A Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part II: Response of Components and Systems and Mitigation Strategies in the United States

Raquel Hakes[1], Sara Caton[1,2], Daniel J. Gorham[3] and Michael J. Gollner[1,*]

[1]Department of Fire Protection Engineering, University of Maryland, 3106 J.M. Patterson Building, College Park, MD 20742-3031, USA

[2]Fire Research Division, Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Dr., Gaithersburg, MD 20899, USA

[3]Fire Protection Research Foundation, 1 Batterymarch Park, Quincy, MA 02169-7471, USA

*Corresponding author, mgollner@umd.edu

Abstract

Structure loss in wildland fires has significantly increased over the past few decades, affected by increased development in rural areas, changing fuel management policies, and climate change, all of which are projected to increase in the future. This paper is Part II of a two-part review, which presents a summary of fundamental and applied research on pathways to fire spread in the wildland urban interface (WUI). Part I discussed the fundamentals of wildland fire spread via radiative heat transfer, direct flame contact, and firebrand exposure. Here in Part II, we cover the response of building components and systems, as well as mitigation strategies used to prevent fire spread into and within communities in the United States. Post-fire investigations, full-scale structural testing, individual component testing, and combined systems or assembly testing have been used to identify building component and system vulnerabilities such as roofs, vents, siding, decks, fences, and mulch. Using results from these tests and investigations at different scales, some knowledge has been gained on specific vulnerabilities and the effectiveness of mitigation strategies, but a quantitative framework has not yet been established. On a community level, the layout of structures and the space between them has been shown to be incredibly important in mitigating wildfire risk. More locally, defensible space around homes has been effective in mitigating exposure from both radiation and direct flame contact. Firebrands still remain a challenge; however, many design recommendations have been proposed to harden structures against firebrand exposures. Recommendations for future research and development are also presented.

Keywords: wildland urban interface, WUI, wildfire, wildland fire, firebrands, embers, fire spread

Sara Caton: scaton@terpmail.umd.edu

Raquel Hakes: rhakes@terpmail.umd.edu

Daniel Gorham: DGorham@nfpa.org

Michael Gollner: mgollner@umd.edu

A Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part II: Response of Components and Systems and Mitigation Strategies in the United States

Abstract

Structure loss in wildland fires has significantly increased over the past few decades, affected by increased development in rural areas, changing fuel management policies, and climate change, all of which are projected to increase in the future. This paper is Part II of a two-part review, which presents a summary of fundamental and applied research on pathways to fire spread in the wildland urban interface (WUI). Part I discussed the fundamentals of wildland fire spread via radiative heat transfer, direct flame contact, and firebrand exposure. Here in Part II, we cover the response of building components and systems, as well as mitigation strategies used to prevent fire spread into and within communities in the United States. Post-fire investigations, full-scale structural testing, individual component testing, and combined systems or assembly testing have been used to identify building component and system vulnerabilities such as roofs, vents, siding, decks, fences, and mulch. Using results from these tests and investigations at different scales, some knowledge has been gained on specific vulnerabilities and the effectiveness of mitigation strategies, but a quantitative framework has not yet been established. On a community level, the layout of structures and the space between them has been shown to be incredibly important in mitigating wildfire risk. More locally, defensible space around homes has been effective in mitigating exposure from both radiation and direct flame contact. Firebrands still remain a challenge; however, many design recommendations have been proposed to harden structures against firebrand exposures. Recommendations for future research and development are also presented.

1. Introduction

Building components and systems in the WUI react to the exposure conditions produced by nearby wildland fires. In Part I of this review, these exposure conditions were defined as flame radiation, direct flame contact, and firebrand exposure [1]. Depending on the exposure conditions, structures may ignite as a wildland fire spreads toward a WUI community. Ultimately, structures must ignite in order for fires to spread into the community. Therefore, understanding the ignition potential of structures and mitigation strategies to reduce or prevent their ignition is one approach to reducing WUI losses. These mitigation strategies may include engineering-based approaches to hardening structures, community design and planning practices, and active or passive suppression strategies. Detailed information on structure ignition will also be invaluable toward improving risk-based planning tools and the development of future WUI fire models.

In Part II of this review, we address specific vulnerabilities of components and systems and their response to radiation, direct flame contact, and firebrands. Figure 1 shows a structure with components and systems which have well-known vulnerabilities labeled: roofing, dormers, gutters, eaves and vents, sidings, windows and glazing, decks, porches and patios, fences, and mulch and debris. Section 2 follows the framework suggested by the National Institute of

Standards and Technology (NIST) [2]. Here we review information available in each area and provide references to quantifiable information for risk-informed planning where cited. Mitigation strategies that have been shown to reduce the potential for structure ignition and fire spread, from the scale of individual components to whole communities, are summarized in Section 3. Finally, gaps in current understanding and recommendations for future work are presented in Section 4.

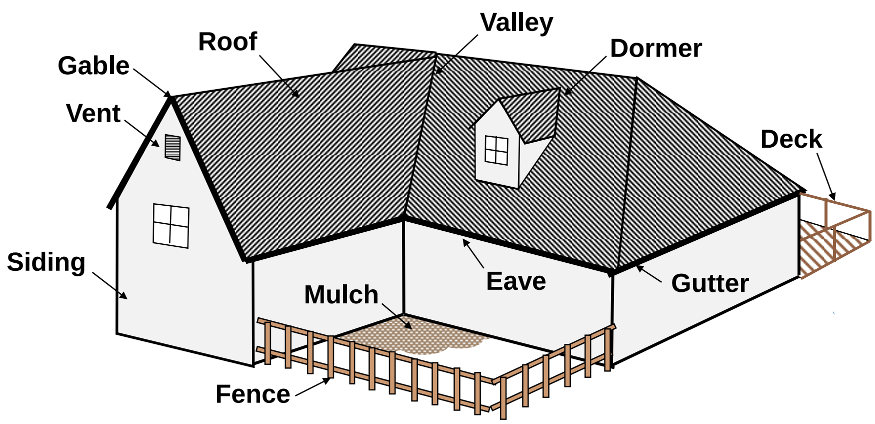

Figure 1. Diagram of typical building components and systems considered as pathways to ignition in typical WUI construction.

2. Components and Systems

As a structure in the WUI is exposed to radiation, flame contact, and firebrands, specific components on the structure may begin flaming directly or first smolder and then transition to flaming ignition. This section reviews the different components shown in Figure 1, which have been found to be vulnerable to these exposure conditions.

2.1 Roofing

Wood shake and shingle roofs are often associated with increased fire risk due to their easy ignitability (with many crevices) and large surface area of flammable material, as well as their propensity to produce a large number of aerodynamically-shaped firebrands upon ignition, further spreading the fire [3]. Wood shakes, in particular, have long been recognized as a significant contributor to fire spread through urban communities. After the 1991 Oakland Hills fire in California, it was estimated that each burning home with a non-fire-retardant wood shake roof contributed to the ignition of ten other homes [4].

Fire ratings of roofs are typically governed by the American Society for Testing and Materials (ASTM) Standard E-108 [5], Underwriters Laboratory (UL) Standard 790 [6], and the National Fire Protection Association (NFPA) Standard 276 [7]. These standards follow essentially the same test protocols and are designed to evaluate three fire-related characteristics of a roof assembly: its ability to resist the spread of fire into the attic, to resist flame spread onto the roof covering, and to resist generating burning firebrands. Roofs are ranked into three classes: Class A, B, and C, where Class A is considered the most effective against severe fire testing exposures. Tests include an air flow over an inclined roof, which is subjected both to flames and burning “brands”, namely a wood crib made of Douglas fir sticks. 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 (CBC) require a Class A rated roof in high fire severity zones [8], which are further described in section 3.4.

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 in gaps [9]. Embers generated by the wood crib are blown off the roof and, therefore, do not serve as a realistic simulation of firebrand attack because they cannot accumulate.

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, which may affect the performance of fire retardants. Studies on the effectiveness of fire retardants after significant weathering have been conducted by the Forest Products Laboratory (FPL) in Madison, Wisconsin. A series of studies by Holmes et al. [10–13] evaluated various fire retardant treatment systems for wood shingles and shakes for their fire performance and durability. An 8-foot tunnel test (ASTM E-286-69), a modified Schlyter Test simulating vertical flame spread [13], and a modified class C burning-brand test (ASTM E-108-58) were used in the evaluation. Some treatments were able to achieve Class B or C fire resistance (ASTM E-108 [5]); however, no treatments achieved a Class A rating, which is a worrying factor in their use in the WUI. Accelerated weathering tests also found leaching of chemicals which degraded performance when re-evaluated after up to 10 years of exposure [11]. More recent reviews are also available on the use of fire retardants for wood [14, 15], including their degradation over time [16], but they do not specifically address roofs in the WUI. These reviews highlight a lack of consistency in terms of fire performance and wood preservation testing [16]. The authors recommended a uniform testing method to compare preservatives added to wood and their effectiveness under fire conditions.

Table 1 highlights several experiments that have advanced the knowledge of current roofing vulnerabilities specific for WUI protection. Investigations have included roofing assemblies of asphalt shingles, wood shake, and ceramic and terracotta tile, which have been exposed to firebrand showers and wind, a missing component in current testing standards.

Table 1 Experiments involving WUI firebrand exposure to roofs

Authors	Assembly	Exposure	Results
Quarles [17]	Untreated wood shake roof and asphalt shingle assembly on full-scale home	Wind-blown embers, 4.5 – 6.7 m/s wind speed	Brands ignited the wood shake roof and penetrated and ignited the structure. The debris in gutter ignited and damaged the asphalt shingles but fire did not penetrate through to the attic
Manzello et al. [18]	Full roofing assembly (oriented strand board (OSB), tar paper, asphalt shingles) and exposed OSB, with 35° pitch and crevice angles 60-135° (see Fig. 2).	NIST Dragon, 7 m/s wind speed	Brands collected and initiated smoldering in steeper crevices of OSB but did not transition to flaming for the test duration

Manzello et al. [19]	Four variations of: OSB, tar paper, ceramic tile, and bird stops with 25° pitch. Three conditions: perfectly aligned (new), vegetation under tiles, and gaps between ceramic tiles	NIST Dragon, 7 and 9 m/s wind speed	Smoldering ignition occurred under ceramic tiles in many cases, with transition to flaming only when tar paper was removed
Manzello [20]	Concrete and terracotta (flat and profile tile) with aluminum foil laminate bonded with fire retardant adhesive polymer fabric under tile battens.	NIST Dragon (10 g/m^{2}s mass flux), 9 m/s wind speed	Firebrands penetrated tile gaps and melted sarking material but did not cause ignition. Flat tiles allowed less penetration and melting due to their interlocking design

Recent full-scale research performed at the Insurance Institute for Business and Home Safety (IBHS) Research Center exposed a full house to a firebrand shower. Roof ignition occurred 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 vegetative debris, even for properly rated roofs [17]. Dormers provided a crevice into which debris could accumulate near a roof-to-siding intersection. Ignition of rated roofs at the roof-to-siding intersection shows additional gaps in the current roof testing methodology. Tests incorporating the junction between different components – here the connection between the plane of the roof and the siding – are clearly needed.

