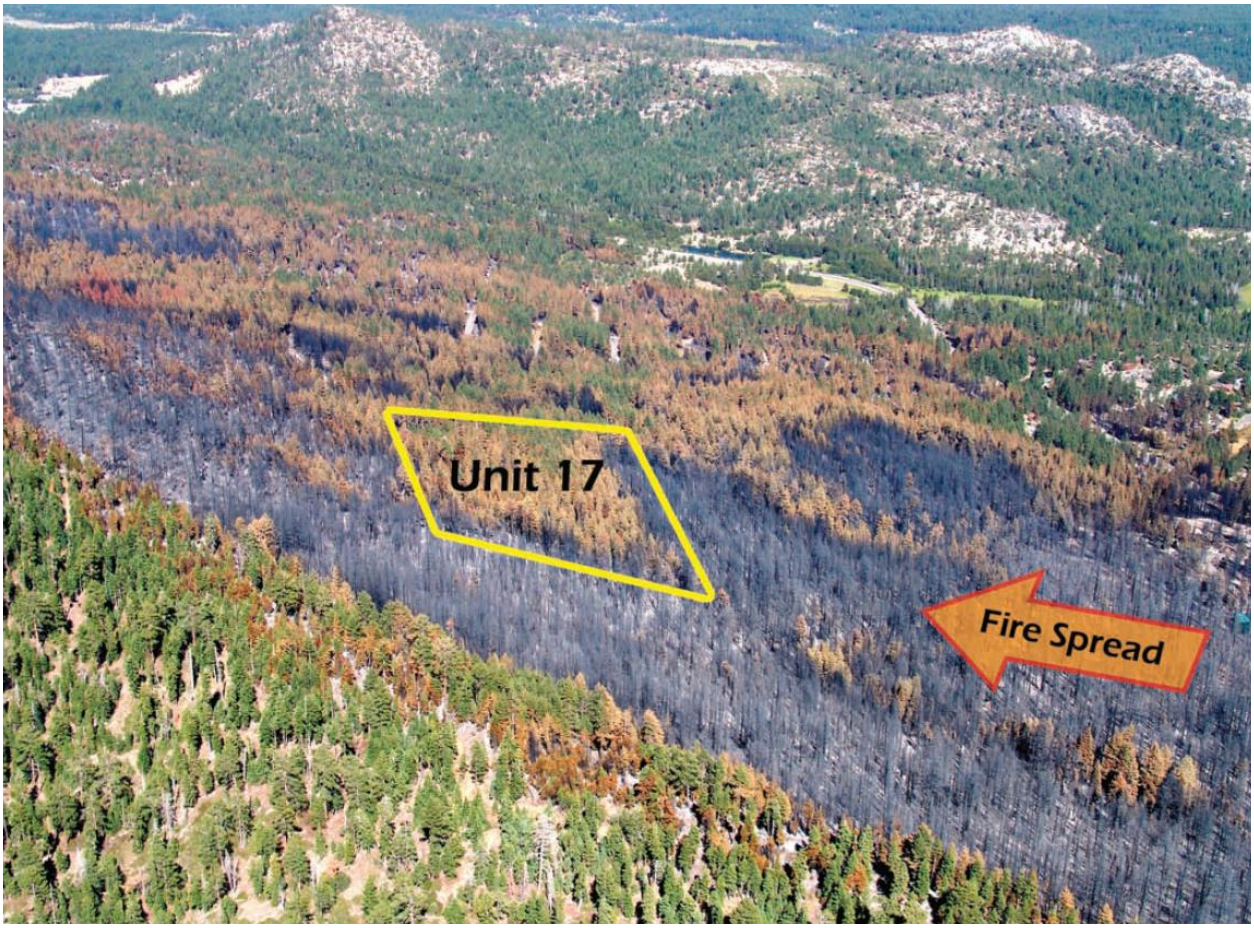

Figure 30: This telling photo from (Murphy et al., 2007) shows one fuel treatment area which met the full force of a crowning headfire, torching trees along the southern edge of the unit. After penetrating the treated area, the crown fire lost momentum and transitioned to a lower intensity surface fire due to a greatly reduced amount of surface fuel, limited ladder fuels, and wider crown spacing.

There is some information available in the literature regarding the placement of fuel treatments in order to optimize their effectiveness in reducing fire severity. Using tools such as FARSITE, Finney (2004, 2006) has computationally investigated methods to optimize fuel treatment locations, particularly to reduce the spread rate of a fire and its intensity or propensity for crowning. Massada et al. (2011) studied the most efficient approach for community or organizational scale fuel management. Their simulation approach's goal was to protect a group of clusters to minimize treatment area and reduce costs. It was acknowledged that different types of fuel treatments should be explored (they only tested 30 m wide fuel breaks) and that minimizing treatment area is not necessarily the best method for protection. Their research provides a starting point for studies on fuel breaks, but must be continued to explore other options. Unfortunately, these approaches only apply to protection where fire spread by spotting (firebrands) is minimal; however, many documented severe fires include spotting as a method of spread (Albini, 1988).

Long term simulations have also been run to assess the effectiveness of proper fuel treatment maintenance. Ager et al. (2007) modeled fire scenarios of thinning and fuel treatments in Eastern Oregon where repeated thinning, thinning with underburning and maintenance burns were performed every 10 years and compared these results to those where treatments stopped after some time period. They found that even without continued maintenance, some thinning and fuel treatment effects are long lasting (20-40 years). Some treatments, such as one-time thinning without continuous treatments may also result in less desirable fire conditions (larger fires) than no treatment at all.

A special case for fuel treatments involves the large swath of beetle-killed forests across North America which present some potential for increased fire severity, due to the accumulation of dead, dry fuel. Aronson and Kulakowski (2013) investigated the intersection of these beetle-killed forests and the WUI. They found that the majority of beetle killed areas (>98%) occurred far from the WUI and, therefore, only 1-2% of affected areas would require mitigation efforts (such as fuel treatments to create defensible space) to reduce the risk of structure ignition. They concluded that if the focus is solely on protection in the WUI, costs for this reduction would be minimal in comparison to managing entire forests.

Benefits of Treatment

Despite the obvious benefits of reduced fire severity and lower probabilities of ignition after developing and maintaining fuel treatments around WUI communities, there are sometimes drawbacks to prescribed burning, with residents complaining about air pollution and a risk of uncontrolled fires. In Florida, results from an air quality study measured amounts of particulate matter from both prescribed burns and wildfires (Harvey and Fitzgerald, 2004). After comparing results from uncontrolled wildfires and prescribed burns, the wildfires were found to have a higher health risk because they produced higher particulate amounts for longer periods of time; however, neither prescribed nor wildfires exceeded the 24-hour standard of 150 micrograms per cubic meter exposure. Florida burns 125,000 acres per year, one of highest prescribed burning rates in the country.

Another concern has been the effect of prescribed burning on carbon emissions from forested areas. Carbon sequestration by forested ecosystems offers a potential climate change mitigation benefit; however, wildland fires have the potential to reverse this benefit. One potential means of reducing carbon emissions from wildland fires is the use of prescribed burning, which consumes less biomass and, therefore, releases less carbon to the atmosphere. Wide-scale prescribed fire application can reduce CO_2 fire emissions for the western U.S. by 18-25% in the western U.S., and by as much as 60% in specific forest systems. (Wiedinmyer and Hurteau, 2010).

Homeowner Educational and Outreach Programs

Programs such as Firewise, Ready Set Go!, Fire Adapted Communities, Fire Safe Council (CA), Living with Fire (NV) and many others offer resources to homeowners to help them prepare for eventual WUI fires, by performing defensive procedures on and near their property as well as encouraging community-wide interactions as a way to prepare for WUI fires. These programs are a key component of WUI fire mitigation, as much of the problem resides within the home ignition zone, which homeowners must independently maintain. Studies, such as one recently conducted in Florida, have begun to show that increased spending on education efforts can reduce spending on wildfire losses and suppression efforts (estimated to be a 35:1 benefit to cost ratio) (Prestemon et al., 2010).

In the few WUI fires with detailed investigations, community-based approaches seem to be effective in reducing structure loss (Maranghides et al., 2013). This effectiveness is mostly due to the fact that small changes, such as clearing brush and reducing home vulnerabilities that could lead to ignition, are most important to reducing structure vulnerability; however, this fact places responsibility on the homeowners (Cohen, 2008). Whereas the built environment tends to be heavily regulated with little responsibility on the homeowner, WUI fire protection involves continual maintenance that requires active homeowner participation. Even small homeowner retrofits can significantly decrease fire damage, as was shown in a study of the 2007 California Wildfires (IBHS, 2008). The effect of small changes suggests that the approach to WUI fires needs to change from what it traditionally was, with less focus on broader changes such as fuel treatments and increased focus on the home ignition zone (Cohen, 2008). This should not discount the development of engineering solutions that, while never a complete solution, may significantly assist the problem via reducing burdens on homeowner maintenance, etc. by providing more fire-safe designs to begin with.

Many community-based programs are available to homeowners. Reams et al. (2008) provided the results of a survey of non-federal fire protection programs for the WUI. State and local programs were taken from the USFS National Wildfire Programs website (http://www.wildfireprograms.usda.gov/)[15], which provides a search engine for programs in local areas. The survey focused on how managers approached these programs, rather than the programs' specific effectiveness. In general, many homeowners expressed apathy and lack of responsibility or belief in wildland fire risk. Public education has been the most effective way to combat this problem and is an action taken by most of the surveyed programs (Reams et al., 2008). A summary of nationwide programs is provided in the Appendix of this report.

Firewise

Firewise is a program of the National Fire Protection Association, which "encourages local solutions for safety by involving homeowners in taking individual responsibility for preparing their homes from the risk of wildfire" (NFPA, 2014b). A collection of tools for homeowners and communities including landscaping guides, community assessment resources and recommendations for firefighter safety in the WUI is provided. Some tools are also useful for land managers, outreach coordinators and public information officers. Details on some elements of Firewise, such as the "Zone Concept" were provided earlier in this report.

Through an extensive investigation of the Trails community by NIST after the 2007 Witch Creek and Guejito fires, the effectiveness of several Firewise treatment strategies in reducing home ignition were, for the first time, able to be quantitatively assessed (Maranghides et al., 2013). Figure 31 shows the Firewise treatments assessed as related to items recommended off of a Firewise checklist. Data was collected on nearly all checklist items, but investigators found the Firewise checklists difficult to interpret, in terms of effectiveness, in a scientific manner. No

[15] Note, the USDA National Wildfire Programs Directory stopped being updated after January, 2010.

treatments were found to be ineffective. Not all treatments could be statistically evaluated due to lack of data, while many that were evaluated had different levels of effectiveness. The statistically significant effective treatments included having an irrigated area around the house, pruning and clearing vegetation, clearing out leaf clutter and overhanging branches, and avoiding wood use (roofs, fences, decks, etc.) (Maranghides et al., 2013).

Treatment Number	Treatment Description	Treatment Number	Treatment Description
1a	**Zone 1™.** This well-irrigated area encircles the structure for at least 30' on all sides. *(If one section does not meet this it is a "fail")*	12	Set your single-story structure at least 30 feet back from any ridge or cliff; increase distance if your home will be higher than one story.
1b	**Zone 1.** Provide space for fire suppression equipment in the event of an emergency.	13	Use construction materials that are fire-resistant or non-combustible whenever possible. (**The presence of a wood roof, siding, eave, deck, pergola, fence or wood pile receives a "no"***)*
1c	**Zone 1.** Plantings should be limited to carefully spaced low flammability species.	14	Roof construction from materials such as Class-A asphalt shingles, slate or clay tile, metal, cement and concrete products, or terra-cotta tiles.
2	**Zone 2.** Low flammability plant materials should be used. Plants should be low-growing, and irrigation should extend into this zone.	15	On exterior wall facing, fire resistive materials such as stucco or masonry are much better choices than vinyl which can soften and melt.
3	**Zone 3.** Place low-growing plants and well-spaced trees in this area, remembering to keep the volume of vegetation (fuel) low.	16	Driveway 12 feet wide with a vertical clearance of 15 feet and a slope that is less than 5 percent and include ample turnaround space near the house.
4	**Zone 4.** This furthest zone from the structure is a natural area. Selectively prune and thin all plants and remove highly flammable vegetation.	17	Periodically inspect your property, clearing dead wood and dense vegetation at distance of at least 30 feet from your house.
6	Take out the "ladder fuels" — vegetation that serves as a link between grass and tree tops.	18	Move firewood away from the house or attachments like fences or decks. (**30 feet is defined as a minimum distance**)
7	Provide added protection with "fuel breaks" like driveways, gravel walkways, and lawns.	19	*Is the structure free of an attached wood fence?*
8	Keep vegetation pruned. Prune all trees so the lowest limbs are 6' to 10' from the ground.	20	Prevent combustible materials and debris from accumulating beneath patio decks or elevated porches.
9	Remove leaf clutter and dead and overhanging branches.	21	Screen or box-in areas below patios and decks with wire screen no larger than 1/8 inch mesh.
10	Store firewood away from the house. (**30 feet is defined as a minimum distance**)	22	Elevated wooden deck not located at top of hill where in direct line of a fire.
11	Slope of terrain; build on the most level portion of the land.		

Figure 31: Firewise checklist treatments from Maranghides et al. (2013) used to assess treatment effectiveness following the 2007 Witch Creek and Guejito fires.

By statistically analyzing data following investigation of the Witch Creek and Guejito fires, NIST was able to show that there were relationships between some preventative measures and a decreased probability of structure damage or destruction. The statistical analysis included a Chi-Square test to determine whether the null hypothesis was true or not, in essence determining whether preventative measures listed in the Firewise Treatments in Figure 31 had an association with damage to a property's primary structure. They found the following treatments proved to be significant to a p-value of 0.001 (very strong presumption against null hypothesis)

- Treatment 1a is present (pass) if an irrigated area encircles the structure for 9 m (30 ft) feet on all sides.
- Treatment 7 is present (pass) if fuel breaks like driveways, gravel walkways and lawns are present.
- Treatment 8 is present (pass) if vegetation on the property is pruned to 6 to 10 feet from the ground.
- Treatment 9 is present (pass) if leaf clutter and dead and overhanging branches are removed from the property.
- Treatment 13 is present (pass) if there is no wood roof, wood siding, wood eave, wood deck, wood pergola, wood fence or wood pile on the property.
- Treatment 17 is present (pass) if there dead wood and dense vegetation is cleared at least 30 feet from the house
- Treatment 19 is present (pass) if there is no wood fence attached to the house.