Manzello has investigated the performance of a number of roofing components using a firebrand generator (NIST Dragon), which was described in more detail in Part I of this report [1], at the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FWRTF) in Japan. Angled crevices of asphalt shingle roofing assemblies (oriented strand board (OSB), tar paper and asphalt shingles), shown in Figure 2, were subjected to firebrand showers to study the influence of crevices, which could be formed by a roof valley, on promoting firebrand ignition. To simulate worst-case weathering or damage, some tests were performed with OSB alone. Firebrands were found to cause flaming ignition of the inclined samples with only OSB exposed at a 60° crevice inclination and smoldering ignition at 90°. As the angle was increased to 135°, ignition no longer occurred. For asphalt shingle roofing assemblies, firebrands accumulated at the seams of shingles at 60° and 90°; however, they only melted some of the roofing shingles and did not ignite the roof [18].

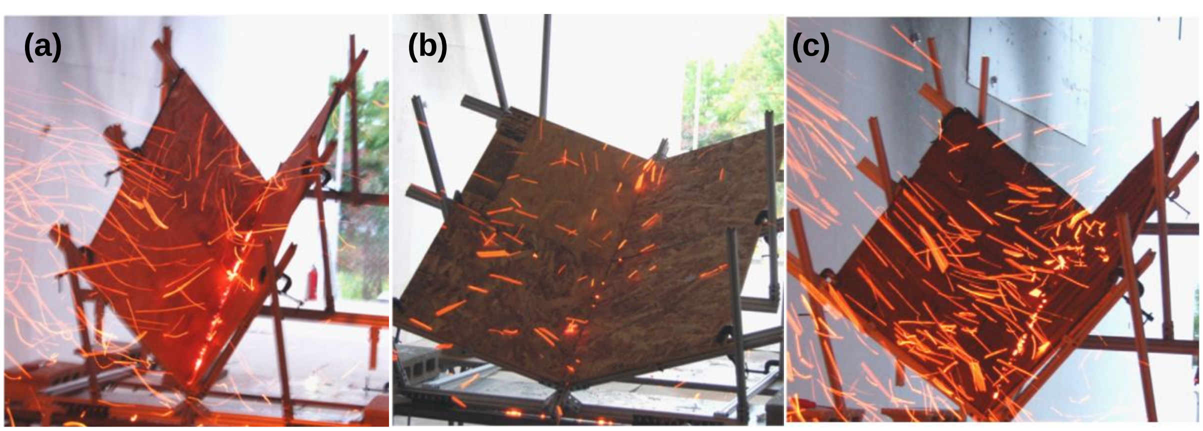

Figure 2: Photographs of OSB (a,b) and an asphalt roofing assembly (c) subjected to a firebrand shower [18]. *The OSB subjected to firebrands at a 60° angle (a) was able to achieve smoldering ignition while at 135° it was not. In (c), the full asphalt assembly at 90° did not achieve smoldering or flaming ignition under the test conditions, but firebrands accumulated at the seams of the shingles. Figure reproduced from*[18].

The NIST Dragon was also used at BRI to investigate ceramic tile, concrete, and terracotta tile (both flat and profiled) roof assemblies performance under combined wind and firebrand exposure [18–20]. In general, firebrands were sometimes found to occasionally penetrate tile assemblies and melt 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). Firebrands became trapped in the interlocking sections of the flat tiles, which stopped them from penetrating the sarking material. While no full roofing assemblies ignited under the given test conditions, roofs may be improperly installed, weather over time, or be exposed to conditions exceeding those used in tests, so Manzello et al. repeated tests without underlying sarking. When the sarking was removed and OSB alone was used as an under layer, smoldering or flaming ignition occurred under some configurations. Manzello et al. therefore recommended using a continuous underlayment of firebrand-resistant sarking as a cost-effective mitigation strategy [20]. Bird stops also helped to reduce the possibility of embers penetrating to the roof assembly, but they did not prevent it entirely [20]. When an underlying sarking layer was installed properly, flaming ignition did not occur to the roofing assembly for the tested conditions.

Some tests described above have demonstrated the potential for Class A rated roofs populated with typical debris (pine needles, etc.) to achieve smoldering ignition under wind-driven firebrand attack; however, in the current tests, the smoldering front did not penetrate into the structure via the attic. Test standards should evolve to mimic more realistic conditions (higher winds and firebrand exposure), as well as incorporate ignition potential beyond the plane of the roof (e.g. connections with siding) to test the true performance of products in the WUI.

2.2 Gutters

Gutters are a potential pathway to ignition of a home, primarily because debris collected in the gutter can be ignited by firebrands, potentially spreading the fire to the home at the roof-gutter intersection. Studies have begun to explore the structure ignition hazard from gutters, and results are summarized in Table 2.

Table 2: Experiments and events involving WUI fire exposure to gutters.

Authors	Assembly	Exposure	Results
Cohen et al. [21]	Homes in the WUI in Lake Arrowhead, California	Firebrands from the Grass Valley Fire which burned under high winds through chaparral and conifer vegetation.	Pine litter collected in gutters was found to be a significant cause of ignitions
Manzello et al. [22]	Polyvinyl chloride (PVC) gutter with dry vegetation placed inside, attached to the front of a flat roof (OSB, tar paper, asphalt shingles) at 35 degree pitch.	NIST firebrand generator (mass up to 0.2 g), 7 m/s wind speed	Pine needles in gutter ignited and asphalt shingles on roofing assembly melted; roof did not ignite

Quarles [17]	Vinyl and metal gutters with pine needle debris placed inside	Wind-blown embers, 4.5 – 6.7 m/s wind speed	Debris caught fire in both cases. Vinyl gutter fell off building and metal gutter remained attached

Manzello et al. performed testing on flat roofing assemblies with a polyvinyl chloride (PVC) gutter in a wind tunnel with firebrand exposure from the NIST Dragon [22]. When flammable materials, such as pine needles, were placed in the gutter, the firebrands deposited in the gutter produced smoldering ignition which transitioned to flaming. The asphalt shingles on the roofing assembly then melted but did not fully ignite under the limited conditions tested. IBHS also performed tests in their wind tunnel facility on a full single-story home and observed ignition of flammable materials such as pine needles and other litter inside the gutters. When the debris in a vinyl gutter caught fire, the gutters melted, disconnected from the house, and fell to the ground [17]. In similar tests with a metal gutter, the gutter stayed attached to the house, and the flaming debris appeared to catch part of the roofing assembly on fire. Despite potential concerns with metal gutters, vinyl gutters are not necessarily recommended, because the roof could ignite during the initial flaming of the debris in the gutter 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.

Despite several devices available on the market to prevent accumulation of debris in gutters, such as metal meshes or reverse curve covers, the authors found no work addressing their effectiveness under fire or no-fire conditions. California has adopted requirements for these types of devices [8], but provides no guidance for performance. More open and peer-reviewed testing of available devices on the market is recommended to assess their effectiveness.

2.3 Eaves and Vents

Eaves and vents have been recognized as significant sources of ignition of homes in the WUI [18]. Vents provide an opening through which burning brands may penetrate the interior of a structure, often the attic. Eaves serve as a connection point between siding and roofing assemblies, where potential vulnerabilities can occur. This connection point is addressed by few standards. Most homes have vents both for thermal efficiency and to minimize the chance of moisture buildup. Meshes used on these vents were traditionally designed to stop entry of rodents, etc. into attic and crawl spaces; more recently, vents have been considered as a possible means of blocking the entry of firebrands. This consideration has led to testing on vent sizes needed to stop firebrand penetration.

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 (Figure 1). The 2007 CBC of Regulations, Title 24, Part 2, Chapter 7A required building vents to be covered with a metal mesh of 6 mm to mitigate firebrand penetration [8]. Because these regulations were not based on any testing, Manzello et al. has used a firebrand generator to test the effectiveness of different vent configurations and opening mesh sizes, summarized in Table 3.

Table 3 Experiments and events involving WUI fire exposure to eaves and vents

Authors	Assembly	Exposure	Results
Manzello et al. [23]	Gable vent with 1.5, 3.0, and 6.0 mm mesh opening. Shredded paper used to test ignition potential	NIST firebrand generator, 9 m/s wind speed.	Firebrands were not quenched by the presence of a mesh. Smoldering ignition of loose fuel beds behind the vents occurred
Manzello et al. [24]	Generic building vent with six mesh sizes (1.04 – 5.72 mm opening). Four tested for ignition: paper, cotton, wooden crevice, and OSB crevice	NIST firebrand generator, 7 m/s wind speed	Firebrands were not quenched by the presence of a mesh. As the mesh size was reduced, the number of locations where ignition was observed was greatly reduced
Manzello et al. [25]	Open eave configurations (61 cm overhang) with no vent and with vents. 50 mm holes with 2.75 mm mesh openings were used on the vent	NIST firebrand generator, 7 and 9 m/s wind speed	With no vent opening there was no accumulation under eaves. With vents, the number of brands penetrating increased with increasing wind speed

Manzello et al. studied several different vent configurations under wind-driven conditions with the NIST Dragon. Initial testing was performed on gable vents [23], followed by generic building vents with different meshes [24], and finally an open-eave configuration with and without vents [25]. The results of the tests showed that firebrands were not quenched by the presence of a mesh, but rather continued to burn until small enough to pass through the mesh even with an opening as small as 1.04 mm. Recent dimensional analyses have further described this process, enabling prediction of firebrand sizes that may penetrate a mesh [26]. All mesh sizes tested resulted in ignition of target fuels behind vents; however, larger mesh sizes (6 mm) ignited fuels more quickly. 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 [27]. In the open eave configuration tested, no accumulation was found when vents were not installed; however, during tests where the open eaves had open vents, some firebrands were observed to penetrate. 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 CBC [8]. Based on experimental results, a new standard has been developed by the ASTM E05.14 External Fire Exposure subcommittee: ASTM E-2886, the Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement [28]. The test method includes both an ember exclusion/intrusion test and a flame intrusion test. The ember intrusion test is different than testing performed with the NIST Dragon. In this test, embers fall down 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 [24].