Only treatment 8 with a p-value of 0.01 (strong presumption against null hypothesis) and treatment 13 with a p-value of 0.05 (strong presumption against null hypothesis) did not meet the p-value of 0.001 (Maranghides et al., 2013). Firewise treatment 14 (roof construction) could not be tested for statistical significance due to the fact that all the structures that failed were destroyed, thereby, making the use of the Chi-Square test statistic invalid (i.e., all flammable wood shingle roofs were most likely destroyed). Results indicating the significant role roofing material plays in home ignition in the WUI are found from the same report reproduced here in Figure 17. For treatments 1C, 6, 11, 15, 18, 20, 21 and 22 not listed above, the treatments were not rejected, as the statistical testing by NIST found that there was no observable indication that they reduced a structure's potential for damage. This result may have been because damaged structures were completely destroyed (Treatment 14) or because insufficient data was available during the assessment (such as Treatment 10, whether there is no Firewood within 30 feet of the structure). These items may still play a role in preventing home ignitions, but more data will need to be collected to quantitatively inspect these results (Maranghides et al., 2013).

The NIST study also looked at the percentage of damaged homes at the perimeter of the Trails community affected by the fire versus those at the interior. They found that perimeter properties had 54% (43 of 80) of the residential structures damaged or destroyed, while interior properties had 29% (47 of 162) of the residential structures damaged or destroyed. In total, 37% (90 of 242) of the homes were damaged or destroyed across the entire Trails community (Maranghides et al., 2013).

The authors noted that Firewise does not explicitly recognize the hazard that an untreated property can have on adjacent properties (Maranghides et al., 2013), despite the importance of structure-to-structure or property-to-property interactions within a WUI community (Syphard et al., 2012). In these cases, the authors believed that the Firewise Zone Concept assumes a potential fire would burn through zones 3 and 4 at lower intensities compared to wildland adjacent to these zones. The low intensity burns, combined with treatments in Zone 1 and 2 that should result in no burning, are the essence of the Firewise Zone Concept. The authors wondered whether "*it is desirable for a wildland fire to burn through sections of the community, even if these sections are greater than 100 feet from a structure?"* (Maranghides et al., 2013). This may appear because the Firewise zone concept was developed as a result of studying fires that are in Intermix Communities where structure spacing is much greater than it was in the Trails community. The report notes that the Firewise zoning concept may not be ideal in its current form for WUI communities with closely built structures, as the concept could allow for spread through the community. Additionally, for Firewise treatments and the zoning concept to be most effective, community cooperation is necessary, because untreated properties may affect treated properties (Maranghides et al., 2013; IBHS, 2008; Quarles et al., 2012).

In another study of the Witch Creek fire by IBHS, fire effects on three shelter-in-place (SIP) communities[16] and three conventionally built communities were compared (IBHS, 2008). The most significant finding was that no homes in SIP communities were lost during the fire. Data was collected via aerial photos (for physical damage as well as community characteristics), site visits, and via interviews and focus groups (to understand community awareness, procedures, etc.). The investigators observed that houses along the edge of a community or densely placed within a community are most at risk for burning (the latter referred to as *cluster burning*). They recommended that the focus in mitigation shift to educating homeowners on a community basis as to what measures they can take to protect their homes. This recommendation was developed because residents were more aware of the risks and mitigation strategies for WUI fires, or because manual suppression was used by residents to prevent small firebrand-ignited fires or low intensity surface burns from igniting the structure. Interviews and focus groups with home owners found that owners do not wish for mandatory government stipulations on housing requirements in WUI zones, but want education on how to take care of their homes.

Fire Adapted Communities

Fire Adapted Communities (FAC) is a collaborative effort to bring together effective programs, tools and resources for reducing community wildfire risk. The collaborative nature of the program covers responsibilities and means for working together between various community members, from the individual homeowner to the city planner or policy maker, represented visually in Figure 32. These recommended collaborative actions are shown in Figure 32. The primary elements of a fire adapted community according to (Quarles et al., 2012) are:

1. An informed and active community that shares responsibility for mitigation practices.
2. A collaboratively developed and implemented Community Wildfire Protection Plan (CWPP).

[16] "SIP is a term used in San Diego County; however, the SIP restrictions and covenants that combine to protect homes community-wide could be referred to as "Wildfire Resistant Communities" for purposes of exporting the standards to other areas. They do serve as a useful comparison because every home must share the same fire-resistive design qualities, including a well-maintained fire district-approved vegetation management plan" (IBHS, 2008).

3. Structures hardened to fire and including adequate defensible space practices; advocated by Firewise Communities, IBHS and others.
4. Local response organizations with the capability to help the community prepare and can respond to wildfire; advocated by Ready, Set, Go!
5. Local response organizations with up-to- date agreements with others who play a role in mitigation and response.
6. WUI Codes, Standards or Ordinances, where appropriate, which guide development
7. A visible wildfire reduction prevention program that educates the public about the importance of a communitywide approach and the role of individual homeowners.
8. Adequate fuels treatments conducted in and near the community, including development and maintenance of a fuels buffer or firebreak around the community.
9. Established and well-known evacuation procedures

Quarles et al. (2012) Fire Adapted Communities report on the Waldo Canyon fire in Colorado Springs provided mostly qualitative assessments on how effective these mitigation strategies were at preventing home ignitions and identifying vulnerabilities. Approximately 90% of homes ignited by the Waldo Canyon Fire were completely destroyed. Of those that were damaged (rather than destroyed), firefighter intervention was the likely reason the house was saved. The post-fire assessment in Colorado Springs credited mitigation work conducted in high risk areas of the community as helping the fire department achieve an 82% rate of saving homes.

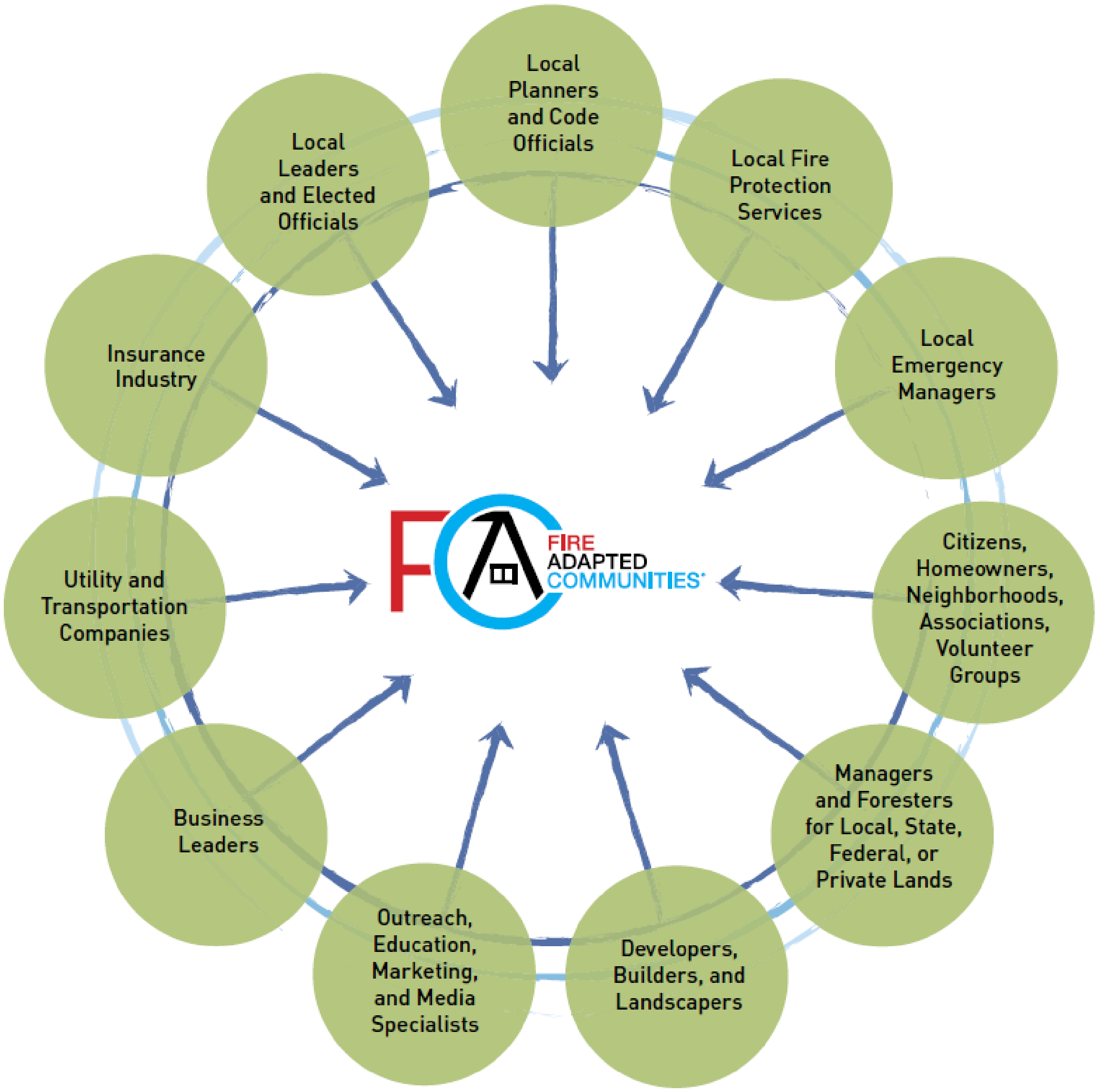

Figure 32: Fire Adapted Communities collaborative framework (Fire Adapted Communities, 2014).

Social Interaction and Response

There are various reasons why homeowners choose to take action or not to mitigate risk from WUI fires. Often WUI residents feel that government agencies, such as the USFS, need to take protective action on public lands to reduce wildland fire risk (Raish, 2011). This perception often may keep homeowners from taking action, though, because most WUI structure ignitions occur within the HIZ, where protection is primarily dependent on homeowner actions, and not on public lands, (Cohen, 2000b).

How residents react to and understand the risk to their homes from wildfire plays a crucial role in the means by which groups perform outreach. In a study of respondents in Boulder County, Colorado in 2007, only 33% of the respondents said they thought it was likely their home would be destroyed by a wildland fire, while 72% said they thought their trees and landscape would be destroyed (Champ et al., 2011). This result does not correlate with the effects of a fire, because homes are more likely than vegetation to ignite on a property, often due to firebrand ignition when defensible space is maintained around the home.

A recent study by Brenkert-Smith looked at the role informal social interactions have on WUI mitigation efforts. Information was gathered from six communities consisting of full-time and part-time residents (Brenkert-Smith, 2010). Full-time residents put more effort into mitigation and trying to develop pathways for informal communication between neighbors. Part-time residents explained that they received information from full-time neighbors that increased their mitigation efforts. They also felt that their full-time neighbors were looking out for them and would give them notice if something needed to be done. The study found that when the residents feel that they have strong ties to each other, even when the majority of the social interactions are informal, they are more educated.

A study by Gordon et al. was conducted comparing WUI communities in Pennsylvania and Minnesota (Gordon et al., 2010). The main result was a link between social barriers and a lack of community-based hazard planning and mitigation. Social barriers arose as a result of new and longtime residents with different values and lifestyles. Many new residents were unaware of wildland fire risk and, in Pennsylvania, did not believe that it was their responsibility to mitigate risk. In both Minnesota and Pennsylvania, long-term residents knew about and worked to mitigate the wildland fire risk; however, in Minnesota, most longtime residents had little interest in community programs to mitigate risk. In general, dealing with wildland fire risk on a community level is most effective. Social barriers in these communities with changing populations puts those communities at a higher risk because they do not approach mitigation on a community level. The authors recommended that such communities create grassroots and educational campaigns to teach about wildland fire risk, and that they engage in hazard mitigation and planning by building trust between longtime and new residents.

Risk Assessment Methodologies including Mapping

In the United States, the National Fire Danger Rating System (NFDRS) is used to provide a measure of the relative severity of burning conditions and the threat of fire during a particular time period (Cohen and Deeming, 1985). These assessments are based primarily on factors that affect a fire's steady rate-of-spread (fuel, weather and topography), but they miss important risk components if the goal is to evaluate risks to WUI communities (firebrands, structure ignition potential, structure-to-structure interaction, community features and suppression). Therefore, a number of different approaches have been taken to perform risk assessments of individual homes or communities, mapping everything from local areas to whole nations.

Mapping

Many approaches for determining fire risk to structures specifically focus on mapping the results of such risk assessments as a means to inform residents, first responders and local governments of specific risks. WUI risk maps vary depending on their purpose. A map could focus on vegetation and housing or have local purposes or national purposes Because of the different purposes of maps, it is important for map users to be aware of the map's purpose and data and analysis methods to use it as efficiently as possible (Stewart et al., 2009). There are limitations, for instance, to combining simple census-based data with vegetation mapping to map WUI risk; however, dasymetric mapping addresses this limitation. Wildfire simulations and burn probability models have been used to create risk matrices that allow for ranking of counties and local areas according to total area of risk and area of elevated risk (Haas et al., 2013).

Factors such as population density, potential fire exposure, and extreme fire weather potential are three layers that have been used to map the potential risk of a WUI fire. In a study by Menakis et al., a matrix was created and risk ratings were assigned based on the lowest class of risk of the three layers. Firebrands were taken into account by using buffer areas around high density housing. There were some anomalies in the methods used to develop the mapping, but the general classes of risk are meant to smooth over these (Menakis et al., 2000).

Risk Assessment Tools

Calkin et al. recently proposed a new risk management framework that could directly apply the principles of risk analysis to the WUI and provide information on fire loss reduction to land management agencies, first responders, and affected communities who face the possibility of wildland fires (Calkin et al., 2014). Their conceptual model (reproduced in Figure 33) highlights major objectives needed to prevent WUI disasters and the groups responsible for these actions (land management agencies, local governments and homeowners). By using this new risk framework, Calkin et al. investigated how pre-fire mitigation efforts failed to prevent significant structure loss during the Fourmile Canyon fire outside Boulder, CO (Calkin et al., 2014). They highlight the sequence of events that lead to WUI fires with large-scale losses (Figure 34). They highlight the importance of overcoming perceptions of WUI fire disasters as a wildfire control problem rather than a home ignition problem, as losses are primarily determined by home ignition conditions (Calkin et al., 2014). They propose strategic planning using risk management and decision concepts to guide cost-effective investments in risk mitigation efforts.

It has been suggested that a specific WUI fire inventory system should be created to address feedback on structure ignitability and suppression effectiveness, magnitude of risk in terms of loss and homeowner responsibility (Cohen and Saveland, 1997). The Structure Ignition Assessment Model (SIAM), developed by the USFS, addressed some of this need, using fire characteristics and location and a structures design to determine the structure’s potential ignitability. The model includes structure design, topography, fire weather severity, fuels, and expert designated fire behavior to characterize exposure from flames, firebrands and radiation, then solves heat transfer equations and provides an ignition risk rating depending on the conditions (Cohen, 2000b). SIAM has been used to model high intensity crown fires where experimental data shows that SIAM provides an over estimate of heat transfer (worst case scenario). Through the studies, they concluded that unless flames or firebrands ignite within 40 m of the structure, the structure is not likely to ignite. (Cohen, 2000b). SIAM could help homeowners understand their risk and achieve a Firewise condition by making cost-benefit tradeoffs, however more fire effects (e.g. firebrands and home-to-home interactions) need to be included first.

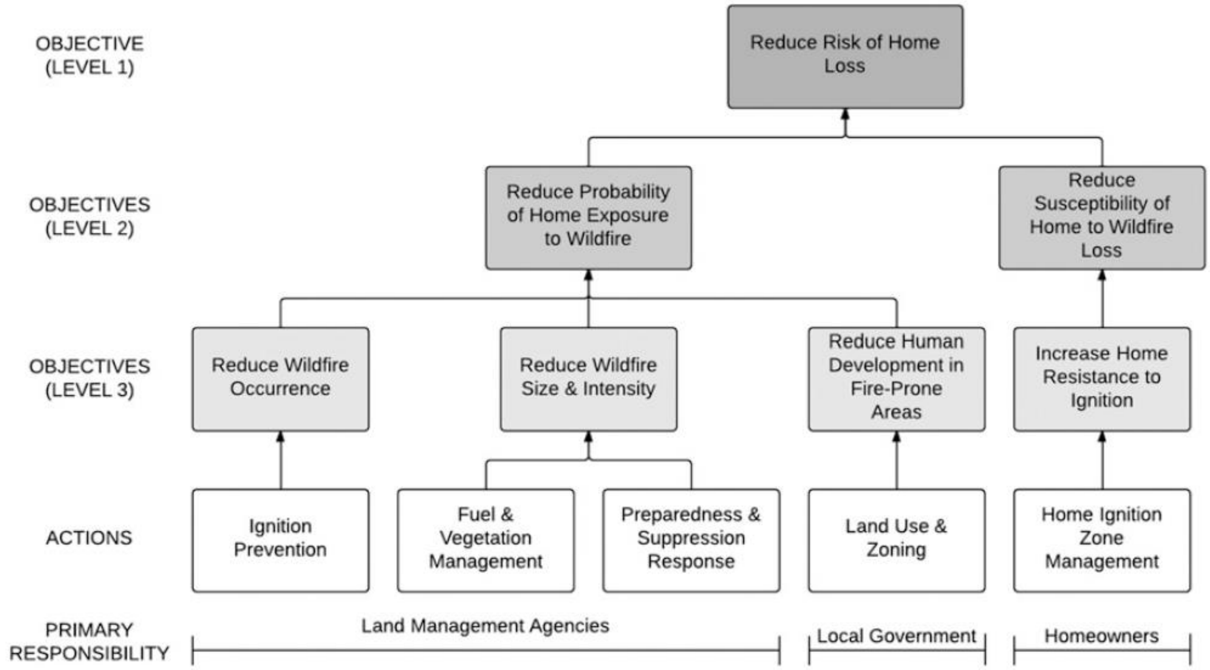

Figure 33: Conceptual model highlighting the major fundamental objectives (level 1), means-based objectives (levels 2 and 3), and actions for reducing the risk of home loss as a result of wildfire. The risk of home loss is jointly determined by the probability of home exposure to wildfire and the susceptibility of home to wildfire, which in turn are influenced by other factors. Actions and responsibilities for strategically managing risk factors vary across land management agencies, local government, and private landowner from (Calkin et al., 2014).

The CAL FIRE FRAP program produces Fire Hazard Severity Zone maps to demarcate WUI and non-WUI areas throughout the state of California in order to impose stricter codes for areas bordering wildland fuels (FRAP, 2015). The hazard mapping determines fire threat to WUI areas based on ranking fuel hazard, assessing the probability of wildland fire and defining areas of suitable housing density that lead to WUI fire protection strategy situations. Fuel hazards are determined as a function of rate of spread and heat-released per unit area (each functions of weather and slope). The probability of burning is taken from fire frequencies from past fire data. The urban interface was demarcated into urban (more than one house in 0.5 acres), intermix (from one house per 0.5 acres to one house per 5 acres), rural (from one house per 5 acres to one house per 50 acres) and wildland (less than one house per 50 acres). These three categories are then combined to an overall 3-category hazard ranking as described above.

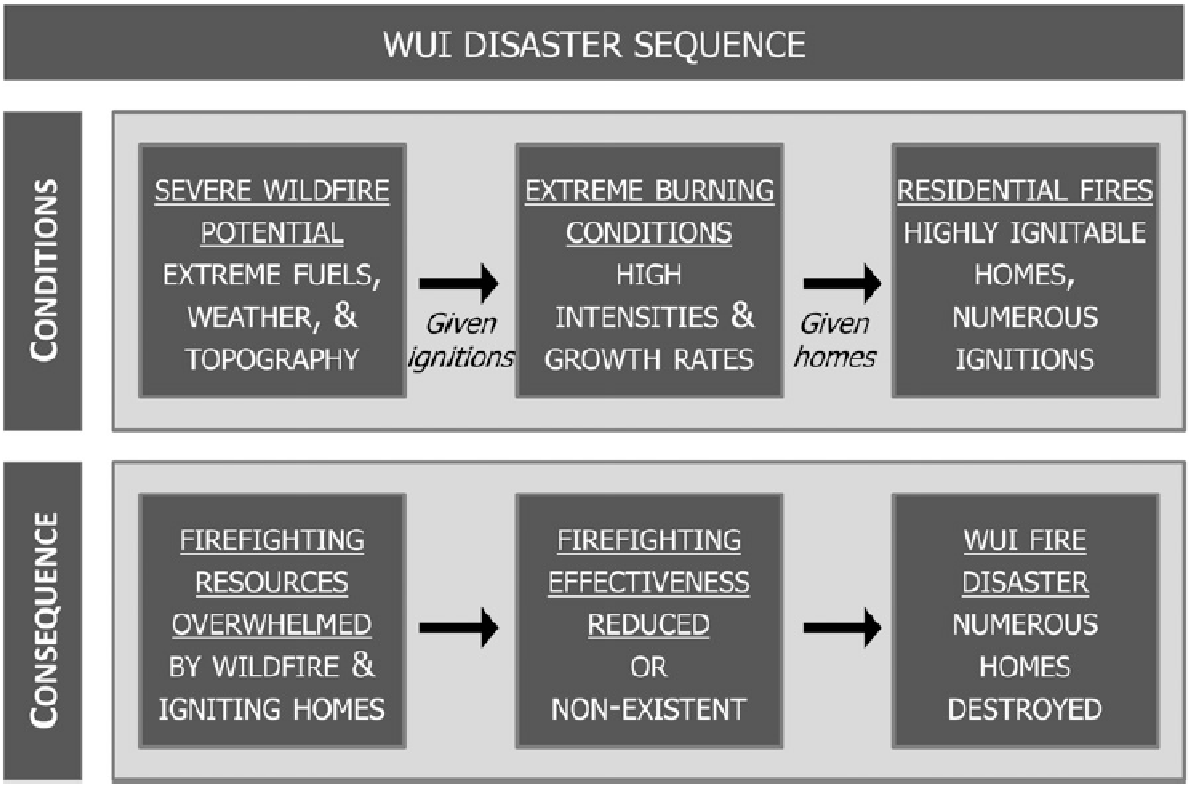

Figure 34: WUI disaster sequence. Each box corresponds to a factor that critically contributes to high numbers of destroyed homes during a WUI fire. Note that, if homes are ignition-resistant and numerous home ignitions do not occur (step 3), structure protection effectiveness is greater for home ignitions that do occur, thereby preventing disastrous losses from (Calkin et al., 2014).

More detailed risk assessments can be accomplished using additional methods such as ensemble fire modeling, historical weather data, probabilities of ignition, etc. Some open-source software tools such as Wildland Fire Hazard Modeling Tools (WFHMT) are available (Lautenberger, 2015). Other commercial tools are available that have performed assessments for corporations and government.

In Australia, the simulator PHOENIX RapidFire is able to provide a more realistic representation of fire behavior than using the Australian Standard Model, because it can take into account the hazard in terms of multiple impact mechanisms (Tolhurst et al., 2014). The PHOENIX RapidFire spread model has also been used in a risk-informed framework in Australia to determine fire risk for communities. Although more research still needs to be conducted, researchers suggest that moving to a more fire-centric view of the landscape (utilizing ensembles of modeled fires) as opposed to the static fuel-centric view (where static fuel maps are used) has the ability to improve landscape planning in multiple ways. Similar tools used in the United States for risk management, such as the Wildland Fire Decision Support System (WFDSS) or FARSITE, do not yet incorporate WUI hazards; however, they can useful in determining potential fire exposures to communities (Finney, 2004).

A variety of checklists are also available which attempt to determine the risk of destruction or damage of different components of structures or communities to WUI fires. These checklists often follow a framework similar to the reactions of components discussed in this report, including subdivision design, vegetation, topography, roofing materials, existing building construction, available fire protection, utilities, etc. These are often aimed at homeowners, inspectors or both. While there is a basis for many of these recommendations, there is little quantitative information which could be incorporated into a risk-informed model which predicts community or structure resilience. A selection of these checklists and rating forms from NFPA 1141, Firewise, IBHS and the ICC WUI Code are available in the Appendix of this report.

A recent NIST report addresses this point in more detail, suggesting a new framework for the assessment of WUI fire risk based on exposure conditions and vulnerabilities of structures to these exposure conditions (Maranghides and Mell, 2013). They propose a WUI fire and ember exposure scale to be used to form the basis of building codes that they suggest could prevent structure ignition at such exposure conditions. Their concept is to quantify the expected fire and ember exposures first; however, only limited information to fill this exposure and structure response database has been collected, though a technical plan to collect such data is outlined by Mell et al. (2010). Exposure conditions are grouped into four zones of differing severity, ranked by potential ember and incident radiant heat fluxes. Convective heat fluxes from smaller, local fires adjacent to structures are not considered. Structures in the zone must then follow appropriate guidelines for protection at that level of exposure for all components of a building.

Wetting/Covering Agents

Several new technologies have been suggested as a means to reduce the likelihood of structure ignition in the WUI. Some of these are mentioned in the 2012 International WUI Code (ICC, 2012); however, most have not been evaluated in actual-scale WUI events. Some means of protection include exterior sprinklers, gel and foam agents and full exterior blankets for structure protection.

Urbas et al. (2013) investigated the effectiveness of pre-wetting structural components, dead fuels, and landscaping plants using water, type A foam and gel agents in preventing fire spread from wildland fires to structures. Intermediate-scale radiant panel tests were conducted on 10 landscaping plants, mulch and four external materials (vinyl siding, plywood siding, asphalt shingle roofing, and cedar shake roofing) where their susceptibility to radiant ignition after 60 min of drying was evaluated. It was found that water and foam had very little effect in preventing radiant ignition of any material after prolonged radiant exposure. Gel agents did have some effectiveness in delaying ignition of some fuels and siding materials, particularly if those materials were not dried in advance. This test focused on radiant exposure only, which is unlike a realistic wildland fire where embers or small fires may contribute to ignition within the HIZ (Cohen, 2000b). There have been some reports (not documented) of mulch ignition in pockets not covered by gels which then smolder to the home and ignite the whole building. These do not appear in the literature, but are a serious concern needing substantiated investigation.

Glenn et al. (2012) also investigated material coatings for protection of exterior structure surfaces in the WUI. They examined sodium bentonite gel and foam coatings through burn tests and looked at their ability to protect a sample of commercial lap siding from radiant ignition (at 42 kW/m^2). Starch was added to some treatments to determine whether it stabilized the coating and prevented vertical slumping. Also included in the study was a commercial fire protection gel. Fire protective gel coatings studied (8 mm thick) were able to extend the time to ignition (determined at a critical temperature of 200°C) at fixed radiant heat fluxes for up to 30 minutes.

Takahashi et al. investigated blanket materials to protect structures in wildland fires with radiant exposures of up to 84 kW/m^2. These materials could be effective to prevent ignition from radiant exposure, direct flame contact or firebrands. How these will be deployed or remain cost effective is not yet known. Tests of over 50 materials were conducted, the best material being an aluminized insulation; however, weight concerns exist still. Future tests are planned to drape these materials as a blanket over outside walls of a house (Takahashi et al., 2013).