2.4 Siding, 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) which can in turn lead to direct flame contact and radiant heat exposure to siding materials on the exterior walls. 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 [29], re-entrant corners are a significant hazard that are now thought to be a worst-case scenario for siding ignitions. Table 4 provides a summary of experiments involving fire exposure to sidings, windows, and glazing.

Table 4 Experiments and events involving WUI fire exposure to siding, windows and glazing

Authors	Assembly	Exposure	Results
Cohen [30]	Exterior plywood wall, OSB board roof, solid wood trim, composite board cave fascia	Radiant heat exposure and direct flame contact from five crown fires	At 10 m from the trees, flames directly contacted walls and ignited them. At 20 m, only light scorch occurred. At 30 m, no scorch occurred
Maranghides and Johnsson [31]	Adjacent structures consisting of unrestricted construction (OSB, weather wrap, and vinyl siding) and fire resistant construction (OSB, 1.27 cm gypsum board, weather wrap, and vinyl siding)	Burning adjacent structure, nominal peak heat release rate (HRR)15 MW. Radiant heat flux nominally 30 kW/m^2	Structures spaced 1.8 m apart can ignite one another. A fire resistant barrier can slow down flame spread between separate structures
Manzello et al. [25]	Sidings of vinyl with OSB sheathing and polypropylene with OSB sheathing were tested along with a moisture barrier (Tyvek). Horizontally and vertically sliding double pane windows were also installed in OSB	NIST firebrand generator, 7 and 9 m/s wind speed. Fine fuel (pine needles) placed adjacent to wall assembly	Firebrands penetrated both polypropylene and vinyl siding, and firebrands accumulated in glazing assemblies, but did not break glass or penetrate the structure
Quarles et al. [17]	Several assemblies including OSB and vinyl wall siding with and without windows	Radiant heat exposure	Wall siding generally ignited before breakage of windows

During the International Crown Fire Modeling Experiments (ICFME), Cohen found that even full scale crown fires were unable to fully ignite wooden panels 20 m from the fire [30]. Following these experiments, it has been the general contention that separation between fuels (vegetation or other structures) is sufficient to prevent radiative ignition, which was discussed in detail in Section 3.1 of Part I of this review [1]. Even though it is clear that most siding materials will not ignite from radiant exposure when adequate separation distances are used, there is still the possibility that these fuels are nearby, especially in the form of adjacent structures in the WUI.

Maranghides and Johnsson performed large-scale experiments at NIST in which they compared a building clad with combustible underlying materials against one with non-combustible underlying materials and measured the time for fire to spread from one ignited assembly to another [31]. They found that during tests with a 1.8 m separation between buildings, fire spread could be slowed but not prevented with a 1-hour fire rated assembly that incorporated fire-rated gypsum wallboard. The most rapid flame spread resulted from penetrations at windows, both from flames exiting the burning structures and from flames entering/heating broken windows on an unignited assembly. In separate tests, dual-pane tempered glass was not found to fail even with a 25 min exposure to 35 kW/m^2 of radiant heating, indicating that dual-pane glass is unlikely to fail due to radiative heating in a wildfire scenario, which will often only reach 35 kw/m^2 for one minute. This conclusion supports code, such as NFPA 1144 section 5.7.1, that requires the use of tempered or other fire-resistant glass [32]. These tests used a small separate distance (1.8 m) compared to the 4.5 to 9 m recommended in most codes and standards [32–34]. Cohen et al. has performed preliminary calculations based on expected radiant heat fluxes to siding, which concluded that two-story structures should be spaced about 12 m apart [35]. More testing will be necessary in order to inform future recommendations of separation distance between structures with different construction.

Some preliminary tests by Quarles et al. also showed that painted siding generally ignited before windows broke, with times for all siding ignition ranging from 4 to 16 minutes when exposed to a radiant panel of 35 kW/m^2 [17]. Additionally, windows broke before igniting curtains behind them and tended to absorb enough heat flux to prevent radiant ignition within the home while still intact. While this data is useful, it is important to note Quarles et al. [17] does not have published, peer-reviewed data available on the tests.

Exposure by firebrands is an equally important mechanism of ignition that has only recently been shown to affect siding materials. Tests by Manzello et al. using the NIST Dragon at BRI's FRWTF studied ignition of siding treatments (siding material on top of a layer of a moisture barrier housewrap, i.e. Tyvek) in a re-entrant corner configuration [25]. During experiments with vinyl siding, firebrands melted through the siding material creating visible holes. Ignition of the OSB sheathing underneath the vinyl and Tyvek was only observed for vinyl siding with 9 m/s of wind applied and for OSB that was oven-dried. During this ignition, the OSB burned through completely, eventually igniting the structural wood members underneath [25]. Accumulation of firebrands at the base of a wall assembly can also be responsible for ignition, even without other combustibles at the base [25]. 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 [25]. Manzello et al. tested both horizontally and vertically sliding window assemblies. Both types of assemblies were double hung, as this configuration might present the worst-case scenario for ember accumulation and ignition [25]. Their experiments showed that embers could accumulate in the framing of the assembly, especially in the vertical wall assembly. No tests resulted in sufficient damage to break the glass or penetrate the structure.

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 this assessment. Ignition of roofing or siding near skylights seems 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. Nonetheless, no data in the literature shows them to have be of particular hazard in the past.

2.5 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 sixteen damaged home, the ignition location was most often a detached structure or decking [36]. Similar observations were made during the Waldo Canyon fire, where wooded slopes with overhanging decks created a large hazard [37]. 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 ignition potential from direct flame contact, but is not tested for ignition from firebrand exposure or for its potential to ignite an adjacent structure with radiant energy [8, 38]. 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 [39]. Experimental studies which investigate ignition mechanisms on decks are shown in Table 5.

Table 5 Experiments and events involving WUI fire exposure to decks, porches and patios

Authors	Assembly	Exposure	Results
Wheeler [38]	Three configurations: wood product, composite materials, and combined wood/composite	Hot embers placed on top surface and pine needles underneath decks (2.2 to 3.6 m/s wind)	Only smoldering when no wind for ember test. Flaming ignition of all decks for fire beneath deck – composites produce most severe fires
Manzello and Suzuki [40]	Western red cedar, Douglas fir, and redwood decks attached to a reentrant corner assembly	NIST firebrand generator, 6 m/s wind speed	Firebrands accumulated on all wooden deck assemblies and all ignited. Apparent correlation between wood density and ignition time

Manzello and Suzuki have performed the only comprehensive tests found by the authors on deck ignition [40]. Decks were exposed to a total firebrand mass flux of 17.1 g/m^2s from the NIST Dragon under a 6 m/s wind. The 1.2 × 1.2 m decks had boards oriented perpendicular to the airflow direction and were placed in a reentrant corner assembly. About 20% of the firebrands released from the NIST Dragon accumulated on top of the deck surface, and every assembly experienced flaming ignition. 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 [40]. Wheeler also performed 6 (non-repeated) tests on various wood and Trex (a wood-plastic composite) decking materials. While the tests were not peer-reviewed and offer little scientific insight, they offer a rare practical comparison of decking materials. When hot embers were placed directly on wood members with no wind, decking material smoldered, but did not transition to flaming. When a pile of pine needles (debris) was lit underneath each deck and a 2.2 – 3.6 m/s wind was applied, all decks ignited; however, wood ignited last and self-extinguished. Composite materials ignited quickly and produced large, severe fires, with Trex being the slowest composite to ignite. The authors recommend keeping the underside of decks clear of debris [38].

2.6 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 [41]. In most cases, there was evidence that flames came dangerously close to homes, by igniting sections of or entire wooden fences. Wooden trellises and other yard structures were also burned. Post-fire investigations conducted by NIST on the 2012 Waldo Canyon Fire in Colorado determined that wood fences were vulnerable to ignition from firebrand showers in WUI fires [9]. As a result of these observations, NIST conducted a series of experiments to expose cedar and redwood fencing assemblies to wind-driven firebrand showers, summarized in Table 6.

Table 6 Experiments conducted to study WUI fire exposure to fences and related WUI observations

Study	Assembly	Exposure	Results
Witch and Guejito Fires [41]	N/A	WUI Fire	45% of homes with attached wood fences were destroyed
Waldo Canyon Fire [9]	N/A	WUI Fire	Wood fences were found to be vulnerable to ignition from firebrand showers
Suzuki et al. [42]	Western red cedar and redwood fencing. Seven configurations with adjacent fine fuels: flat wall (with and without fine fuel), inside corner (with and without fine fuel), outside corner, long flat wall, and V-corner	NIST dragon, 8 m/s wind speed	All configurations resulted in flaming ignition of fencing assemblies, with or without mulch beds present

Suzuki et al. performed experiments investigating the ignition of fences exposed to a continuous firebrand shower (17.1 g/m^2s) from the NIST Dragon [42]. Fences were arranged in seven configurations, as indicated in Table 6. Dried mulch beds placed at the base of fencing assemblies began smoldering ignition, transitioned to flaming, and subsequently ignited the fencing assembly. After igniting, the fences began to produce their own firebrands. In tests without dried fuels at their base, the fences achieved ignition both at the joints in the fencing and at the base, through accumulation of firebrands. It is unknown whether ignited fencing assemblies could produce ignition of adjacent building elements.

2.7 Mulches 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, in order to minimize the chance of ignition from subsequent radiant heat and flame exposure [17, 32, 43]. Several experimental tests have been performed on mulch and other dead vegetative debris located near homes, summarized in Table 7. More fundamental work that quantifies ignition of debris and fuel beds in terms of moisture content (MC) and other variables in a statistical form (reviewed under section 3.3.3 in Part I [1]) may also be useful in risk assessment methodologies.

Table 7 Experiments and events involving flame and firebrand exposure to mulches and debris

Authors	Material	Exposure	Results
Steward et al. [44]	Shredded pine bark, shredded hardwood, shredded cypress, composted yard waste, pine bark nuggets, pine straw, mixed grass sod, brick chips, and ground rubber-tire mulches	Lit cigarette, match, and propane torch	Ground recycled pallets and composted yard waste ignited with cigarettes; other fuels ignited with more difficulty or not at all. All fuels ignited when exposed to direct flame
Quarles and Smith [45]	Composted wood chips, medium pine bark nuggets, pine needles, shredded western red cedar, Tahoe chips, Tahoe chips with fire retardant, Tahoe chips (single layer), and shredded rubber	Drip torch ignition, 4.5 – 6.7 m/s air flow	All mulch except for composted wood chips exhibited flaming combustion. Shredded rubber, pine needles, and shredded western red cedar demonstrated the most hazardous fire behavior based on ignition, flame spread and flame heights measured
Manzello et al. [46]	Shredded hardwood, pine straw, and dry grass	Simulated firebrands under 0.5 and 1 m/s wind speeds	Fuel beds were easier to ignite as the number of firebrands increased
Zipperer et al. [47]	Pine straw, large and small pine bark, and shredded Cypress	Drip torch ignition	Pine straw found to have the largest flammability, followed by large and small pine bark, with shredded cypress mulch the lowest flammability tested
Quarles [17]	Near-building combustible mulch (bark) and vegetation	Wind-blown embers, 4.5 to 6.7 m/s wind speed	Flammable debris on the ground can cause rapid upward flame spread on the side of a house
Beyler et al. [48]	Mulch: pine bark, hardwood, pine bark nugget, and pine straw	Ignition test – ASTM E-108 protocol [5] Flame spread – gas-fired line burner.	Test standard proposed that differentiates the relative flammability of different mulches
Suzuki et al. [49]	Shredded hardwood mulch, varying moisture content (9 – 83%)	NIST dragon, 6 and 8 m/s wind speed	Hardwood mulch beds were able to ignite at MC up to 83% under 8 m/s winds. Accumulation of firebrands was a key factor to produce ignition

Manzello et al. performed small-scale experiments on several mulches where a single *glowing* or *flaming* firebrand was placed on a fuel bed [46]. When flaming firebrands were placed in the beds, all fuel beds were observed to achieve either glowing or flaming ignition with the exception of shredded hardwood mulch fuel beds held at 11% MC. Multiple glowing firebrands were also unable to ignite cut grass fuel beds and shredded hardwood mulch fuel beds held at 11% MC. The probability of fuel bed ignition was increased when exposed to an increased mass flux of firebrands, whether the brands were in the glowing or flaming state. This result stresses the importance of understanding the flux of firebrands.

Steward performed experiments on 13 different mulches to measure their relative ease of ignition [44]. Plots were left to sit for 2 weeks before a lit cigarette, match, or propane torch was placed on the bed. A plot was monitored for 20 minutes to see if it ignited. Cigarettes ignited ground, recycled pallets, and composted yard waste every time, shredded pine bark 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 ignited. All mulches eventually ignited when a torch was used, 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.

Zipperer et al. studied the flammability of four mulch types: pine straw, large and small pine bark, and shredded cypress mulch [47]. They performed exterior experiments on 2 meter diameter plots, which were weathered under different drought conditions. Rate of spread, temperature, flame length, fuel consumption, and percentage of total area burned were measured. A separate series of experiments was performed in the laboratory under wind conditions and HRR was measured. Pine straw and shredded cypress were found to have relatively fast ignition and spread rates, which was expected due to the fine size of the fuels. Pine straw and large pine bark also had the highest flame heights and HRR, followed by small pine bark and shredded cypress. Shredded cypress appeared to have the lowest flammability in testing, although all mulches were flammable. While detailed measurements were described, their quantitative results were not presented.

Quarles and Smith measured some relative flammability properties for 8 mulches in 2.5 m diameter plots [45]. Mulches were exposed to over two and a half months of typical hot, dry weather in Nevada. They were burned under fan-produced winds of 4.5 - 6.7 m/s, and the resulting flame height, rate of spread (ROS) 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, with shredded rubber, pine needles, and shredded western red cedar exhibiting 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 heights for a prolonged period. Pine needles represented the second most-hazardous mulch material, based on combustion characteristics. It is important to note that 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.

Suzuki et al. experimentally studied the ignition of mulch beds exposed to continuous wind-driven firebrand showers in a reentrant corner assembly. Wind speeds and moisture contents of the mulch beds were varied. Hardwood mulch beds were observed to ignite up to 83% MC under wind speeds of 8 m/s. Interestingly, accumulation was a key factor producing ignition; currently, there is a lack of fundamental studies on ignition by firebrand accumulation [49]. The authors noted future test plans to vary the type of mulch and systematically study whether different mulches could ignite walls with different sidings adjacent to them.

A test protocol has been proposed to more quantitatively evaluate ignition and flame spread of different mulch beds [48]. This test method uses a "brand" (the same wood crib used in ASTM E-108) to determine the ignition potential of a 0.6 x 0.6 m mulch bed [5]. Characteristics such as mulch depth, moisture conditioning, bed dimensions, ignition properties, slope, and wind speed were varied during development of the protocol to test that it is capable of ranking the flammability properties of different mulches. While the test is able to quantitatively compare two mulches, it does not intend to provide worst-case conditions or to evaluate the exposure to nearby structures via flames, radiation, or firebrands from ignited mulches. Some tests performed at IBHS have demonstrated that flammable debris on the ground can ignite and cause rapid upward flame spread on the side of a house, but these results must be coupled to the materials and exposure conditions to be more useful for WUI fire mitigation [17].

3. Mitigation Strategies

Post-fire analyses have shown that some mitigation strategies are effective in decreasing fire damage to structures while others are not. These strategies include codes and standards that seek to harden structures, homeowner education, defensible space, community planning, wetting/covering agents, and fire service intervention. The following sections will detail these strategies.

3.1 Codes and Standards

Codes and standards are useful guidelines for regulatory bodies to adopt in order to help mitigate potential WUI home ignitions. Some of these guidelines also include homeowner protection checklists, etc. that are more useful directly in the Home Ignition Zone (HIZ), which is described in Section 3.2. A number of relevant codes and standards exist for the WUI. Table 8 shows these standards and their applicability to regulate infrastructure, community design, pre-plans and assessments, and building components and systems. These standards include those by NFPA, International Code Council (ICC) and the CBC.

NFPA 1141: *Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas* primarily addresses means of access, building access and separation, fire protection, water supply, community safety, emergency preparedness, and fire protection during construction [33]. NFPA 1142: *Standard on Water Supplies for Suburban and Rural Firefighting* regulates water supplies required in rural areas, which may include the WUI [50]. NFPA 1143: *Standard for Wildland Fire Management* addresses wildland fire management, but does not pertain to the WUI [51]. NFPA 1144: *Standard for Reducing Structure Ignition Hazards from Wildland Fire* applies to home or property owners in the WUI, as it includes means of assessing fire hazards in the HIZ, building design, location and construction, and fuel loads in the defensible space around a home [32].

The ICC Wildland-Urban Interface Code addresses many issues similar to NFPA 1141-1144, but in a single document [34]. It addresses minimum regulations for land use and the built environment in WUI areas. Definitions of WUI areas, building construction regulations, and fire protection requirements are covered. Recommendations are similar to those found in other codes and standards, such as CBC Chapter 7A [8], NFPA 1141, and 1144.

In order to protect against WUI fires, Section 701A of the 2009 CBC addresses topics 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 [8]. In the aftermath of the 2007 San Diego fires, investigation showed that houses built following the 2001 and 2004 CBC standards were much less likely to burn than those built before 2001; of the exposed homes, 2-3% of those houses built after 2001 burned, as opposed to 13-17% of homes built before 2001 [52]. Many other standards related to testing of materials are referenced in sections specific to the applicable components for the test standard.

Table 8: Codes and standards relevant to the WUI and the topics they address.

	Infrastructure	Community Design	Pre-plan/Assessment	Building Components and Systems	Fire Management
NFPA					
1141	Water supply	Access/Egress, building separation	Community Safety	Automatic sprinklers, manual systems	
1142	Water supply				
1143					Prevention, mitigation, preparation, and suppression
1144			Structure ignition zone, fuel modification	Construction materials	
ICC	Water supply	Access/Egress, building separation	Fire protection plan, defensible space, fuel modification	Construction materials	
CBC, Chp. 7A				Roofing, vents, exterior covering, windows and doors, decking, accessory structures	

3.2 Vegetation, Separation, Defensible Space and Fuel Treatment

Extensive work by Cohen et al. [53], including the ICFME, showed that separating homes from surrounding vegetation by at least ~30 m will prevent radiant ignition of the home from most fires. 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, which can cause subsequent radiant or direct flame contact ignition of the home. Firewise[1], NFPA 1141, and the ICC WUI Code all define the HIZ as the area within the first 60 m of a home [33, 34, 43]. Clearing vegetation and flammable materials from this zone, or making appropriate adjustments, often helps to make this area a defensible space. Some details on how this zone is defined are listed in the Annex of each of these documents; however, details from Firewise will be presented here, as their recommendations have been quantitatively assessed in the aftermath of a WUI fire [41].

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[2]. Firewise specifically calls for limiting the amount of flammable vegetation and materials surrounding the home and increasing the moisture content of remaining vegetation. The HIZ is typically divided into three zones, as shown in Figure 3 [43]. The first zone encircles the structure and all its attachments (wooden decks, fences, and boardwalks) for at least 9.1 m on all sides. There are specific recommendations concerning vegetation, furniture, and removal of combustibles in this zone. The second zone is 9.1 – 30.5 m from the home, and plants in this zone should be low-growing, well irrigated, and not very flammable. Fuel breaks, including drives, gravel walkways and lawns, should be considered to limit fire spread. The third zone is 30 to 60 m from the home. This area should be thinned to reduce canopy torching.

Figure 3: Diagram of three zones recommended by Firewise, from [43].

The NIST investigation of the Witch Creek and Guejito Fires found that 67% of homes with vegetation in Zone 1 were destroyed, whereas only 32% of homes without vegetation (i.e. modified) in this zone were destroyed [41]. Similar results were found in Zone 3 and for treatments

---

[1] Firewise is a community program which provides resources for wildland fire preparedness, including recommended practices, local community programs, etc. (http://www.firewise.org).
[2] Note that these zones are designed solely 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.

beyond Zone 3. One potential problem occurs when homes are close to one another. Zone 3 for one home may fall within Zone 1 or Zone 2 of another person’s home. In this case, the first homeowner could push a pile of flammable material 30 m away from their own home, only to leave it within 30 m of a 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. Recent analysis by Syphard et al. found that the most effective mitigation strategy was to reduce up to 40% of the woody cover immediately adjacent to structures and to ensure that no vegetation was touching or hanging over the structure [54].

Fuel treatments involve physically altering vegetation (e.g. removing, thinning, pruning, mastication) on natural wildland, with the intent of reducing the probability of extreme fire behavior, including reducing a potential fire’s intensity, flame lengths, and ROS [55]. There are many methods to accomplish treatments, including mechanical removal of ladder or surface fuels, and grazing by goats, where appropriate [56]. 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 [57]. 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, fuel treatments can be used to reduce the intensity of fire behavior regardless of the presence of a community. 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 [39]. Several references are available pertaining to specific fuel treatment methods, including Agee and Skinner [58] on site-specific fuel treatments and Reinhardt et al. [59] on reducing the cost of fuel treatments by reusing biomass.