Following a severe wind event in 1999, a large number of exterior fire sprinklers were installed on homes in a heavily-wooded area to prevent ignition by wildfires (Johnson et al., 2008). It was found that the systems, when properly installed and maintained, were extremely effective in protecting not only structures, but also trees and surrounding vegetation. Of the threatened structures during a subsequent fire event that survived, 72% had working sprinklers. All but one structure with a working sprinkler system survived the fire. While the study provided only anecdotal evidence of the effectiveness of sprinklers, as other items such as hardening structures or defensible space were not be measured after-the-fact, it appears that the use of these systems may have had a positive effect on low to medium intensity fires experienced. Resources for maintenance of outdoor sprinkler systems were also provided (Johnson et al., 2008). If implemented in a larger, community-scale, issues such as water availability during a WUI fire emergency will need to be considered.

Fire Service Intervention

During the 2007 Witch Creek and Guejito fires, defensive actions by the fire service were found to be more than twice as effective in saving structures in low-exposure sections of the community as compared to in high-risk areas (Maranghides et al., 2013). Attempting to reduce the severity of fire behavior nearby homes is then an important approach. During the 2007 Witch Creek and Guejito fires, of 19 properties in areas of high fire intensity that were defended, 10 structures were destroyed and 4 damaged, whereas in low exposure areas, of the 66 defended properties, 10 were destroyed and 12 were damaged (Maranghides et al., 2013). Fire service intervention is also dependent on available resources, which often may be strained during a large-area fire.

While the application of firefighting during WUI fires is shown to decrease the numbers of structures lost, it can also put firefighters into a dangerous situation. The Yarnell Hill fire was an example of this, where 19 firefighters lost their lives in a burnover. There are many reasons for this loss, but the proper application of firefighting resources has recently been a subject of discussion. Appropriate first response activities, such as the number of resources to devote to a fireline versus structure protection is a question needing answers. Also, means of integrating wildland and structural firefighting crews, as they drastically differ in training and equipment, is another area of concern (Farris, 2005).

Rahn performed a staffing study on wildland firefighting initial attack effectiveness in San Diego (Rahn, 2010). Emergency response effectiveness was found to depend on four things: land management practices, existing environmental conditions, equipment and resources available to fight the fire, and the number of firefighters dispatched to an incident. This study observed varying firefighter staffing numbers on a 1,000 foot and 2,000 foot hose lay over 0% grade and 25% slope. Time efficiency to lay the hose-line 100 feet increased by 21 and 31 percent, for 0% and 25% slope, respectively, when increasing from 2 firefighters to 3 and by 49 and 47 percent, for 0% and 25% slope, respectively, when increasing from 3 firefighters to 4. In the 1,000 foot and 2,000 foot time trials similar patterns were observed, where going from 2- to 3- staffing showed the largest increase in time. It was found that a 2- person crew was between 15-40 minutes slower than a 3- person crew. Since the first 10-30 minutes of a wildland fire are the most crucial, this one person increase can make a significant difference. Another concern is the health safety of the firefighters. Firefighters' heart rates were measured before and after the hose-lay. The highest heart rate changes were found in the 2 person crews, and the difference decreased by about 34% when adding just one more person (Rahn, 2010).

Rhode performed a survey of incident management schemes used during the first several hours of response at six different WUI fires in Southern California (Rhode, 2002). Of the six fires studied, the most successful incident command structures were immediately organized into a unified command and ordering point. Incidents that included law enforcement in the unified command were highly successful in mounting evacuations. Nonetheless, all six fires studied resulted in significant injury to firefighters and half cost lives. General wildland fire factors such as abundant native chaparral fuels, conflagration behavior with mass structure involvement, high burning intensity, fire whirls, long range spotting, mass ignition and rapid rates of spread contributed to extreme fire conditions. Communities were also largely constructed of non-fire resistant materials such as wood shake roofs, lacked adequate fuel modification or brush clearing and used combustible landscaping. On all fires, public volunteerism proved unmanageable and an impediment to firefighting operations (Rhode, 2002).

During a WUI fire, two main firefighting strategies are possible: performing offensive perimeter control to keep the advancing fire front within a contained area and defensive structural prevention preventing ignition from firebrands and flames. A common strategy is to “pinch the flanks” through perimeter control to limit the width of the fire’s head as it enters areas with structures. The ideal strategy found in Rhode’s study was to provide both offensive perimeter control and defensive structural protection simultaneously. Abandoning perimeter control in favor of structural protection risked unabated fire expansion, increased structural risk, and difficulty of control. In some situations, perimeter control might have to be abandoned for a period of time, but it must be reestablished as soon as possible (Rhode, 2002).

Rhode stressed that organizational development and control can be as complex as the fire itself. Therefore, pre-fire planning can be critically important, including conceiving strategies and tactics, identifying values at risk, planning deployments and evacuations, calculating resource needs, and projecting fire behavior and spread. Some issues identified in firefighting included the presence of threatened or endangered species which served as obstacle to pre-suppression activities, water systems that were unable to provide adequate fire flow or failed during fires and egress and road access that was limited (Rhode, 2002).

PART II: GAP ANALYSIS

Summary

Despite the wide array of research presented above, there are still many areas related to the pathways to fire spread in the WUI in need of additional research. As part of this gap analysis, these areas have been broken down based upon both scientific and practical contexts. These contexts are divided into two areas, widely defined as those related to the quantification of risk and hazard and more practical and specific issues. This format is chosen as those areas related to the quantification of risk and hazard are ubiquitous to all practical and specific issues, necessary to provide a basis for future engineering design efforts. These include

- Quantification of Risk and Hazard
- Pre- and Post-Fire Data Collection
- Testing of Firebrands
- Understanding of Ember Fundamentals
- Understanding of Wildland Fire Fundamentals
- Structural Ignition

Each area under this category therefore relates to fundamental or applied research areas that have the ability to quantitatively inform risk mitigation efforts, and are not listed in a specific order. There are also many other practical issues, which relate to specific areas of code and standard development, WUI community protection or firefighting that are in need of rapid research and development. The overarching goal of these items is to reduce the fire exposure to communities, harden them to resist ignitions and improve the effectiveness of evacuation and suppression once a fire is in progress. We defined these practical and specific issues to include

- Fuel Management, Defensible Space and Community Planning
- Test Standards and Design of WUI Materials
- Effectiveness of Mitigation Strategies
- Impact of Wildland Fires on Health and Environment
- Firefighting Techniques
- Identification of Educational Needs

These categories represent a wide spectrum of subjects within possible WUI research. Some needs are directly related to a specific goal (i.e. to develop test standards for materials to be used in the WUI), while others lend more to the modeling of wildland fires or to a better general understanding of fire. These latter categories may indirectly or directly affect applications.

It's important to recognize that, throughout this review most work has focused on important test scenarios but has not *quantified* effects in a repeatable manner. While it is useful to identify vulnerabilities and best practices, protection of WUI communities cannot evolve without more quantitative analyses to optimize protection schemes. Codes and standards rely on precise thresholds, such as separation distances between homes, which must be defined for a wide variety of exposure conditions and standardized for a known worst-case scenario. Many studies reviewed here have also been presented without peer review and/or are not available in the open literature. It is critical that test and analyses supporting codes and standards be available to the public, while peer review ensures the technical credibility of the work. An effort has been made in the references section to link referenced studies to their most recent sources.The overarching research categories below help to describe some major gaps identified throughout the review, however they should not limit other future areas of research. The order does not reflect a particular higher or lower ranking on each topic but is simply used to organize the topics in a logical presentation. Surely through additional investigation and research new priority areas will be recognized and should be added to this list in the future.

Quantification of Risk and Hazard

In the era of performance-based design many design choices in the built environment are based upon knowledge of fire behavior and its effects on risk. Such an understanding of wildland fire behavior coupled with its impact on WUI communities, however, does not yet exist. Two main areas are necessary to inform risk and hazard quantification, data collection from real fires and expanded fundamental understanding. A statistical representation of data from previous fires, when carefully collected and analyzed, has the ability to inform our understanding of how fires will affect real structures and, with enough data, quantify these effects in a risk model. These risk models can then be used to perform cost-benefit analyses for fire mitigation that optimize resources available and estimate potential impacts of decisions made. The amount of data needed for such an approach, however, is most likely a limiting factor. Fundamental research, on the other hand, has more potential to provide simplified tools for the design of WUI communities. Most of the following sections describe some means in which we can inform the quantification of risk and hazard.

Several frameworks are available to perform risk and hazard analysis in order to optimize protective strategies or fire management, however most would be greatly improved with additional information on the response of structures in the WUI to fire (Calkin et al., 2014; Maranghides and Mell, 2013). This type of data does not exist; so, for the most part risk modeling today only incorporates features of surrounding wildland fire behavior (fuel, slope, weather, etc.) and the density of structures (Maranghides and Mell, 2013; Tolhurst et al., 2015; Lautenberger, 2015; FRAP, 2015).

Maranghides and Mell (2013) laid out what they thought were the missing components by defining a WUI hazard scale broken up into fire and ember exposure, shown in Figure 33. While such a defined structure is not necessarily absolute, their description of how most every “box” of possible fire exposure conditions has yet to be studied highlights the lack of data currently available, shown in Figure 35. The necessary step of connecting these exposures to the response of specific structural components will require additional effort. Since all components are hazards, it is necessary to include exposure from nearby structures and surrounding fuels, not just those directly intimate with the main structure.

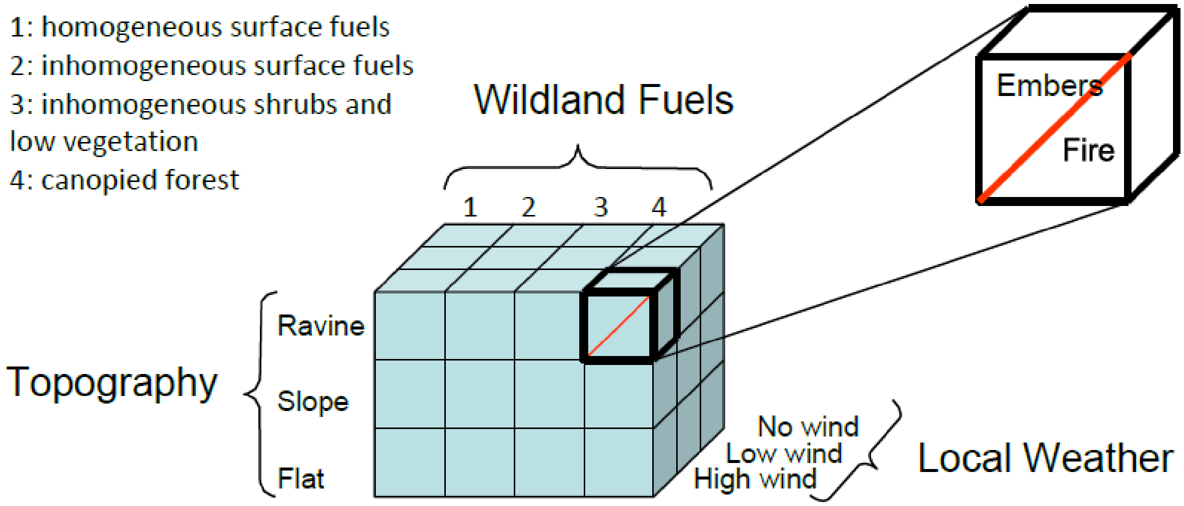

Figure 35: Capturing exposure from wildland fuels from Maranghides and Mell (2013).

Pre- and Post-Fire Data Collection

While so much about the spread of wildland fires into WUI communities is still not known, an effective means of increasing our knowledge is to assess the effects of WUI fires on real communities. For this data to be repeatable and applicable between many different communities, especially if used in the context of hazard and risk analysis, some standardization of pre- and post-fire data collection is necessary. This data could greatly enhance our current understanding of how WUI fires spread to help better address the problem. Currently there is some WUI data collection after fires, but this is not mandatory or standardized.

Some guidelines and tools for WUI data collection have been proposed by NIST (Pellegrino et al., 2012), however these are not yet widely distributed or used. Teams or organizations responsible for collecting data should be consistent in specific regions or states, so that incidents are not double counted or missed during both pre- and post-fire assessments. Terminology that is necessary for the data collection also needs to be uniformly understood by all involved. If these topics are not all standardized, then the pre- and post-fire data will not be as effective. With clearer guidelines for data collection, it is likely that there will be more data available to help researchers understand WUI fires and better characterize their risk or hazard based on exposure conditions and the reaction of components or systems.

Testing of Firebrands

Although only limited fundamental knowledge is available on firebrands, many tests have recently been performed to observe their effects on specific structural components and measure the distribution of firebrands from real fires from both vegetative and structural fuels (Manzello, 2014). These tests have been a good first step; however, future tests can consider additional aspects. There are many potential fuel types, from large pine stands to Mediterranean chaparral that may invariably generate different ember fluxes that should be studied and compared. Higher winds speeds have yet to be approached in order to create a more realistic WUI fire situation. Most experiments have been conducted with wind speeds up to 10 m/s, while wind speeds in excess of 20 m/s are often observed during WUI fires (Manzello, 2014). Along with these higher wind speeds, real WUI fires have up to several hours of continuous firebrand generation. Therefore, experiments need to incorporate longer firebrand exposure to simulate actual WUI fires.

To further understand ignition from firebrands, testing should consider different elevations and higher velocities of firebrand generation. Testing that includes the combined influence of firebrands and radiative heat flux is another area that should be further investigated as both may be present during WUI fires. It is also important to test multiple building components, observing their interaction. Single component testing alone would not have been able to reveal firebrand collection spots, such as re-entrant corners (Manzello et al., 2012b), however these appear to play a critical role in structure ignition. Important components that need test standards will be discussed in another section.

Understanding Firebrand Fundamentals

The lifetime of a firebrand has been separated into three stages, generation or production of a firebrand, lofting and transport, and finally deposition and subsequent ignition of recipient fuels. In terms of generation, some research has been conducted to measure firebrand generation from both vegetation and structures, presented as mass or size distributions collected downstream (Manzello and Foote, 2014; Suzuki et al., 2013, 2014). Research should continue on collection of firebrands from real and simulated fires, including different vegetation, structures, winds, etc. Very limited research appears in the literature on the actual process of firebrand generation and how it relates to the materials which generate firebrands. If more understanding can be garnered from specific fuel types, perhaps these distributions can be better understood *a priori*.