Most research on fuel treatments has focused on the wildland rather than the WUI; as a result, current assessments do not include the effectiveness of reducing structural ignition potential with a given fuel treatment. Hudak et al. discuss the reduction of fire behavior as a result of fuel treatments in the wildland [55]. In the Angora fire, fuel treatments located adjacent to subdivisions provided important safety zones for firefighters, increasing suppression effectiveness which saved structures. Treatments in or near the HIZ 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 burned from firebrands generated by other burning structures, rather than by wildland fuels [39].

Syphard et al. studied the effectiveness of fuel breaks in Southern California, the main approach used in the region to mitigate wildfire risk [60, 61]. They referred to two studies, one done over a 28 year period by the United States Geological Survey (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. The authors believed that it would be useful to have a fire model that accurately determines the effectiveness or size of a needed fuel break; however, such models are not yet available [60–62].

3.3 Homeowner Education and Outreach Programs

Programs such as Firewise, Ready Set Go![3], Fire Adapted Communities[4], Fire Safe Council[5], Living with Fire[6] and many others offer resources to homeowners to help them prepare for 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 HIZ, which homeowners must independently maintain. Studies, such as one 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) [63].

In the few WUI fires with detailed investigations, community-based approaches seem to be effective in reducing structure loss [41]. Although 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 [52]. 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 some the main contributors to reducing structure vulnerability [64]. The effect of small changes suggests that the approach to WUI fires needs to change from a focus on larger-scale changes such as fuel treatments to an increased focus on the HIZ [64]. Despite the importance of homeowner actions, engineering solutions of fire-safe designs for structure protection could help reduce the burden of homeowner maintenance.

Recent studies have found that social interactions affect the level of mitigation in which community members engage. A recent study by Brenkert-Smith examined the role that informal social interactions have on WUI mitigation efforts in six communities [65]. He found that full-time residents put more effort into mitigation and developing pathways for informal communication amongst neighbors. Part-time residents felt that their full-time neighbors would inform them of changes that needed to be made and this information increased their mitigation efforts. The study found that residents are more educated when they feel they have strong ties to one another, even if these ties are a result of informal social interactions. A study by Gordon et al. compared WUI communities in Pennsylvania and Minnesota [66]. In general, dealing with wildland fire risk on a community level is most effective. They found that social barriers in communities with changing populations put those communities at a higher risk because they approached mitigation individually, if at all, rather than on a community level. The authors recommended that such communities create grassroots and educational campaigns to teach community members about wildland fire risk and that they engage in hazard mitigation and planning by building trust between longtime and new residents.

---

[3] Ready, Set, Go! emphasizes communications between fire departments and residents in WUI areas and is organized by the Internation Association of Fire Chiefs. More information can be found at: http://www.wildlandfirersg.org/.

[4] Fire Adapted Communities provides resources for residents to protect their own homes and communities. More information is available at: http://www.fireadapted.org/

[5] The Fire Safe Council is a California non-profit organization which provides information on community wildfire protection plans. More information is available at: http://www.cafiresafecouncil.org/.

[6] Living with Fire is a Nevada organization which provides recommendations to homeowners on decreasing their risk. More information is available at: http://www.livingwithfire.info/.

3.4 Community Planning

The location and arrangement of homes contributes to the overall fire risk within a community. For example, in the Waldo Canyon fire in Colorado, home-to-home ignition occurred in areas where spacing between homes was typically only 3 to 6 m [37]. Several reviewers have noted that the arrangement and density of structures has a significant impact on community-wide fire resilience. In the Witch and Guejito fire, investigators found that spread within the community was primarily governed by structure-to-structure spread [41].

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 [67]. In particular, they found that using combustible housing materials in their models resulted in a sharp increase in the probability of a greater fire size. On the basis of these results, the authors suggested that homes should be hardened against ignition from wildland fires and that the density and spacing of housing be taken into account when assessing fire risk in the WUI [67].

Syphard et al. have done a variety of work studying past fires and the effect of land use planning in Southern California [68]. Using fire perimeter data compiled by the California Department of Forestry and Fire Protection (CAL FIRE) Fire and Resource Assessment Program (FRAP), they created a continuous raster map representing the number of times an area had burned from 1878-2001. They studied properties where structures had been lost in two Southern California regions prone to wildfires. Their work found that structures in areas with low to intermediate structure density were more likely to burn than the highest density housing. This result is most likely due to the fact that the highest densities of housing have less vegetation near homes, while lower density housing may be more interspersed with vegetation. Structures located at the edge of developments or near steep slopes were also more susceptible to wildland fires. The location-dependent results indicate the importance of identifying regions where mitigation strategies, such as hardening structures, may be most effective in reducing losses. These regions might be highlighted using risk mapping techniques.

Table 9 Overview of spatial arrangement studies related to the WUI

Author	**Event/Region Studied/Modeled**	**Summary & Conclusions**
Syphard et al. [68]	Santa Monica Mountains, CA and San Diego County, CA	The highest hazard was found in isolated housing clusters with low- to intermediate housing density and fewer roads. Historical fire frequency was an important location-dependent variable.
Quarles et al. [37]	Waldo Canyon Fire	Many of the destroyed houses were spaced only 3.6 - 6 m apart, so home-to-home fire spread was thought to be the major cause of destroyed homes in this event
Maranghides et al. [41]	Witch Creek and Guejito Fires	Homes that were on the interior of the community were less likely to be destroyed than ones on the perimeter

Spyratos et al. [67]	Percolation-theory based fire model with housing an vegetation data	A home's combustibility and nearby vegetation flammability contributed to the fire size. These factors, along with density and house spacing, need to be considered when assessing fire risk
Alexandre et al. [69]	Cedar and Fourmile Canyon Fire	Results varied. In one community, loss was greater when cluster size was smaller and there were many buildings in a cluster. In another community, probability of loss was greater when building density was lower

3.5 Wetting/Covering Agents

Several new technologies have been suggested to reduce the likelihood of structure ignition in the WUI. Some of these are mentioned in the 2012 ICC WUI Code [34]; however, most have not been evaluated in full-scale WUI events. Some means of protection include exterior sprinklers, gel and foam agents, and full exterior blankets for structure protection.

Urbas et al. [70] investigated the effectiveness of certain covering agents to prevent fire spread from wildland fires to structures. They studied the susceptibility of structural components, dead fuels, and landscaping plants to radiant heating, after the fuels were pre-wetted using water, type A foam, or gel agents. They found that water and foam did not prevent radiant ignition of any material after prolonged radiant exposure. Gel agents delayed the ignition time of some fuels and siding materials, particularly if those materials were not dried in advance. In a real WUI fire, embers and direct flame contact also contribute to ignition in the HIZ [30]. There have been undocumented reports of ignition in pockets of mulch not covered by gels which smolder and ignite the home. These reports do not appear in the literature, but could be a serious concern if shown to be true.

Glenn et al. also investigated material coatings for protection of exterior structure surfaces in the WUI [71]. They examined the ignition response of siding coated with sodium bentonite gel, a commercial fire protection gel, and foam, by exposing the siding to 42 kW/m^2 of radiant heat flux. Starch was added to some treatments to determine whether it stabilized the coating and prevented vertical slumping. An 8 mm coating of fire protective gel was 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 the potential of 50 different blanket materials to protect structures from radiant exposures of up to 84 kW/m^2 [72]. The best material at preventing ignition was aluminized insulation. There are further design and usage concerns which need to be addressed.

Following a severe wind event in Cook County, Minnesota, exterior fire sprinklers were installed on many homes in a heavily-wooded community to prevent ignition by wildfires [73]. During the Ham Lake Fire in 2007, only one of the 100 structures with exterior sprinklers was destroyed. 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 [73]. If implemented in a larger, community-scale, issues such as water availability during a WUI fire emergency would need to be considered.

Mitchell discusses the effectiveness of The Wind Enabled Ember Dousing System (WEEDS), which was designed to quench embers that landed on homes [74]. A single case of the system's effectiveness is found, but the home also had proper clearance and other protective measures, making it unclear whether WEEDS would be effective as the only protective measure.

3.6 Fire Service Intervention

Firefighting has been found to be an effective method of intervention in wildland and WUI fires. Rahn performed a study on wildland firefighting effectiveness in San Diego County, California [75]. He found that the time efficiency of attack increased with the number of firefighters on the crew. A study by Rhode explores different firefighting strategies that can be used in the WUI, rather than the wildland [76].

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 [41]. Attempting to reduce the severity of fire behavior near homes is therefore an important approach. 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 [41]. Fire service intervention is also dependent on available resources, which often may be strained during a large-area fire. A recent study of the Waldo Canyon Fire by NIST provides more insight into the benefits of fire service intervention [77].

3.7 Risk Assessment Methodologies

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 [78]. These assessments are based primarily on factors, such as fuel, weather and topography, that affect a fire's steady ROS, 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.

Many approaches for determining fire risk to structures 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 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 [79]. There are limitations, for instance, to combining simple census-based data with vegetation mapping to map WUI risk; however, dasymetric mapping addresses this limitation by taking into consideration changes within the map boundaries. 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 [80].

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 [81].

Risk assessment tools like the risk management framework proposed by Calkin et al. [82] 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. Their conceptual model highlights major objectives needed to prevent WUI disasters and the groups responsible for these actions (land management agencies, local governments, and homeowners). Using this new risk framework, the researchers investigated how pre-fire mitigation efforts failed to prevent significant structure loss during the Fourmile Canyon fire outside Boulder, Colorado [82]. They highlight the sequence of events that lead to WUI fires with large-scale losses. They also 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 [82]. The authors 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, suppression effectiveness, magnitude of risk in terms of loss, and homeowner responsibility [83]. The Structure Ignition Assessment Model (SIAM), developed by the United States Department of Agriculture (USDA) Forest Service (USFS), addresses some of this need, using fire characteristics, fire location, and structure characteristics to determine a structure's potential ignitability. The model includes structure design, topography, fire weather severity, fuels, and fire behavior to characterize exposure from radiation, flames, and firebrands, then solves heat transfer equations and provides an ignition risk rating depending on both the exposure conditions and structural materials [30]. This system does not consider firebrand and home-to-home interactions but can still be a tool to understand structural risk.

The CAL FIRE FRAP program produces Fire Hazard Severity Zone maps to demarcate WUI and non-WUI areas throughout the state of California. These demarcations are used because California building codes have extra restrictions in WUI areas [84]. The hazard mapping determines fire threat to WUI areas based on ranking of fuel hazard, assessing the probability of wildland fire, and defining areas of suitable housing density. These three categories are then combined to an overall 3-category hazard ranking. Fuel hazards are determined as a function of ROS and HRR per unit area. The probability of burning is taken from past fire frequency data. The urban interface is demarcated into urban (more than one house in 0.2 hectares), intermix (one house per 0.2-2 hectares), rural (one house per 2-20 hectares), and wildland (less than one house per 20 acres).

More detailed risk assessments can be accomplished using additional methods such as ensemble fire modeling, historical weather data, and probabilities of ignition. Some open-source software tools, such as Wildland Fire Hazard Modeling Tools (WFHMT), are available [85]. Although more research still needs to be conducted, researchers suggest that moving to a more dynamic 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. Wildland Fire Decision Support System (WFDSS) and FARSITE, risk management tools used in the United States, only incorporate wildland hazards; however, they can be useful in determining potential fire exposures to communities [86].

A variety of checklists are also available which attempt to determine the risk of destruction or damage to 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, and utilities. These are often aimed at homeowners or inspectors. 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. Another method of quantifying risk is discussed in [1].

4. Discussion and Future Recommendations

Despite the wide array of research presented above, there are still many areas related to the pathways for fire spread in the WUI in need of additional effort. Similar to recommendations from Part I of this paper [1], increased quantification of hazards through more measureable quantities, documentation, and peer-reviewed work would greatly increase our knowledge of the pathways for fire spread and enable us to perform risk-informed modeling of WUI fires.

4.1 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 through pre- and post-fire investigations. While there is some WUI data collection after fires, investigations are not mandatory or standardized. For this data to be repeatable and applicable among 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.

Some guidelines and tools for WUI data collection have been proposed by NIST [87], but they 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 fire spread to better characterize their risk or hazard based on exposure conditions and the reaction of components or systems.

4.2 Structural Ignition

Cohen has described the WUI problem as a structural ignition problem [64]. While exposure conditions affect structures, WUI fires would not pose as severe a threat to residents and communities if ignition of structures can be prevented. While radiative ignition is understood, structure to structure ignition is less well defined [64]. Nonetheless, structure to structure ignition can be a significant or sometimes primary form of fire spread once a wildland fire enters a community [41]. Participants of a recent WUI fire workshop [87] 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 structure-to-structure ignition cases have been mentioned anecdotally in reports, there is only one detailed study on a scaled configuration of structure-to-structure ignition [31]. This test could not measure the influence of embers and was too limited to completely 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.

If more research is conducted on how firebrands ignite a structure, as suggested in Part I [1], future structures can be hardened against ignition from firebrands. Investigations of actual WUI fires may also help to better determine the fraction of ignitions that are due to firebrands, both directly and indirectly, as a result of direct flame contact from nearby fuel sources originally ignited by a firebrand. Further knowledge on firebrand ignition may similarly help future development of WUI community design.

While many authors have recognized a need to harden structures against embers [87], 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.). Although specific components have been studied [9], 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.

4.3 Fuel Management, Defensible Space, and Community Planning

Land-use planning, in the form of fuel breaks and defensible space, appears to significantly influence home survivability in the WUI [68]. Fuel 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 analysis of past fire data has shown that these breaks are not as effective as once thought [60]. Instead, the overall layout of communities appears to greatly affect a building's probability of ignition [68]. Research should be undertaken to understand exactly what features are most significant and to assemble guidelines for future community planning. Additional research on defensible space should be conducted 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. The primary effectiveness of fuel or fire breaks 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 [68]. Fuel breaks also provide an added measure of safety, providing safety zones that allow responders to operate in a wider region. Still, active fire suppression by fire crews has the potential to put them in harm's way.

Little work has been done to develop strategies to design a WUI community. No publications have been found in which a strategy was proposed to aid in the design of a WUI community. These items have been mentioned anecdotally in codes and standards; however, the majority of standards address home protection and operational needs for firefighters, rather than a how-to guide to designing or retrofitting WUI fire-resilient communities. 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 [87]. Guides aimed toward professional engineers, architects, and authorities having jurisdiction (AHJs) could be very effective at improving community resilience once general guidelines are established via peer-reviewed research.

Fuel treatments have been shown to reduce the intensity of a crown fire, typically by reducing the crown fire to a surface fire [39]. Fire intensity reduction does not prevent ignition by firebrands, but it 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 [88], more work is needed to support these conclusions. The effectiveness of fuel treatments is an ongoing research area that requires more research, particularly on its impact on WUI communities. The influence of a fuel treatment on fire behavior in a nearby WUI community has not been well studied (studies have instead focused on the wildland) and specific means for studying the problem are lacking. Different fuel types must also be assessed, as previous work has only assessed large pine stands which support crowning. Many communities are located in scrub or chaparral (e.g. California), 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 develop appropriate economic or risk-optimized guidelines.

4.4 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 that future designs are ignition and fire resistant. Development of these standards will require additional study on possible exposures (including ember flux and radiative 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 nearby burning structure. It is recommended that all future test development efforts involve quantitative measures of material or component performance (e.g. flame height, flame spread rate, or HRR).

Some specific components in need of standards include roofing assemblies, gutters, vents, eaves, fences, sidings, and landscaping/mulch. Roof tests need to involve more realistic ignition from embers and ignition in the valleys of the roof. Roofs that are currently Class A rated by UL 790, ASTM E-108 or NFPA 276 [5–7] have not performed as expected in wind-tunnel firebrand shower tests [89], which highlights 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 which have been found to be specific vulnerabilities during WUI fires [87].

Gutters and other roofing products also need to be developed to keep debris accumulation minimal or nonexistent. Test methods to evaluate the performance of these devices under specific exposure conditions should be developed. The sizes of vents and vent meshes are a concern requiring further study because firebrands can penetrate meshes. Recent code developments, such as ASTM E-2886 have started to address this issue [28], but their effectiveness will need to be verified with more large-scale testing.

Fences and sidings are both areas where research is 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, as shown by reports from the Waldo Canyon Fire [9]. Initial testing indicates that wooden fencing is easy to ignite [42]; however, the ignition properties of increasingly more prevalent materials such as plastic, vinyl, and composite fencing have not been studied.

Little work has done to quantitatively determine the flammability of different mulches; however, a new test method proposed by Beyler et al. may serve as a basis from which to standardize the process [48]. Future tests should quantify separation distance required between burning mulches and structures to prevent fire spread under worst-case conditions. Tests should evaluate whether burning mulch can produce embers that can ignite other nearby fuels. These conditions may serve as a pass/fail line; however, it would be useful for the test to rank fuels quantitatively based on each aspect of performance.

Additionally, decks, porches, and patios have been identified as a significant source of structure ignitions [36, 37]. Some test standards exist for decking materials (e.g. CBC 12-7A-4 [8]); however, these tests have not been corroborated with exposure conditions that might occur under realistic WUI fires. The threshold conditions for ignition of an adjacent house are incorporated into the test standard primarily through measurements of the HRR. Current approaches to test deck ignitibility do not consider home ignition, so future studies need to be conducted that couple a deck-home system. Observed accumulations of firebrands over long timescales on decks [40] may or may not be represented by the relatively crude wood crib “brand” used in testing.

Weathering protocols for different materials and coatings, especially fire retardant materials, are another major research need. The components susceptible to ignition are all exterior building features which could experience significantly varied weather conditions in different parts of the country. Test methods on materials should simulate accelerated weathering, as weathering may adversely affect fire performance [87]. Short-term coatings such as gels or foams require further research if they are to be operationally used by homeowners or firefighters. While limited testing has been conducted [70, 71], results have not been corroborated at larger scales with realistic WUI fire conditions to show that they are operationally effective. Exterior sprinklers should also be tested in realistic WUI fire conditions. Although they have been shown to be effective in two cases [73, 74], the practicality of their use on a large scale and their applicability to different fire scenarios is unknown.

A better means to incorporate firebrands in all testing strategies is desirable. 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.

4.5 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, e.g. home and business owners, community groups, local government, developers and firefighters. A variety of resources, including how-to guides and checklists for home protection, are currently available in community education and awareness programs, several of which can be found in the full report [90].

Even relatively small education efforts, such as one performed in Florida between 2002 to 2007, have been shown to be cost-effective ways to limit damages from wildfires [91]. 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 [91]. As knowledge of WUI fire fundamentals increases, this information needs to be passed to various stakeholders, through improvements to codes and community resources. For example, the influence of firebrand showers on ignition of buildings has been emphasized. As this mechanism appears to be a significant source of losses, it may be worth finding ways to stress its effects and methods to minimize ignition from firebrands.

4.6 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 been explored in recent years. The majority of this work focuses on respiratory effects due to small particulate matter (smoke) exposure [92–94]. 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, who 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 captured the unique influence of WUI fires, where structure losses may contribute a different fraction or spectrum of emissions than vegetative fuels alone [95]. Other recent work indicates that proper prescribed fire use and management practices could sequester 18-25% of CO_2 emissions in the Western United States, or as much as 60% in some ecosystems [57].

4.7 Effectiveness of Mitigation Strategies

Several recommendations exist for homeowners on strategies to mitigate risks from WUI fires to homes; however, there is not much literature data to support these changes. Investigations from the Witch and Guejito fires [41] cite some effective and ineffective components of Firewise which are incorporated in several other standards and guidelines, but 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 standards such as the CBC Chapter 7A requirements have already been implemented [8].

Specific requirements, such as home separation distance in NFPA 1141, which can be decreased from 9.1 m to 4.6 m if an in-home fire sprinkler system is installed, have no data in the literature to support them [33]. NFPA 13R does not require fire sprinklers to be installed in the attic [96]; therefore, the effectiveness of sprinklers in limiting home-to-home spread in the WUI could be called into question. The protection offered by fire sprinklers would also diminish if water supply shortages occur during power outages.

Although 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 to standardize the recommendations for defensible space across wildland fire-prone areas [87]. The size of the fuel modification area and how best to treat it is debatable and dependent on worst-case weather conditions. More guidance and tools based on solid science are necessary, including recommendations 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, and effectiveness of fuel breaks.

NFPA 1144 requires roof classes (as determined by ASTM E-108) to be selected based on expected wildland fire behavior; however, there is no guidance or scientific basis with which to determine exposure conditions. Recent research showing smoldering ignition of some Class A roof assemblies with accumulated vegetative debris exposed to firebrand showers [17, 20] highlights the need for further studies to design specific protections and assess them in real wildland fire situations, especially at the roof-to-siding intersection. Vents, eaves, roof and attic components similarly have only limited data to support their design, construction and location.