Lofting and transport of firebrands has been the best-studied aspect of the problem. While there is still work to do, several models exist which are adept at incorporating firebrands and investigating their transport through a fire plume (Sardoy et al., 2007; Koo et al., 2012) or statistically investigating their transport numerically (Tolhurst et al., 2014).

The least-understood process is ignition by firebrands. Ignition of a recipient fuel by a firebrand may depend on many characteristics: firebrand properties (i.e. size), ambient winds, fuel moisture content, geometry, whether the ember is flaming or smoldering on landing, and how many embers land in a particular recipient fuel (Mell et al., 2010). Little is known on how these various characteristics interact and the actual effect they have on how and when ignition occurs.

Recent studies on ignition behavior by Hadden et al. (2010) and Zak et al. (2014) have looked at the simplified problem of hot particles landing on a cellulose fuel bed, however this configuration more closely resembles firebrand ignition of vegetative fuels. The relative influence of solid-phase chemistry, re-radiation, brand size, configuration, etc. must be determined before better models for ignition can be developed. Some of these should focus on denser materials, such as wood or plastic often found on structures in the WUI. Most studies which have taken a closer look at ignition phenomena by firebrands have been somewhat restricted to loose, vegetative fuels (Viegas et al., 2012; Manzello et al., 2006) which may behave differently than the higher density, varying geometries found on or near structures.

Understanding of Wildland Fire Fundamentals

While fire dynamics is a fairly developed field used to analyze the built environment (Quintiere, 2006; Drysdale, 2011), such knowledge is limited or non-existent applied specifically to WUI fires. Tools are available to predict the spread of wildland fires, their intensities, and expected radiative fluxes (Andrews, 2003; Finney, 2004), however these tools are based on steady assumptions of flame spread that have limited or no physical basis (Finney et al., 2013). This leaves gaps as no tool can assess whether a fire will accelerate, decelerate or stop, critical elements when looking at the effectiveness of fire breaks in protecting a community. There is also no way to incorporate the influence of structures or fire suppression. New tools under development such as WFDS (WUI Fire Dynamics Simulator) hope to bridge some of these gaps but still require significant advancement in fundamental understanding of fire behavior to be accurate enough to further enhance our picture of the problem. Enhanced research on wildland fire behavior and its coupled effect on structures in the WUI, such as recent numerical efforts (Porterie et al., 2007) could enhance our understanding of structure-wildland and structure-structure interactions. Development of software with a firm technical and scientific basis could be a valuable tools in a WUI community designer’s toolbox.

Other research needs include those surrounding firebrands, as discussed above. The mechanisms governing transition from smoldering to flaming combustion is not well-understood. This transition is of particular importance in determining whether ignition will occur in a fuel (whether vegetative or structural) due to a firebrand. Ignition due to flames and firebrands needs to be more completely characterized. How fire behavior influences the WUI in different ecosystems, e.g. tall pine stands, Mediterranean chaparral, etc. should be studied. Additionally, research on fire behavior and smoke transport is necessary, with the latter affecting health and environmental concerns.

Structural Ignition

Cohen has described the WUI problem as a structural ignition problem (Cohen 2004). While there is still an influence of the exposure conditions on structures, if ignition of structures can be prevented in whole, WUI fires would not pose as severe a threat to residents and communities. While some aspects of ignition from the fire front to target structures (primarily based on radiative exposure) are understood, structure to structure ignition is less well defined (Cohen 2004). Nonetheless, structure to structure ignition can be a significant or sometimes primary form of fire spread once a wildland fire enters a community (Maranghides et al., 2013). Participants of a recent WUI fire workshop (Pellegrino et al., 2012) also highlighted hardening of structures as their top research priority. Research needs to include greater detail on the effect of radiation and embers from nearby structures and the components which are most vulnerable to exposure.

While several anecdotal cases have been mentioned in reports, only one detailed study on a scaled configuration was found on structure-to-structure ignition (Maranghides and Johnsson, 2008). This test could not measure the influence of embers and was too limited to truly characterize realistic radiant heat fluxes, which should be characterized for a variety of potential fires. Additional testing at many scales, culminating in measurements during full community structural burns would be invaluable at determining means to prevent home-to-home spread which drastically increases damages during WUI fires.

If more research is conducted on how exactly firebrands ignite a structure (as suggested above) that may guide design of future structures hardened from ignition from firebrands from both vegetative and wildland fuels. Investigations of actual WUI fires may also help to better-determine the fraction of ignitions that are due to firebrands or, indirectly, by direct flame contact from nearby fuel sources originally ignited by a firebrand. These may similarly help future development of WUI community design.

While many authors have recognized a need to harden structures against embers (Pellegrino et al., 2013), there is little information on what hardening tactics might be effective. At a building level, there is little information on the response of different *types* of buildings (i.e. how the response of homes differs from that of commercial occupancies, warehouses, etc.) Finally, although specific components have been studied (Manzello, 2014), there is a great need for research on the interaction between coupled components under realistic WUI fire conditions. For example, a Class A roof might survive ignition from embers, but ignite as a result of direct flame impingement if flammable siding is ignited. Research on coupled systems will better represent how a structure reacts to hazards of WUI fires.

Fuel Management, Defensible Space and Community Planning

Fuel or fire breaks are a common feature in wildland areas and may either be deliberately provided in the design of a WUI community or subconsciously developed. The theory behind a fuel break is to introduce a discontinuity into the fuel that an approaching wildland fire would consume, thus slowing the fire or ceasing further spread. Recent analyses of past fire data, however, have shown that these breaks are not as effective as once thought (Syphard et al., 2011b), however the overall layout of communities (land-use planning) appears to greatly affect a building's probability of ignition (Syphard et al., 2012). Their primary effectiveness appears to be in providing working space for suppression efforts. Adequate fuel breaks allow access for active fire suppression which has been shown to be very effective (Syphard et al., 2012). Fuel breaks also provide an added measure of safety, forming safety zones which allow them to operate in a wider region. Still, active fire suppression by fire crews has the potential to put them in harm's way.

Fuel treatments have been shown to reduce the intensity of a crown fire, typically reducing the crown fire to a surface fire (Murphy et al., 2007). This does not prevent ignition from firebrands, but does have the potential to remove the radiative exposure component to nearby homes. While some work has suggested that fuel treatments far outside the WUI are effective in reducing potential fire effects (Schoennagel et al., 2009), more research is needed to support these conclusions. The effectiveness of fuel treatments is an ongoing research area that requires more research, particularly on its impact to WUI communities. The influence of a fuel treatment on fire behavior in a nearby WUI community has not been well studied (instead focusing on the wildland) and specific means are lacking. Different fuel types must also be assessed, as much work is toward large pine stands which support crowning. Many communities are located in scrub or chaparral (California, etc.) and little guidance is available for these fuel types. How to place these fuel breaks in terms of their effectiveness to WUI communities must be further studied to come up with appropriate and economic or risk-optimized guidelines.

Because land-use planning appears to significantly influence home survivability in the WUI (Syphard et al., 2012), additional research should be undertaken to understand exactly what features are most significant and guidelines for future community planning assembled. Recent work investigating defensible space (Syphard et al., 2014) appears to show that clearing the area around a home also increases home survivability. This research should be continued over larger sample sizes, however it needs to start being coupled to other features on the home and related to suppression efforts to narrow down exactly what mitigation strategies are effective. Because the analysis to date is focused on overhead observations instead of detailed assessments on the ground, they can't be coupled to specific recommendations on the use of retaining walls, landscaping choices, etc.

Very little work has been done to develop strategies to design a WUI community. As it stands now, no publication was found in which a strategy was proposed to aid in the design of a WUI community. The incorporation of greenbelts, parks, walking/bike paths or other defensible spaces may be particularly effective design strategies, however no guidance appears available for their use (Pellegrino et al., 2013). Guides aimed toward professional engineers, architects and AHJs could be very effective at improving community resilience once general guidelines are established via peer-reviewed research.

Test Standards and Design of WUI Materials

Many building components are considered possible ignition sources in WUI fires. One major research need is to create test standards for specific components in order to ensure future designs are ignition and fire resistant. Development of these standards will require additional study on possible exposures (ember flux and radiating heating from vegetative and structural fuels) to reflect realistic conditions encountered during extreme fire behavior. The goal of these test standards should be to ensure that all test components can resist ignition from an approaching wildfire or a burning nearby structure. Enough, perhaps is already known to start designing some test methods that can critically assess the ability of a structural component to resist ignition from some exposure level, however more research must be conducted to determine what specified exposure levels will be encountered in different environments. It is therefore recommended all future test development involve a quantitative measures of material or component performance (e.g. flame height, flame spread rate, heat-release rate, etc.) so that as exposure conditions are better understood these effects on existing features can be estimated without massive re-testing campaigns.

Some specific components in need of standards include roofing assemblies, gutters, vents, eaves, fences, sidings, and mulch. Specifically for roofs, more realistic ignition from embers needs to be considered. Roofs that are currently Class A rated by UL 790, ASTM-E108 or NFPA 276 have failed wind-tunnel firebrand shower tests (Manzello et al., 2013) highlighting the need for testing under conditions more representative of WUI fires. These tests should ideally be conducted with roofs as a system, including construction and joining techniques as these have been found to be specific vulnerabilities during WUI fires (Pellegrino et al., 2013).

Gutters and other roofing products also need to be developed to keep debris accumulation minimal or nonexistent. Test methods or observed performance should be understood to evaluate these new products. The size of vents and vent meshes are a concern where development needs to be made because firebrands, even small ones, can penetrate the meshes. Recent code developments such as ASTM E2886 have started to address this issue (ASTM, 2014a), but its effectiveness will need to be verified with more large-scale testing.

Fences and sidings are both areas where research is very minimal and needs to be conducted in order to create test standards. The mechanisms of ignition of fences and siding and the means by which these fires spread to ignite the rest of a structure are a critical area for research after reports from the Waldo Canyon Fire (Manzello, 2014), as they will be needed to design an appropriate test standard.

There is very little work done quantifying the flammability of different mulches, however a new test method (Beyler et al., 2014) may serve as a basis from which to standardize the process. Still, these tests should eventually go further to quantify limits of what distance away ignited mulches should be used from a structure under worst-case conditions. Embers also should not be produced by any ignited mulch that could be transported, especially under winds to spread to other nearby fuels. These conditions may serve as a pass/fail line, however its important the test still numerically ranks the fuels based on each aspect of performance as knowledge on exposure conditions is evolving.

Decks, porches and patios have, similar to fences, been identified as a significant source of structure ignitions (Mell and Maranghides, 2009; Quarles et al., 2012). Some test standards exist for decking materials (e.g. CBC 12-7A-4), however these tests have not been corroborated with exposure conditions that might occur under realistic WUI fires. The exact conditions so that they do not ignite an adjacent house are mostly incorporated into the test standard through measurements of the heat-release rate, however this is not directly applicable to home ignition and more studies on the coupled deck-home should be undertaken to see how previous decks may have ignited a home and minimize those effects. Observed accumulations of firebrands over long timescales on decks (Manzello and Suzuki, 2014) may or may not be represented by the relatively crude wood crib "brand" used in testing.

It is also necessary to consider materials testing in light of weathering. Weathering protocols for different materials and coatings, especially fire retardant materials is another major research need, since the components are all exterior building features which could experience significantly varied weather conditions in different parts of the country and drastically affect performance. Test methods to simulate accelerated weathering should be incorporated on materials that may adversely change in fire performance (Pellegrino et al., 2013). On a similar note, short-term coatings such as gels or foams are an area of significant research need if they are to be operationally used by homeowners or firefighters. While limited testing has been conducted (Urbas, 2013; Glenn, 2012), this has not been corroborated at larger scales with realistic WUI fire conditions to show that they are operationally effective. The same goes for exterior home sprinklers that have been shown to be effective in one case (Johnson, 2008), however the practicality of their use on a large scale or applicability to different fire scenarios is unknown.

An enhanced understanding of how firebrands ignite materials may greatly assist in the development of new standards and new component designs that can resist firebrand showers. A better means to incorporate firebrands in all testing strategies is desirable. Only one test method uses anything similar to a firebrand (ASTM, 2014a); however, this does not incorporate behavior such as the accumulation of firebrands in crevices or corners observed in experimental tests(Manzello, 2014), therefore research and development should work toward a rigorous test standard that incorporates more realistic elements in an economical manner.

If more test methods are coupled with quantitative measures of fire performance in the future it may also be possible to use this data to better evaluate hazard and risk modeling in the WUI, enhancing its usefulness.

Identification of Educational Needs

Often, residents of at-risk WUI communities do not understand areas vulnerable to ignition near their homes or in their broader communities. It is important to provide education on mitigation strategies to different stakeholders within these communities, i.e. home and business owners, community groups, local government, developers, firefighters, etc. So far, a variety of resources such as how-to guides and checklists for home protection are available as part of community education and awareness programs, several of which are provided in the appendix of this report.

Even relatively small education efforts, such as one performed in Florida between 2002 to 2007 have been shown to be a cost-effective way to limit damages from wildfires (Harvey et al., 2004). Increased understanding of people's perceptions of risk may assist in communicating research on effective local and community-wide mitigation strategies to homeowners and other stakeholders within the WUI. Community-wide mitigation efforts such as Firewise or Fire Adapted Communities should continue as they have been seen to be effective in encouraging active participation in mitigation strategies (Harvey et al., 2004). As the science of WUI fires increases, this knowledge must trickle down through various stakeholders. One piece that has only recently started to appear in literature is the influence of firebrand showers on ignition of buildings. As this mechanism appears to be a significant source of losses, it may be worth finding ways to emphasize its effect and ways to minimize ignition from firebrands.