5. Conclusions

Studies over the past few decades have significantly advanced our knowledge regarding ignition of structures in the WUI. Starting with an initial focus on radiant heat exposure, researchers now acknowledge the role of firebrands in the HIZ. This research has begun to be incorporated in peer-reviewed publications; however, there is still much more work needed to quantify the knowledge. A risk-informed approach necessitates such knowledge in a quantifiable manner coupled with exposure conditions from surrounding wildland fires or structures. Building such a framework should be a goal of the research community, and the work reviewed here is moving in that direction. Continued attention to quantifying observational and experimental data is paramount to finding solutions to this problem.

While there continues to be a debate on whether to focus on active fire suppression, hardening of structures, or community mindset to prevent WUI disasters, clearly all three need to improve to make meaningful gains. A goal of the research community should be to engineer-out human error and involvement, but such a lofty goal can never fully be reached; therefore, continued attention to community education and active fire suppression must also continue. As additional research is incorporated into codes and standards that govern the construction of communities, firefighting tactics to defend these communities, and new approaches to mitigation, we can make meaningful gains toward protecting communities from WUI fires.

6. Acknowledgements

The authors would like to acknowledge the National Fire Protection Association, Fire Protection Research Foundation, the National Institute of Standards and Technology, and the Joint Fire Science Program under project JFSP 15-1-04-4 for financial support of this project. They would also like to thank Casey Grant for his efforts coordinating this project, Kyle Kohler for his assistance compiling data, and comments from many experts in the field, especially Randall Bradley, Nelson Bryner, Jack Cohen, Ryan Depew, Steve Gage, Samuel Manzello, Alexander Maranghides, Don Oaks, Stephen Quarles, Michele Steinberg, Kevin Tolhurst and Rick Swan.

References

1. Caton SE, Hakes RSP, Gorham DJ, Zhou A, Gollner MJ (2016) Review of Pathways for Building Fire Spread in the Wildland Urban Interfae Part I: Exposure Conditions. Fire Technol. doi: 10.1007/s10694-016-0589-z
2. Maranghides A, Mell W (2013) Framework for Addressing the National Wildland Urban Interface Fire Problem – Determining Fire and Ember Exposure Zones using a WUI Hazard Scale. doi: 10.6028/NIST.TN.1748
3. Babrauskas V (2003) Ignition handbook. Fire Science Publishers, Issaquah, WA
4. Pagni P, Woycheese JP (2000) Fire Spread by Brand Spotting. In: Bryner SL (ed) 15th Meet. UJNR Panel Fire Res. Saf. NISTIR 6588, pp 373–380
5. American Society for Testing and Materials (2011) ASTM E-108-11: Standard Test Methods for Fire Tests of Roof Coverings.
6. Underwriters Laboratory (2014) UL 790: Standard Test Methods for Fire Tests of Roof Coverings.
7. National Fire Protection Association (2011) NFPA 276 Standard Method of Fire Test for Determining the Heat Release Rate of Roofing Assemblies with Combustible Above-Deck Roofing Components.
8. State of California (2012) California Building Code: Materials and Construction Methods for Exterior Wildfire Exposure. doi: http://publicecodes.cyberregs.com/st/ca/st/b200v10/
9. Manzello S (2014) Enabling the Investigation of Structure Vulnerabilities to Wind- Driven Firebrand Showers in Wildland-Urban Interface (WUI) Fires. Fire Safety Sci 11:83–96. doi: 10.3801/IAFSS.FSS.11-83
10. Holmes CA (1971) Evaluation of fire-retardant treatments for wood shingles. USDA FPL-158. doi: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp158.pdf
11. LeVan SL, Holmes CA (1986) Effectiveness of fire retardant treatments for shingles after 10 years of outdoor weathering. USDA FPL-474. doi: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp474.pdf

12. Holmes CA, Knispel RO (1981) Exterior weathering durability of some leach-resistant fire-retardant treatments for wood shingles: A 5-year report. USDA FPL 403. doi: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp403.pdf
13. Holmes CA (1973) Correlation of ASTM exposure tests for evaluating the durability of fire-retardant treatment of wood. USDA FPL 194. doi: http://www.fpl.fs.fed.us/documnts/fplrp/fplrp194.pdf
14. Marney DCO, Russell LJ, Mann R (2008) Fire performance of wood (Pinus radiata) treated with fire retardants and a wood preservative. Fire Mater 32:357–370. doi: 10.1002/fam.973
15. Lowden L, Hull T (2013) Flammability behaviour of wood and a review of the methods for its reduction. Fire Sci Rev. doi: 10.1186/2193-0414-2-4
16. Marney DCO, Russell LJ (2008) Combined Fire Retardant and Wood Preservative Treatments for Outdoor Wood Applications – A Review of the Literature. Fire Technol 44:1–14. doi: 10.1007/s10694-007-0016-6
17. Quarles SL (2012) Vulnerabilities of Buildings to Wildfire Exposures. 1–13. doi: http://articles.extension.org/pages/63495/vulnerabilities-of-buildings-to-wildfire-exposures
18. Manzello SL, Suzuki S, Hayashi Y (2012) Enabling the study of structure vulnerabilities to ignition from wind driven firebrand showers: A summary of experimental results. Fire Safety J 54:181–196. doi: 10.1016/j.firesaf.2012.06.012
19. Manzello SL, Hayashi Y, Yoneki T, Yamamoto Y (2010) Quantifying the vulnerabilities of ceramic tile roofing assemblies to ignition during a firebrand attack. Fire Safety J 45:35–43. doi: 10.1016/j.firesaf.2009.09.002
20. Manzello SL (2013) The Performance of Concrete Tile and Terracotta Tile Roofing Assemblies Exposed to Wind-Driven Firebrand Showers. doi: 10.6028/NIST.TN.1794
21. Cohen J, Stratton R (2008) Home Destruction Examination Grass Valley Fire. USDA R5-TP-026b. doi: http://www.treesearch.fs.fed.us/pubs/31544
22. Manzello S, Shields J, Hayashi Y, Nii D (2008) Investigating the Vulnerabilities of Structures to Ignition From a Firebrand Attack. Fire Safety Sci 9:143–154. doi: 10.3801/IAFSS.FSS.9-143
23. Manzello SL, Shields JR, Yang JC, Hayashi Y, Nii D (2007) On the use of a firebrand generator to investigate the ignition of structures in wildland--urban interface (WUI) fires. Elev Int Fire Sci Eng Conf 3–5.
24. Manzello SL, Park S-H, Shields JR, Hayashi Y, Suzuki S (2010) Comparison Testing Protocol for Firebrand Penetration through Building Vents: Summary of BRI / NIST Full Scale and NIST Reduced Scale Results NIST TN 1659. Gaithersburg, MD
25. Manzello SL, Suzuki S, Hayashi Y (2012) Exposing siding treatments, walls fitted with eaves, and glazing assemblies to firebrand showers. Fire Safety J 50:25–34. doi: 10.1016/j.firesaf.2012.01.006
26. Yang JC, Manzello SL (2015) A dimensional analysis on firebrand penetration through a mesh screen. Fuel 160:114–116. doi: 10.1016/j.fuel.2015.07.098
27. Manzello SL, Park S-H, Suzuki S, Shields JR, Hayashi Y (2011) Experimental investigation

of structure vulnerabilities to firebrand showers. Fire Safety J 46:568–578. doi: 10.1016/j.firesaf.2011.09.003

28. American Society for Testing and Materials (2014) ASTM E-2886: Standard Test Method for Evaluating the Ability of Exterior Vents to Resist the Entry of Embers and Direct Flame Impingement.

29. Drysdale D (2011) An introduction to fire dynamics. John Wiley & Sons, Ltd, Chichester, UK

30. Cohen JD (2000) Preventing Disaster: Home Ignitability in the Wildland-Urban Interface. J Forest 98:15–21. doi: http://www.fs.fed.us/rm/pubs_other/rmrs_2000_cohen_j002.pdf

31. Maranghides A, Johnsson E (2008) Residential Structure Separation Fire Experiments. NIST TN 1600. Gaithersburg, MD

32. National Fire Protection Association (2013) NFPA 1144 Standard for reducing structure ignition hazards from wildland fire.

33. National Fire Protection Association (2012) NFPA 1141 Standard for fire protection infrastructure for land development in wildland, rural, and suburban areas.

34. International Code Council (2012) International Wildland-Urban Interface Code.

35. Cohen JD (1995) Structure Ignition Assessment Model (SIAM). doi: http://www.firewise.org/wildfire-preparedness/wui-home-ignition-research/the-jack-cohen-files.aspx?sso=0

36. Mell W, Maranghides A (2009) A Case Study of a Community Affected by the Witch and Guejito Fires. doi: http://iawfonline.org/NIST_Witch_Fire_TN1635.pdf

37. Quarles S, Leschak P, Cowger R, Worley K, Brown R, Iskowitz C (2012) Lessons Learned From Waldo Canyon: Fire Adapted Communities Mitigation Assessment Team Findings. Fire Adapted Communities Coalition, IBHS Richburg, SC

38. Wheeler J (2004) Testing for Deck Material Flammability. Fire Manag Today 64:13–15.

39. Murphy K, Rich T, Sexton T (2007) An Assessment of Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition on the Angora Fire. USDA R5-TP-025. doi: http://www.cnpssd.org/fire/angorafireusfsfullreport.pdf

40. Manzello SL, Suzuki S (2014) Exposing Decking Assemblies to Continuous Wind-Driven Firebrand Showers. Fire Saf Sci Proc 11th Int Symp. doi: http://www.nist.gov/customcf/get_pdf.cfm?pub_id=913383

41. Maranghides A, McNamara D, Mell W, Trook J, Toman B (2013) A case study of a community affected by the Witch and Guejito fires : Report #2 - evaluating the effects of hazard mitigation actions on structure ignitions. doi: 10.6028/NIST.TN.1796

42. Suzuki S, Johnsson E, Maranghides A, Manzello SL (2015) Ignition of Wood Fencing Assemblies Exposed to Continuous Wind-Driven Firebrand Showers. Fire Technol. doi: 10.1007/s10694-015-0520-z

43. National Fire Protection Association (2014) Firewise Communities. http://www.firewise.org/usa-recognition-program/cwpps.aspx?sso=0. Accessed 3 Oct 2015

44. Steward LG, Sydnor TD, Bishop B (2003) the Ease of Ignition of 13 Landscape Mulches. J

Arboric 29:317–321.