A cultural shift to self-enforcement, and inspections at the local level is also needed. A discontinuity of opinion and enforcement of fuel placement and building practices amongst local officials can provide a lack of public trust and confusion amongst citizens of the community. Unifying codes will certainly assist with this effort.

Finally, guidelines for overall design of WUI communities were hard to come by. Development of these guidelines, especially geared toward professional engineers and architects will enable communities to be better equipped to handle the devastating effects of wildland fires in the WUI from their inception.

Impact of Wildland Fires on Health and Environment

The effects of wildland fires on human health, including respiratory effects, water quality and air pollutants have only started to be explored. The majority of this work focuses on respiratory effects due to small particulate matter (smoke) exposure (Bowman et al., 2005; Kunzli et al., 2006; Fowler et al., 2003). There may be other, unexplored aspects of exposure not yet assessed, such as impacts from water quality or other airborne pollutants. A special focus should be devoted toward effects on firefighters, which are often in close proximity to these fires without any breathing apparatus.

Research continues on the effect of wildland fires on the environment, however no resources were found that coupled the unique influence of WUI fires, where structure losses may contribute a different fraction or spectrum of emissions than vegetative fuels alone (Bryner and Mulholland, 1991). Other recent work indicating that proper prescribed fire use and management practices could sequester 18-25% of CO_2 emissions in the Western US, or as much as 60% in some ecosystems (Widinmyer and Hurteau, 2010) may provide additional motivation for responsible ecosystem fire management.

Firefighting Techniques

While tactics for structural and wildland firefighting are better developed, little guidance is available for operations in the WUI where these two techniques intersect. Further research on best practices for reducing structural losses in a variety of scenarios as well as ways to ensure firefighter safety should be conducted to develop best practices and, perhaps, supplemental training for wildland firefighters tackling WUI fires and vice versa. Guidelines for many factors, especially aimed at optimizing resources such as crew size, water capacity and where to distribute crews during fire spread could be improved. Recent work by Rahn (2010) has shown that the efficiency of a three-person crew fighting a wildfire increses 50% with the addition of a fourth crew member. These types of studies may help to improve the efficiency of suppressing fires in the WUI as well as safety of crews in the future, but need to go beyond just the size of the crew and inspect many other tactics and techniques. Improvement in coordination and planning both for firefighter response and resident evacuation may also improve the effectiveness of suppression efforts.

The virtue of protecting property at the risk of human life should continue to be debated in the community while mitigation efforts which don't require active suppression are pursued to the fullest extent possible.

Effectiveness of Mitigation Strategies

Several recommendations exist for homeowners in terms of strategies to mitigate risks from WUI fires to homes. Many organizations produce check lists for homeowners to follow to decrease risk (provided in the appendix), as well as standards which encourage or require certain mitigation strategies however there is not much literature data to support these changes. Investigations from the Witch and Guejito fires (Maranghides et al., 2013) does cite some effective and ineffective components of Firewise which are incorporated in several other standards and guidelines, however the majority of regulations for WUI homes and communities have not been assessed due to a lack of reliable data. Increased pre- and post- event investigation should be conducted, as recommended above, to address these gaps in communities where such standards have already been implemented such as California's CBC Chapter 7A requirements (CBC, 2009).

Specific requirements, such as the implementation of home fire sprinklers, which is offered to decrease home separation distance from 30 ft to 15 ft in NFPA 1141 have no data in the literature to support them. This is potentially a very high hazard if such fire sprinklers are not installed in the attic and could therefore contribute to firebrand production and increased home-to-home spread. This could be made worse if water supply shortages occur during power outages and firestorms.

Despite the fact that many recommendations are available to homeowners and community planners, few of these recommendations have been scientifically validated. There is a need for research on defensible space: both to quantify the effectiveness of current recommendations and then to standardize the recommendations for defensible space across wildland fire-prone areas (Pellegrino et al., 2013). The size of the fuel modification area and exactly how to treat it at the moment is debatable and certainly dependent on worst-case weather conditions. While standards may not want to explicitly define these spacings, more guidance and tools are necessary based on solid science, such as approvals for specific mulch, vegetation, etc. compared with relative exposures and home construction. Other areas include guidelines for home spacing, access routes, proper storage of nearby flammable materials, effectiveness of fuel breaks, etc.

Roof requirements in NFPA 1144 5.3.1 require compliance with ASTM E 108 for the class that relates to expected wildland fire behavior, however there is no guidance or scientific basis with which to support what types of surroundings may provide different exposure conditions to structures. With recent research showing smoldering ignition of some Class A roofs with accumulated vegetative debris to firebrand showers (Quarles, 2012; Manzello, 2013) highlights the need for further insight to design specific protections and assess them in real wildland fire situations. Vents, eaves, roof and attic components similarly have only limited data to support their design, d construction and location.

The provisions for overhanging buildings or projections from buildings constructed with heavy timber construction, noncombustible material, fire-retardant-treated wood, other ignition-resistant materials or be a 1-hour fire-rated assembly is not based on any WUI-specific research that assesses real hazards from firebrands or convective heating from nearby flames. While some tools exist to calculate radiative ignition between homes, more research and data on actual expected conditions is needed.

Best practices for design, such as those that relate to preventing firebrand accumulation and penetration should be developed and better spelled out to engineers, authorities having jurisdiction (AHJ) and homeowners. Currently most home assessment guides are meant for existing construction, where a design guide is not available for new construction. This is a serious deficiency in the field. Ideally, these may be updated to include more quantitative suggestions that are based on some specific research, testing or defined estimations that engineers could modify for their specific conditions. Detailed pre and post-fire data collection can also help to show the impact these types of changes can make, but only when carefully collected.

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APPENDIX

Homeowner Educational Resources and Programs on the Internet

http://www.wildfireprograms.usda.gov/

Comprehensive index of community wildfire programs anywhere in the United States. Note: this source stopped updating in January, 2010.

Firewise: http://firewise.org/

A project of the National Fire Protection Association which includes a recognition program for communities, online courses and education and wildfire preparedness resources. Resources include courses and documentation on proper documentation in the WUI, how to conduct a community assessment and firefighter safety in the WUI.

Fire Adapted Communities: http://www.fireadapted.org/

Fire Adapted Communities (FAC) is a collaborative effort to bring together effective programs, tools and resource for reducing community wildfire risk. Includes a guide to fire adapted communities they recently published:

Ready, Set, Go! http://www.wildlandfirersg.org/.

The Ready, Set, Go! (RSG) Program, managed by the International Association of Fire Chiefs (IAFC), seeks to develop and improve the dialogue between fire departments and the residents they serve. Launched nationally in March 2011 at the Wildland-Urban Interface (WUI 2011) Conference, the program helps fire departments to teach individuals who live in high risk wildfire areas – and the wildland-urban interface – how to best prepare themselves and their properties against fire threats.

IBHS http://www.disastersafety.org/wildfire/

A service of the Insurance Institute for Business & Home Safety. Includes wildfire home assessment, wildfire fact sheet and many other resources and research results.

National Wildland Fire Coordinating Group: http://www.nwcg.gov/

The NWCG is an operational group designed to coordinate programs of the participating wildfire management agencies. They have several resources including fire prevention and education on the WUI.

Missoula Fire Sciences Laboratory http://firelab.org/applications

A collection of software applications including BehavePlus, FARSITE and FlamMap used for wildland fire simulation and assessment.

Living with Fire http://www.unce.unr.edu/blogs/livingwithfire/

A University of Nevada program that provides a set of consistent wildfire threat reduction recommendations for Nevadans.

eXtension Learn www.extension.org/surviving_wildfire

eXtension is an interactive learning environment delivering research-based information emerging from America's land-grant university system. This section provides information on wildfire with lessons and information for WUI residents.

UC Berkeley Center for Fire Research and Outreach http://ucanr.edu/sites/cfro/

The CFRO provides a forum for coordination on emerging research and tools regarding wildland fire in California. The center facilitates working groups devoted to a specific field or topic of research and management that relates to fire. The Center also addresses areas with Mediterranean climates world-wide.

Fire Hazard Checklists

A. ICC IWUIC Fire Hazard Severity Form

APPENDIX C

FIRE HAZARD SEVERITY FORM

The provisions contained in this appendix are not mandatory unless specifically referenced in the adopting ordinance.

When adopted, this appendix is to be used in place of Table 502.1 to determine the fire hazard severity.

A. Subdivision Design Points

1. Ingress/Egress	
Two or more primary roads	1___
One road	3___
One-way road in, one-way road out	5___
2. Width of Primary Road	
20 feet or more	1___
Less than 20 feet	3___
3. Accessibility	
Road grade 5% or less	1___
Road grade more than 5%	3___
4. Secondary Road Terminus	
Loop roads, cul-de-sacs with an outside turning radius of 45 feet or greater	1___
Cul-de-sac turnaround	
Dead-end roads 200 feet or less in length	3___
Dead-end roads greater than 200 feet in length	5___
5. Street Signs	
Present	1___
Not present	3___

B. Vegetation (IWUIC Definitions)

1. Fuel Types	
Light	1___
Medium	5___
Heavy	10___
2. Defensible Space	
70% or more of site	1___
30% or more, but less than 70% of site	10___
Less than 30% of site	20___

C. Topography

8% or less	1___
More than 8%, but less than 20%	4___
20% or more, but less than 30%	7___
30% or more	10___

D. Roofing Material

Class A Fire Rated	1___
Class B Fire Rated	5___
Class C Fire Rated	10___
Nonrated	20___

E. Fire Protection—Water Source

500 GPM hydrant within 1,000 feet	1___
Hydrant farther than 1,000 feet or draft site	2___
Water source 20 min. or less, round trip	5___
Water source farther than 20 min., and 45 min. or less, round trip	7___
Water source farther than 45 min., round trip	10___

F. Existing Building Construction Materials

Noncombustible siding/deck	1___
Noncombustible siding/combustible deck	5___
Combustible siding and deck	10___

G. Utilities (gas and/or electric)

All underground utilities	1___
One underground, one aboveground	3___
All aboveground	5___

Total for Subdivision

Moderate Hazard	40–59
High Hazard	60–74
Extreme Hazard	75+

B. NFPA 1141 Structure Assessment Rating Form

Table A.4.1.2 Example of Structure Assessment Rating Form

Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1)	From Chimney to Eaves (4.2.2)	From Top of the Exterior Wall to Foundation (4.2.3)	From Foundation to Immediate Landscaped Area (4.2.4)	From Immediate Landscaped Area to Extent of Structure Ignition Zone (4.2.5)
Topographical Features					
(1) Topographical features that adversely affect wildland fire behavior (4.2.1)	0–5				
(2) Areas with history of high fire occurrence (4.3.4)	0–5				
(3) Areas exposed to unusually severe fire weather and strong, dry winds (4.2.1.3)	0–5				
(4) Local weather conditions and prevailing winds (4.2.1.2)	0–5				
(5) Separation of structure on adjacent property that can contribute to fire spread/behavior (4.2.1.3)	0–5			0–5	0–5
Vegetation — Characteristics of predominant vegetation					
(1) Light (e.g., grasses, forbs, sawgrasses, and tundra) NFDRS Fuel Models A, C, L, N, S, and T	5			15	5
(2) Medium (e.g., light brush and small trees) NFDRS Fuel Models D, E, F, H, P, Q, and U	10			20	5
(3) Heavy (e.g., dense brush, timber, and hardwoods) NFDRS Fuel Models B, G, and O	15			25	15
(4) Slash (e.g., timber harvesting residue) NFDRS Fuel Models J, K, and L	15			30	20
Topography (4.2.1.1, 4.2.4, 4.2.5)					
(1) Slope 5–9%				1	1
(2) Slope 10–20%				4	2
(3) Slope 21–30%				7	3
(4) Slope 31–40%				10	6
(5) Slope >41%				15	10
Building Setback, relative to slopes of 30% or more (4.2.1.5, 5.1.3.2)					
(1) ≥30 ft (9.14 m) to slope	1				
(2) <30 ft (9.14 m) to slope	5				
Roofing Materials and Assembly, nonrated (4.2.2.1, 4.2.2.3)		50*			
Ventilation Soffits, without metal mesh or screening (4.2.3.4)		20			
Gutters, combustible (4.2.2.4, 4.2.2.5)		5			

Table A.4.1.2 ***Continued***

Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1)	From Chimney to Eaves (4.2.2)	From Top of the Exterior Wall to Foundation (4.2.3)	From Foundation to Immediate Landscaped Area (4.2.4)	From Immediate Landscaped Area to Extent of Structure Ignition Zone (4.2.5)
Building Construction (predominant)† (4.2.4)					
(1) Noncombustible/fire-resistive/ignition-resistant siding and deck			Low		
(2) Noncombustible/fire-resistive/ignition-resistant siding and combustible deck			Medium		
(3) Combustible siding and deck			High		
Fences and Attachments, combustible (4.2.4.3)				15	
Placement of Gas and Electric Utilities					
(1) One underground, one aboveground	3				
(2) Both aboveground	5				
Fuel Modification within the structure ignition zone (4.2.4, 4.2.5)					
(1) 71–100 ft (21–30 m) of vegetation treatment from the structure(s)					5
(2) 30–70 ft (9–21 m) of vegetation treatment from the structure(s)				7	
(3) <30 ft (9 m) of vegetation treatment from the structure(s)				15	
No Fixed Fire Protection (NFPA 13, 13R, 13D sprinkler system)			5		
TOTALS (if numerical ranking is desired)					
Hazard Rating Scale (Compare with above totals)					
Slight Structure Ignition Hazards from Wildland Fire	0–14	0–14	0–14	0–14	0–14
Moderate Structure Ignition Hazards from Wildland Fire	15–29	15–29	15–29	15–29	15–29
Significant Structure Ignition Hazards from Wildland Fire	30–49	30–49	30–49	30–49	30–49
Severe Structure Ignition Hazards from Wildland Fire	50+	50+	50+	50+	50+

*Nonrated and combustible roof assemblies are predominantly structural exposures and severely increase the ignition hazard from wildland fire.

†The table provides both numerical and value rankings (low, medium, high). The user is urged to assign the value ranking of low, medium, or high based on the other ignition factors prevalent at the assessment site. For example, a deck made of combustible materials might rank low if it is small in size and the rest of the site is in a low fuel loading area that will not promote a large amount of firebrands. That same deck might rate high if it is in an area of high fuel loading that will promote numerous firebrands. Numeric values can be substituted as a local option.

C. Firewise Home Ignition Zone Assessment Mitigation Guide

HOME IGNITION ZONE ASSESSMENT MITIGATION GUIDE

Date of Assessment:__________ Property address: __________ Resident Name: __________ Property Owner:__________

	ASSESSMENT ITEMS	MITIGATION RECOMMENDATIONS
1.	**OVERVIEW OF SURROUNDINGS:**	
	How is the structure positioned in relationship to severe fire behavior?	
	Type of construction:	
2.	**CHIMNEY TO EAVES:**	
	Inspect the roof – noncombustible? Shingles missing? Shingles flat with no gaps?	
	Gutters – present? Noncombustible?	
	Litter on roof, in gutters, and crevices:	

3.	Eaves to Foundation:	
	Attic, eave, soffit vents, and crawl spaces:	
	Inspect windows and screens – metal screens? Multi-paned windows? Picture windows facing vegetation?	
	Walls and attachments: noncombustible? Will they collect litter?	
	Decks (combustible materials?)	
	Fences:	
	Flammable material next to or under the structure:	
	Combustible materials near or on the structure where walls meet roof or decking surfaces:	
	Crawl space, attic vents, soffits:	
	Nooks and crannies and other small spaces : All appear to be in excellent condition and protected.	

4.	**FOUNDATION TO IMMEDIATE LANDSCAPED AREA:**	
	Landscaped (*Managed*) vegetation – separation distances, maintenance, plant selection; Firewise landscaping zones?	
	Propane Tanks:	
	Vehicle and RV use and parking, including lawn mowers, etc.:	
5.	**IMMEDIATE LANDSCAPED AREA EXTENT OF THE HOME IGNITION ZONE:**	
	Inspect vegetation clearance and crown separation:	

D. IBHS Wildfire Home and Property Checklist

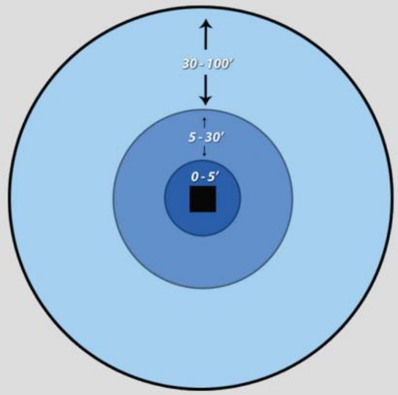
Wildfire Home and Property Checklist

Use the following checklist to help determine what parts of a home and the surrounding property may be most vulnerable during a wildfire. Reduce those risks with the guidance provided in the following pages.

Insurance Institute for Business & Home Safety®

PROPERTY

- ❑ Slope / Terrain
- ❑ Location of home on parcel
- ❑ Defensible space
  - ❑ 0-5′
  - ❑ 5-30′
  - ❑ 30-100′



Know Your Space

Create defensible space to keep wildfire from getting too close to your property.

HOME

- ❑ Roof
  - ❑ Fire rating of covering
  - ❑ Shape
  - ❑ Edges
  - ❑ Skylights
- ❑ Exterior Wall
  - ❑ Type
  - ❑ Foundation type / clearance
  - ❑ Eave type (under-eave construction)
  - ❑ Windows / Doors

- ❑ Vents and Other Openings
  - ❑ Face perpendicular to wind
  - ❑ Face parallel to wind
  - ❑ Ridge vents
  - ❑ Mesh screens
- ❑ Attachments
  - ❑ Deck
  - ❑ Enclosure
  - ❑ Garage
  - ❑ Fence

Insurance Institute for Business & Home Safety 2

Assessment:

WHAT TO KNOW TO BETTER PROTECT YOUR HOME FROM WILDFIRE

SLOPE

The slope of the land around your home is a major consideration in assessing wildfire risk. Wildfires burn up a slope faster and more intensely than along flat ground. A steeper slope will result in a faster moving fire, with longer flame lengths.

Homes located mid- or top of a slope (without set back) are generally more vulnerable because of increased flame length and intensity of a fire moving up the slope. Depending on the location of your home, defensible space may need to be increased.

ZONE 1

0-5 ft. around the perimeter

The objective of this zone is to reduce the chance of wind-blown embers from a nearby fire landing near the home, igniting combustible debris or materials and exposing the home to flames. This zone is closest to the house, so it requires the most careful selection and management of vegetation and other materials.

ZONE 2

5 ft.–30 ft. around the perimeter (or to the property line)

The objective of this zone is to create and maintain a landscape that, if ignited, will not readily transmit fire to the home. Trees and shrubs in this zone should be in well spaced groupings and well maintained. Ladder fuels (i.e., shorter vegetation or shrubs under taller trees) should be avoided to prevent the fire from climbing into the crown or upper portions of trees. If these groupings were to be ignited by wind-blown embers, the resulting fire should not be able to threaten the home by a radiant heat exposure or by flames being able to touch the exterior surfaces of your home.

ZONE 3

30 ft. - 100 ft. (or to the property line)

The objective of vegetation management in this zone is to reduce the energy and speed of the wildfire. Tree and brush spacing should force the fire in the tops of the tree, brush or shrub crowns to drop to the ground. Flame length should decrease.

Assessment:

WHAT TO KNOW TO BETTER PROTECT YOUR HOME FROM WILDFIRE

TREE BRANCHES OVERHANGING OR WITHIN 10 FT. OF THE ROOF

Branches overhanging your roof will result in more debris accumulation on your roof, in your gutters and near your home.

OTHER COMBUSTIBLE ITEMS/STRUCTURES

A fire in close proximity to a propane tank can result in gas releasing at the pressure relief valve, potentially resulting in a column of flame. Flames impinging on the upper surface of the tank can result in an explosion, particularly when the fuel level is low.

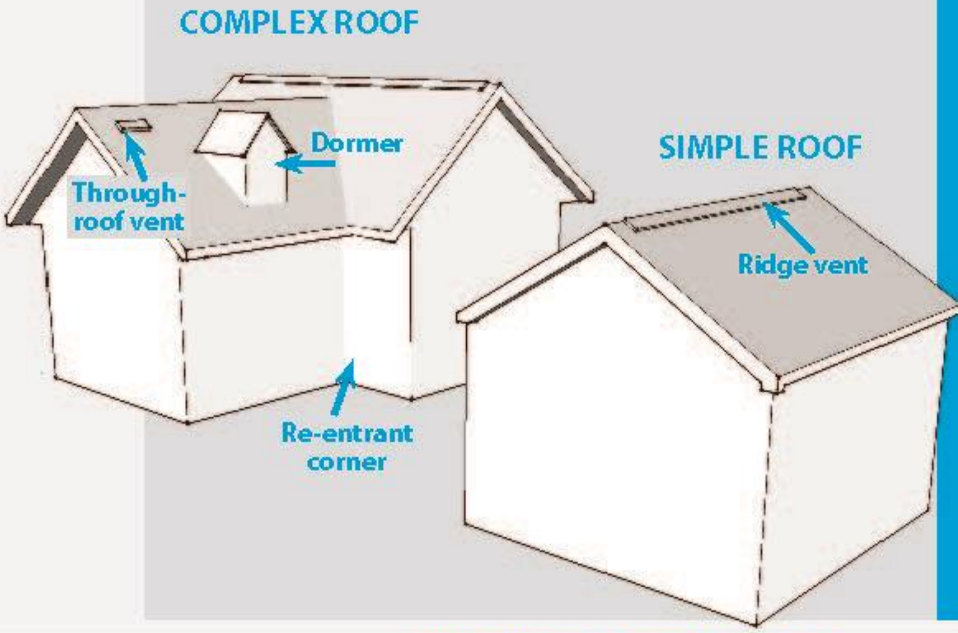
If ignited, other combustible items on your property, such as a tool storage shed or gazebo, could expose your home to radiant heat and flames.

ROOF SLOPE

Roof slope is important because it will affect the amount of debris that accumulates and will also influence the radiant exposure to the roof if nearby vegetation or buildings ignite.

ROOF MATERIAL

Your roof is a large, relatively horizontal surface where debris from trees and other vegetation can accumulate. When a wildfire is threatening your home, wind-blown embers can also land on your roof and ignite this debris, potentially putting your home at risk. Your roof must be able to resist the burning embers from the wildfire and flames from ignited debris. Roof coverings are rated as Class A, B, or C. A Class A fire-rated roof covering offers the best protection.



Assessment:

WHAT TO KNOW TO BETTER PROTECT YOUR HOME FROM WILDFIRE

ROOF DESIGN

Even with a Class A roof, locations where the roof covering meets another material can be vulnerable. Debris can accumulate at these locations, and so can wind-blown embers. It is important to inspect these locations as they are potential "weak links" on your roof (for example, wood shingle siding on a dormer next to a Class A roof covering), or areas where the Class A roof can be by-passed (for example, non-bird stopped tiles at the roof edge).

SKYLIGHTS

During a wildfire, skylights could be an entry point for wind-blown embers and flames if the glass or Plexiglas opening were to fail. Operable skylights would also be vulnerable if left open when a wildfire threatens. Debris accumulation on top of and around skylights will be greater on flat or lower-sloped roofs. Dome-type skylights use an acrylic glass product and flat-type skylights use tempered or other specialized glass. Performance differences between acrylic and glass would make the flat-type skylights less vulnerable to wildfire exposures. All skylights incorporate metal flashing at the base, where it integrates with the roof.

VENTS

Most homes have enclosed spaces that are vented, including attics and crawl spaces. Other openings in an exterior wall include those for dryer vents and vents to supply make-up air for rooms where gas appliances are operating (e.g., furnace and/or water heater). Wind-blown embers that enter the attic or other enclosed spaces can ignite combustible materials that have either accumulated there or have been stored there.

Vents on vertical walls or surfaces have been shown to be vulnerable to the entry of embers. For the attic, these vents would include gable end vents, through-roof vents with a dormer face and under-eave vents used in open-eave construction. Crawl space vents (also called foundation vents), dryer vents and vents to supply make-up air would also be vulnerable to the entry of embers.

Some attic and foundation vents that have been specifically designed to resist the entry of embers and flames are commercially available. Your local fire or building department would know if any of these vents have been approved for use in your area.

Consider using closure devices. There are commercially available options or you can make your own and store in a place where they can be easily retrieved and installed when wildfire threatens. The commercial devices should be deactivated, or home-made covers removed, after the wildfire passes. Some gable end and crawl space vents have been designed to resist the entry of embers and flames - check with your local fire or building official to find out if any have been approved for use in your area.

EXTERIOR WALL - FOUNDATION

There are three basic types of foundations: concrete slab-on-grade, raised floor (i.e., one having a crawl space) and pier (or "post") and beam (unless a perimeter skirting has been installed, this one will be open underneath). An "open underneath" foundation will be vulnerable if combustible materials or vegetation and debris has accumulated or has been stored there. Raised floor and slab-on-grade foundations can be vulnerable if the distance from

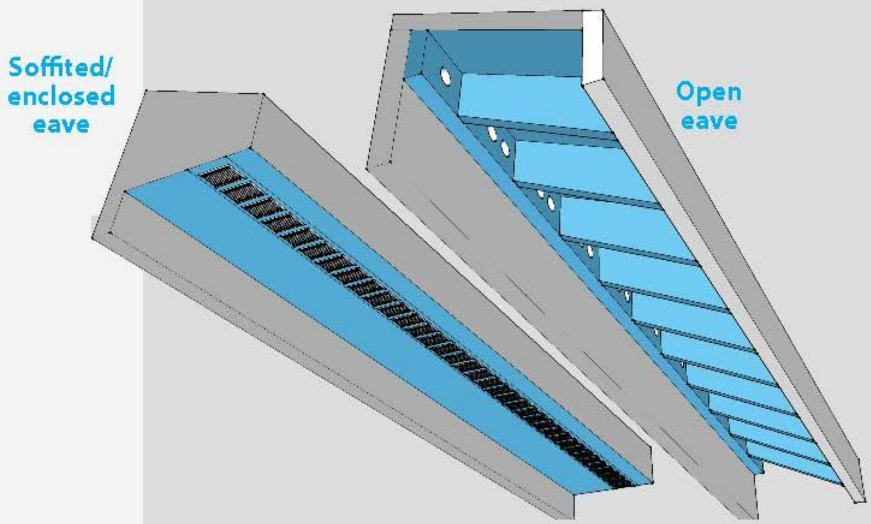
Assessment:

WHAT TO KNOW TO BETTER PROTECT YOUR HOME FROM WILDFIRE

the ground to the siding is much less than 6 in., or, in the case of a crawl space, ember entry occurs through a foundation vent. Combustible siding will be more vulnerable if the ground-to-siding clearance is less than 6-in. if embers can accumulate at the base of the wall. The use of combustible mulch and woody vegetation will make this area even more susceptible to ignition from wind-blown embers. Untreated wood shingle and vinyl siding are relatively more vulnerable to flame contact and radiant heat exposures that would result from an ember ignition of near-home debris or other combustible items.

UNDER-EAVE CONSTRUCTION

Under-eave construction consists of either "open-eave framing" or is enclosed with a "soffit" material (also called "boxing-in"). Vent openings are often found in this area. Vents in open-eave construction can be vulnerable to the entry of embers, and are more vulnerable to ember entry than vents located in a soffited eave. Open-eave construction can also trap heat if subjected to flames, resulting in more rapid ignition of combustible construction materials and lateral flame spread. Flames reaching the under-eave area would be more likely if combustible vegetation and mulch were included in the 0-5 ft. "near-home" zone and similarly, if combustible siding were used.