45. Quarles S, Smith E (2004) The Combustibility of Landscape Mulches. doi: http://plumasfiresafe.org/Documents/mulches.PDF

46. Manzello SL, Cleary TG, Shields JR, Yang JC (2006) Ignition of mulch and grasses by firebrands in wildland–urban interface fires. Int J Wildland Fire 15(3):427–431. doi: 10.1071/WF06031

47. Zipperer W, Long A, Hinton B, Maranghides A, Mell W (2007) Mulch flammability. In: Proc. Emer. Issue. pp 192–195

48. Beyler C, Dinaburg J, Mealy C (2014) Development of Test Methods for Assessing the Fire Hazards of Landscaping Mulch. Fire Technol 50:39–60. doi: 10.1007/s10694-012-0264-y

49. Suzuki S, Manzello SL, Kagiya K, Suzuki J, Hayashi Y (2015) Ignition of Mulch Beds Exposed to Continuous Wind-Driven Firebrand Showers. Fire Technol 51:905–922. doi: 10.1007/s10694-014-0425-2

50. National Fire Protection Association (2012) NFPA 1142 Standard on Water Supplies for Suburban and Rural Fire Fighting.

51. National Fire Protection Association (2014) NFPA 1143 Standard for Wildland Fire Management.

52. Insurance Institute for Busines & Home Safety (2007) MEGA FIRES: The Case for Mitigation. 1–4.

53. Cohen J (2004) Relating flame radiation to home ignition using modeling and experimental crown fires. Can J Forest Res 34:1616–1626. doi: 10.1139/X04-049

54. Syphard AD, Brennan TJ, Keeley JE (2014) The role of defensible space for residential structure protection during wildfires. Int J Wildland Fire 23:1165. doi: 10.1071/WF13158

55. Hudak AT, Rickert I, Morgan P, Strand E, Lewis SA, Robichaud PR, Hoffman C, Holden ZA (2011) Review of Fuel Treatment Effectiveness in Forests and Rangelands and a Case Study From the 2007 Megafires in Central Idaho USA. RMRS-GTR-252.

56. Hood S, Wu R (2006) Estimating Fuel Bed Loadings in Masticated Areas Field Measurements. USDA RMRS-P-41. 333–340.

57. Wiedinmyer C, Hurteau MD (2010) Prescribed fire as a means of reducing forest carbon emissions in the western United States. Environ Sci Technol 44:1926–32. doi: 10.1021/es902455e

58. Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. Forest Ecol Manag 211:83–96. doi: 10.1016/j.foreco.2005.01.034

59. Reinhardt ED, Keane RE, Calkin DE, Cohen JD (2008) Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecol Manag 256:1997–2006. doi: 10.1016/j.foreco.2008.09.016

60. Syphard AD, Keeley JE, Brennan TJ (2011) Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California. Int J Wildland Fire 20:764–775. doi: 10.1071/WF10065

61. Syphard AD, Keeley JE, Brennan TJ (2011) Comparing the role of fuel breaks across

southern California national forests. Forest Ecol Manag 261:2038–2048. doi: 10.1016/j.foreco.2011.02.030

62. Finney MA, Cohen JD, McAllister SS, Jolly WM (2013) On the need for a theory of wildland fire spread. Int J Wildland Fire 22:25–36. doi: 10.1071/WF11117

63. Mercer DE, Prestemon JP (2005) Comparing production function models for wildfire risk analysis in the wildland–urban interface. Forest Policy Econ 7:782–795. doi: 10.1016/j.forpol.2005.03.003

64. Cohen J (2008) The Wildland-Urban Interface Fire Problem: A Consequence of the Fire Exclusion Paradigm. Forest Hist Today Fall:20–26.

65. Brenkert-Smith H (2010) Building bridges to fight fire: the role of informal social interactions in six Colorado wildland–urban interface communities. Int J Wildland Fire 19:689. doi: 10.1071/WF09063

66. Gordon JS, Matarrita-Cascante D, Stedman RC, Luloff a. E (2010) Wildfire Perception and Community Change. Rural Sociol 75:455–477. doi: 10.1111/j.1549-0831.2010.00021.x

67. Spyratos V, Bourgeron PS, Ghil M (2007) Development at the wildland-urban interface and the mitigation of forest-fire risk. Proc Natl Acad Sci USA 104:14272–6. doi: 10.1073/pnas.0704488104

68. Syphard AD, Keeley JE, Massada AB, Brennan TJ, Radeloff VC (2012) Housing arrangement and location determine the likelihood of housing loss due to wildfire. PLoS One 7(3):e33954. doi: 10.1371/journal.pone.0033954

69. Alexandre PM, Stewart SI, Mockrin MH, Keuler NS, Syphard AD, Bar-Massada A, Clayton MK, Radeloff VC (2015) The relative impacts of vegetation, topography and spatial arrangement on building loss to wildfires in case studies of California and Colorado. Landscape Ecol. doi: 10.1007/s10980-015-0257-6

70. Urbas J (2013) Effectiveness of pre-applied wetting agents in prevention of wildland urban interface fires. Fire Mater 563–580. doi: 10.1002/fam

71. Glenn GM, Bingol G, Chiou B-S, Klamczynski AP, Pan Z (2012) Sodium bentonite-based coatings containing starch for protecting structures in wildfire emergency situations. Fire Safety J 51:85–92. doi: 10.1016/j.firesaf.2012.03.005

72. Takahashi F, Abbott A, Murray TM, T'ien JS, Olson SL (2013) Thermal response characteristics of fire blanket materials. Fire Mater. doi: 10.1002/fam.2202

73. Johnson JF, Downing T, Nelson KC (2008) External Sprinkler Systems and Defensible Space: Lessons Learned from the Ham Lake Fire and the Gunflint Trail. University of Minnesota. doi: https://www.forestry.umn.edu/sites/forestry.umn.edu/files/cfans_asset_183520.pdf

74. Mitchell JW (2006) Wind-enabled ember dousing. Fire Safety J 41:444–458. doi: 10.1016/j.firesaf.2006.04.002

75. Rahn M (2010) Initial Attack Effectiveness: Wildfire Staffing Study. Report No. 2. San Diego St Univ.

76. Rhode MS (2002) Command Decisions During Catastrophic Urban-interface Wildfire: A Case Study of the 1993 Orange County, California, Laguna Fire. University of Phoenix

77. Maranghides A, Mcnamara D, Vihnanek R, Restiano J, Leland C (2015) A Case Study of a Community Affected by the Waldo Fire – Event Timeline and Defensive Actions. doi: 10.6028/NIST.TN.1910

78. Cohen JD, Deeming JE (1985) The national fire-danger rating system: basic equations. USDA GTR-PSW-82. doi: http://www.fs.fed.us/psw/publications/documents/psw_gtr082/psw_gtr082.pdf

79. Stewart SI, Wilmer B, Hammer RB, Aplet GH, Hawbaker TJ, Miller C, Radeloff VC (2009) Wildland–Urban Interface Maps Vary with Purpose and Context. J Forest 107(2):78–83.

80. Haas JR, Calkin DE, Thompson MP (2013) A national approach for integrating wildfire simulation modeling into Wildland Urban Interface risk assessments within the United States. Landscape Urban Plan 119:44–53. doi: 10.1016/j.landurbplan.2013.06.011

81. Menakis J, Cohen J, Bradshaw L (2003) Mapping wildland fire risk to flammable structures for the conterminous United States. In: Galley KEM, Klinger RC, Sugihara NG (eds) Proc. Fire Conf. 2000 First Natl. Congr. Fire Ecol. Prev. Manag. pp 41–49

82. Calkin DE, Cohen JD, Finney MA, Thompson MP (2014) How risk management can prevent future wildfire disasters in the wildland-urban interface. Proc Natl Acad Sci USA 111:746–751. doi: 10.1073/pnas.1315088111

83. Cohen J, Saveland J (1997) Structure ignition assessment can help reduce fire damages in the WUI. doi: http://www.firewise.org/wildfire-preparedness/wui-home-ignition-research/the-jack-cohen-files.aspx?sso=d1d65917-4f03-46da-bb5f-0b815f0784ea

84. State of California: CALFIRE (2015) California Fire Hazard Severity Zone Model Map Update Project. http://www.fire.ca.gov/fire_prevention/fire_prevention_wildland_zones_maps.php. Accessed 3 Oct 2015

85. Lautenberger C (2015) Wildland Fire Hazard Modeling Tools (WFHMT). http://reaxengineering.com/trac/wfhmt/. Accessed 3 Oct 2015

86. Finney MA (2004) FARSITE: Fire Area Simulator—model development and evaluation. RMRS-RP-4. doi: http://www.fs.fed.us/rm/pubs/rmrs_rp004.pdf

87. Pellegrino JL, Bryner NP, Johnsson EL (2013) Wildland-Urban Interface Fire Research Needs: Workshop Summary Report. doi: 10.6028/NIST.SP.1150

88. Schoennagel T, Nelson CR, Theobald DM, Carnwath GC, Chapman TB (2009) Implementation of National Fire Plan treatments near the wildland-urban interface in the western United States. Proc Natl Acad Sci USA 106:10706–11. doi: 10.1073/pnas.0900991106

89. Manzello SL, Suzuki S (2013) Experimentally Simulating Wind Driven Firebrand Showers in Wildland-urban Interface (WUI) Fires: Overview of the NIST Firebrand Generator (NIST Dragon) Technology. Procedia Eng 62:91–102. doi: 10.1016/j.proeng.2013.08.047

90. Gollner MJ, Hakes RSP, Caton SE, Kohler K (2015) Pathways for Building Fire Spread at the Wildland Urban Interface. doi: http://www.nfpa.org/research/fire-protection-research-foundation/projects-reports-and-proceedings/for-emergency-responders/fire-prevention-and-administration/pathways-for-building-fire-spread-at-the-wildland-urban-interface

91. Fitzgerald S, Harvey B (2004) Is Florida's Prescribed Fire Program Somthing to Get Choked up About? Fire Manag Today 64:16–18.

92. Bowman DMJS, Johnston FH (2005) Wildfire Smoke, Fire Management, and Human Health. Ecohealth 2:76–80. doi: 10.1007/s10393-004-0149-8

93. Künzli N, Avol E, Wu J, Gauderman WJ, Rappaport E, Millstein J, Bennion J, McConnell R, Gilliland FD, Berhane K, Lurmann F, Winer A, Peters JM (2006) Health Effects of the 2003 Southern California Wildfires on Children. Am J Resp Crit Care 174:1221–1228. doi: 10.1164/rccm.200604-519OC

94. Fowler C (2003) Human Health Impacts of Forest Fires in the Southern United States: A Literature Review. J Ecol Anthropol 7:39–63. doi: 10.5038/2162-4593.7.1.3

95. Bryner NP, Mulholland GW (1991) Smoke emission and burning rates for urban structures. Atmos Environ A-Gen 25:2553–2562. doi: 10.1016/0960-1686(91)90172-4

96. National Fire Protection Association NFPA 13R Standard for the Installation of Sprinkler Systems in Low-Rise Residential Occupancies.