EXTERIOR WALL - MATERIAL

Siding is vulnerable when it ignites and flames or embers get into the cavity behind it or if the flames spread vertically, impinging on windows and the eave. With inadequate ground-to-siding clearance, accumulated embers can ignite combustible siding directly. Ignition is more likely if combustible siding is exposed to a direct flame contact or extended radiant heat exposure. The chance of direct flame contact is greater if you haven't created

Assessment:

WHAT TO KNOW TO BETTER PROTECT YOUR HOME FROM WILDFIRE

and maintained a 0-5 ft. noncombustible zone around your home. An extended radiant heat exposure is possible if nearby combustible materials (for example, a firewood pile) or a nearby building ignite. Untreated wood shingle and vinyl siding are relatively more vulnerable to flame contact and radiant heat exposures.

RE-ENTRANT (INTERIOR) CORNER

An interior corner that is constructed using combustible siding and trim will be more vulnerable to flames. If ignited, flames will spread vertically more quickly.

WALL VENTS AND OPENINGS

Vents located on a vertical wall, including crawl space vents (also called foundation vents), gable end vents, and other openings such as a dryer vent, will be very vulnerable to the entry of wind-blown embers.

WINDOWS

An open window is the most vulnerable window when a wildfire threatens - embers can easily enter the home. Closed windows are vulnerable to radiant heat and direct flame contact exposures. If the frame ignites or melts, the fire may burn into the stud cavity and into the living space of the home. If glass breaks, embers and flame can easily enter the home. Of these, the glass is the most vulnerable component.

GARAGE (ATTACHED OR DETACHED)

Most people store combustible materials in their garage. Garage (vehicle access) doors, particularly on older garages, can have small gaps at the top, sides and bottom that can allow embers to enter. These embers can ignite combustible materials stored in the garage.

DECK

Your decks is a vulnerable part of your home when it ignites. A burning deck will expose the building to radiant heat and flames, potentially igniting combustible siding and breaking glass in windows and doors. The materials used to build the deck, combustible materials you store under your deck, vegetation around it and the location of your deck relative to the slope around your house all contribute to how vulnerable your deck will be. Debris that accumulates between deck boards and at deck-to-wall intersections can be ignited by embers. Rotted wood deck boards and structural support members are more easily ignited when they are dry.

Checklist:
MITIGATION ACTIONS OR RETROFIT OPTIONS

$ < $500
$$ $500 - $1,000
$$$ $1,000 - $5,000
$$$$ >$5,000

SLOPE

Is your home located in the middle of a steep slope or at the top of a slope with minimal setback?

❑ If yes, increase vegetation management in the 5 ft. to 100 ft. zones. Consider installing a noncombustible wall within 15-20 ft. of the down slope side of your home, particularly if you have a deck overhanging the slope.

YOUR DEFENSIBLE SPACE IS COMPRISED OF THESE THREE ZONES. THE SELECTION AND MAINTENANCE OF VEGETATION AND OTHER COMBUSTIBLE ITEMS IN THESE ZONES WILL DETERMINE HOW ADEQUATE YOUR DEFENSIBLE SPACE IS.

ZONE 1

0-5 ft. around the perimeter of the home

❑ Install hard surfaces in this zone, such as a concrete walkway, or use noncombustible mulch products, such as rock. Keep the lawn well irrigated and use low-growing herbaceous (non-woody) plants. Shrubs and trees are not recommended in this zone. Remove dead vegetation and implement a maintenance strategy to keep the area clear of dead plant materials. $-$$

ZONE 2

5 ft.–30 ft. around the perimeter (or to the property line)

❑ Create islands or groupings of vegetation to form a discontinuous path of vegetation to make it difficult for the fire to burn directly to your home. Remove dead plant material and tree branches. Remove lower tree branches and shrubs positioned under the tree line so that a surface fire cannot reach the tree crown. Trees located within this zone should be maintained with a minimum horizontal spacing of 10 ft. between crowns, with the distance increasing with slope. Prune limbs and branches to a height of up to 15 ft. For shorter trees, pruning should not exceed one-third of the tree height. Relocate propane tanks larger than 125 gallons (water capacity) at least 30 ft. from your house. Create 10 ft. of Zone 1 defensible space around the tank. Consider surrounding three sides with a noncombustible wall to help protect it. Free - $$$

ZONE 3

30 ft. - 100 ft. (or to the property line)

❑ Trees located in this zone should be maintained with a minimum horizontal spacing of 10 ft. between crowns, with this distance increasing with slope. Ladder fuels under taller trees should be eliminated. Separation between groupings of shrubs and bushes should be created and maintained. Remove dead plant material from all vegetation. Vegetation management beyond 100 ft. should be considered if the home is located on a steep slope. Free - $$$

Does your home have a tool shed, detached garage, play set or other structures in the yard?

❑ Create defensible space around secondary buildings or relocate them at least 30 ft. from your home. Consider a noncombustible material for a trellis. Carefully maintain vegetation used on trellis-type structures, pruning regularly to remove dead vegetation. Combustible materials used for play sets are typically larger dimensions (and therefore more difficult to ignite). Combustible wood/bark or rubber mulch that are more commonly used as surfacing materials around play sets are easily ignited by embers. Play sets with combustible mulch surfacing materials should be relocated at least 30 ft. from your home. Free - $$

ROOF COVERING

Do you have a Class A fire-rated roof?

❑ If not, choose a product rated Class A when it's time to re-roof. Non-rated products include untreated wood shakes or shingles. Other roof coverings may carry a Class B or C fire rating. A Class A fire-rated roofing product offers the best protection. $$$$

Checklist:
MITIGATION ACTIONS OR RETROFIT OPTIONS

$ < $500
$$ $500 - $1,000
$$$ $1,000 - $5,000
$$$$ >$5,000

ROOF EDGE(S)

Are your gutters full of debris?

- ❑ If yes and you have a *SIMPLE ROOF DESIGN*, clean out gutters and install a drip edge at the roof edge to protect any exposed roof sheathing or fascia. Free - $$
- ❑ If yes and you have a *COMPLEX ROOF*, clean out gutters and install a drip edge at the roof edge to protect any exposed roof sheathing or fascia. Remove any debris that has accumulated at roof-to-wall intersections, for example, near a dormer or a chimney. For added protection, consider replacing combustible siding at any "intersection" location with a noncombustible or ignition resistant siding product. Metal step flashing extending up from the roof a minimum of 6 in. can be installed at the base of combustible siding in lieu of replacing it (integrate with siding to avoid moisture-related degradation problems). If necessary, consult a roofing professional to get help with this. If windows are present, replace with ones that have dual / multi-pane, tempered glass. Free -$$$

Do gaps or openings exist between the roof covering and the roof deck? These gaps are common with clay barrel-style roofs and some types of metal and cement (flat) tile roof coverings. The gaps can occur at the roof eave or ridge.

- ❑ If yes, fill the space with either a commercially available "bird stop" material or plug with a mortar mix (the material used between layers of bricks). This material will minimize the accumulation of debris than can accumulate between the roof covering and the roof sheathing, and will also limit the intrusion of embers when a wildfire threatens your home. $-$$

VENTS ON YOUR ROOF

Are the attic vents located on your roof covered with screening that is free of debris?

- ❑ If there is no screening, install 1/8 in. metal mesh screening. $-$$
- ❑ If you have a turbine vent, enter the attic and inspect the location where the vent attaches to the roof. Attach 1/8 in. screening to the roof sheathing if none is present. $-$$
- ❑ If you have dormer-face vents, replace them with a low-profile vent. $-$$
- ❑ If you have ridge vents, they should be rated for high-wind / rain exposure, and specifically should be a Florida Building Code High Velocity Hurricane Zone approved ridge vent, regardless of where you are in the country. $-$$
- ❑ Consult your local fire or building department to find out if any vents designed to resist the entry of embers and flames have been approved for use in your area. Free

SKYLIGHTS

Are skylights installed on a flat or low-sloped roof?

- ❑ Remove accumulated debris next to and on the skylight. Free

Do you have a dome-type skylight?

- ❑ If yes, consider replacing it with a flat, tempered glass skylight. If the skylight is installed on a steep roof and if vegetation is at the same level, remove and prune vegetation, clear away debris, and trim overhanging limbs. Free - $$
- ❑ Keep operable skylights closed when a wildfire threatens. Free

FOUNDATIONS

Do you have a post-and-beam style foundation?

- ❑ If yes, enclose it with a noncombustible material–this process is sometimes called "skirting". Ventilate enclosed space according to your building code requirements. All foundation vents should have 1/8 in. corrosion-resistant metal screening that is in good condition. $-$$$
- ❑ Remove combustible materials stored in the crawl space, or from under the building if you have a non-skirted post-and-beam foundation. Free

Checklist:

MITIGATION ACTIONS OR RETROFIT OPTIONS

$ < $500
$$ $500 - $1,000
$$$ $1,000 - $5,000
$$$$ >$5,000

VENTS ON THE EXTERIOR WALLS

Do you have foundation vents that are closeable?

- ❑ Some foundation vents are closeable - these vents should be closed when a wildfire threatens, but should be opened after the wildfire has passed. Some foundation vents have been designed to resist the entry of embers and flames - check with your local fire or building official to find out if any have been approved for use in your area. Remove combustible materials stored in the crawl space. Free

Do you have vent covers for foundation and/ or gable end vents?

- ❑ If not, consider using closure devices. There are commercially available options or you can make your own and store in a place where they can be easily retrieved and installed when wildfire threatens. The commercial devices should be deactivated, or home-made covers removed, after the wildfire passes. Some gable end and crawl space vents have been designed to resist the entry of embers and flames–check with your local fire or building official to find out if any have been approved for use in your area. $$

Do you have other vent openings on the wall?

- ❑ Dryer vents and wall-mounted make-up air openings for for furnaces should be screened with 1/8 in. corrosion resistant metal mesh. Consider installing a louver-type dryer vent that is closed unless the dryer is running. $

SIDING

Do you have combustible siding?

- ❑ If yes, create a 0-5 ft. defensible space zone next your home. Remove any accumulated debris as necessary. If siding extends to grade, consult with contractor to determine if your foundation would allow some siding at the base of the wall to be removed to obtain the 6 in. clearance. Moisture-related degradation and insect damage may be present in some siding products that have been installed such that it extends to grade. Free - $$
- ❑ Examine your siding for locations where embers could accumulate or lodge. Apply caulk at trim-to-siding locations where it is missing or has failed ($). $ - $$
- ❑ If you plan to re-side your house, use a noncombustible or ignition resistant material for the siding and corner trim. If you haven't already done so, create a 0-5 ft. noncombustible zone in this area. $$$$

EAVES

Do you have open-eave framing?

- ❑ If yes, consider converting open-eave framing to a boxed-in or soffited-eave design. Venting in the soffit material (and between the soffit and attic space) must be maintained. If you haven't already done so, create a 0-5 ft. noncombustible zone next your home. $$$

Do you have vents in the eaves?

- ❑ If yes, all vents should be covered with 1/8 in. mesh corrosion-resistant metal screening. If an open-eave construction is maintained: Closure devices for vents located in the blocking of open-eave framing are commercially available. Consider purchasing these or making them from 1/4-in. plywood or thin sheet metal. Install these devices when a wildfire threatens and remove or open them after the threat has passed. Under-eave vents have been designed to resist the entry of embers and flames–check with your local fire or building official to find out if any have been approved for use in your area. $-$$$

Checklist:

MITIGATION ACTIONS OR RETROFIT OPTIONS

$ < $500
$$ $500 - $1,000
$$$ $1,000 - $5,000
$$$$ >$5,000

WINDOWS

Do you have single-pane windows?

- ❑ If yes, replace single-pane windows with dual or multi- pane windows, preferably ones with tempered glass. $$$ - $$$$
- ❑ Install window screening to improve performance against radiant heat exposures and to minimize the size and number of embers that could enter the home. Both plastic-clad fiberglass and metal screening will reduce radiant exposure to the glass and protect against ember entry but neither will protect against flames. The fiberglass screen will fail if exposed to flames, thereby allowing embers to enter if the window glass has also failed. If you haven't already done so, create a 0-5 ft. noncombustible zone near your home. $-$$

GARAGE (DETACHED OR ATTACHED)

Do you have a garage door?

- ❑ If yes, weather seal the perimeter of garage doors. $
- ❑ If you do not have a garage door, consider installing one to help protect combustible materials stored there. $$

DECK

Do you have a deck?

- ❑ If your deck overhangs a steep slope, be sure your defensible space is sufficient to minimize flames spreading up the hill and reduce flame length to minimize the chance for a flame contact exposure to the underside of the deck. Consider building a noncombustible wall across the slope approximately 15–20 feet from the edge of the deck. Free - $$$
- ❑ Do not store combustible materials under your deck. If you have no other option, installing a noncombustible siding product around the deck perimeter may be an option. Be sure the enclosed space is adequately ventilated to minimize the chance of water-related damage (i.e., fungal decay, fastener corrosion, etc.). Free - $$$
- ❑ Most deck boards are combustible, including wood, plastic and wood-plastic composites. Solid surface decks, such as those made from lightweight concrete, are usually noncombustible, but are also more expensive. If you live in a wildfire-prone area anywhere in the country, when it's time to replace deck boards, choose a product that complies with the requirements of the California Building Code, as provided in the Office of the State Fire Marshal Wildland Urban Interface (WUI) Handbook (http://osfm.fire.ca.gov/strucfireengineer/strucfireengineer_bml.php). $$$
- ❑ Regularly clean out debris from between deck board joints and other areas where debris has accumulated. Check the condition of wood deck boards and structural support members–replace or repair rotted members. Free
- ❑ When a wildfire threatens, move combustible deck furniture and cushions inside or move as far away from the house as possible. Treat other combustible items, such as a broom, as your furniture and move them inside or far away from the house. Any LP tank for a grill should be moved off the deck and away from the home. Free

FENCE

Do you have a fence?

- ❑ Replace any combustible fencing that attaches directly to your home with a noncombustible section that is at least 5 ft. long. A chain link gate or fence, a wood frame fence with metal mesh infill, or other noncombustible material can be used. If metal wire is used, do not allow climbing vegetation to grow on the fence–this would defeat the purpose of the noncombustible material. $-$$

END