IBHS RESEARCH

WILDLAND FIRE EMBERS AND FLAMES:
Home Mitigations That Matter

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Executive Summary

In a wildfire, buildings ignite through a complex ignition mechanism linked to embers and flames. Due to the variety of possible ignition scenarios, a single hardening strategy is not effective at reducing the chance homes will ignite. To meaningfully reduce the risk, a two-tiered approach that applies the current state of the science is necessary and must include:

1. foundational, systemic protection of a home against embers
2. an additional layer of mitigations to guard against flame exposure

Wildland Fire Embers and Flames: Home Mitigations That Matter discusses available literature on the vulnerability of each component of the home and the need for this systematic, all-inclusive application of these mitigations.

Mitigations Against Embers and Flames

Roofs	As a large, elevated surface with complex geometry and a range of slopes, roofs are prone to ember accumulation and eventual ignition if the roof is not fire resistant. A Class A roof covering reduces this vulnerability.
Gutters	In gutters, leaves and pine needles accumulate, providing embers with a susceptible fuel bed. Gutters should be kept clean with a noncombustible cover to limit debris accumulation. Noncombustible gutters also shield the fascia board from flame exposure.
Vents	Vents are exposed to flames and embers. Protect the vent from flames by choosing vents made of a noncombustible material. Vent openings must be protected with a 1/8-inch or finer noncombustible mesh screen to prevent large embers from entering the house and igniting the house from the inside. Similarly, dryer vents should have a noncombustible louver or flap.
Zone 0	Winds carry debris and embers during wildfires, which settle near homes as the wind interacts with the structure. Combustibles should be kept at least 5 feet from the home to minimize the risk of short flames to the home and provide no fuel for embers to land on. A well-maintained Zone 0 with no combustibles also acts as a fuel break to stop surface fires approaching the home and reduce the likelihood of home ignition.
Fences	Combustible fences provide a path of fuel for fire to reach a home. Even for homes with noncombustible cladding, flames from a burning fence can threaten eaves and nearby windows. Installing a noncombustible fence inside Zone 0 breaks the path of fire to a home. The combination of trapped debris between back-to-back fences and the fence itself creates an extremely susceptible fuel bed for embers. This fence design should be avoided in the WUI.
Decks	Deck assemblies (walking surfaces, joists, and posts) are vulnerable to embers and flames. Embers can fall between deck boards and ignite the joists beneath or combustibles in the underdeck area. The odds of underdeck flame impingement are minimized if the underdeck area is well-maintained with no combustible materials. Where decks are low to the ground, enclosing the underdeck area with 1/8-inch or finer

	noncombustible mesh reduces the likelihood of debris and ember accumulation. A solid walking surface limits the ignition potential of the deck joists as no embers can reach them; this means the joists are unlikely to become a pathway for fire to reach the home. To best reduce the odds of deck ignition, choose a noncombustible deck assembly (including joists, railings, posts, and walking surface).
Accessory Buildings	When spot fires ignite accessory buildings like sheds and gazebos, short local flames transform into tall flames that radiate significant amounts of heat and/or touch nearby buildings. To limit these kinds of exposures, all accessory buildings within 30 ft of the home should be built with the same mitigation measures as the home.
Eaves	The geometry of eaves traps heat from flames and hot gases. While field evidence of ignitions is anecdotal, protecting eaves with noncombustible soffits mitigates the ignition potential.
Walls	When flying embers hit a wall, the embers lose their kinetic energy, fall to the ground, and accumulate. A 6-inch vertical noncombustible clearance at the base of exterior walls limits the exposure to siding from embers. While a 6-inch vertical clearance protects a wall from embers, more action is needed to provide protection from flames. Their geometry makes walls suitable recipients of radiation and flame contact in WUI fires. The spread of flame through walls can be slow, but surface flame spread on combustible siding occurs quickly. This exposes windows and eaves to direct flame contact and can begin the cascade of damage for a home. Noncombustible cladding eliminates the chance of such flame exposures.
Windows	Windows are vulnerable to flame contact and radiation. Multipaned windows are more resilient by providing multiple layers of protection before flames can penetrate the home. Tempered glass further increases resilience because of its higher resistance to flame radiation.
Doors	Flames are less likely to reach exterior doors with proper defensible space around the home. However, wind-blown embers may still accumulate at the base of a door or penetrate small openings around the door and ignite the door jamb. Therefore, the entire door assembly should be mitigated. Fire-rated doors are the most practical solution due to the lack of noncombustible door assemblies (door jamb) on the market.
Bay Windows	The geometry of bay windows traps heat underneath them. While field evidence of ignitions is anecdotal, enclosing this area with noncombustible materials eliminates the risk.

Wildfire Mitigation Issues in Brief

The socioeconomic impact of wildfires on communities has long-lasting consequences when homes are damaged or destroyed. In addition to immediate costs such as fire suppression and rebuilding, local and national businesses are also affected by interruptions in labor, supply chain, demand for goods and services (Dale, 2010), and even virtual needs such as video streaming platforms. To protect communities from these broad impacts, every home within the community must take specific actions to mitigate the risk of wildfire.

Wildfire loss estimates are influenced by drought and climate trends, population growth in high-hazard areas, and construction culture in wildfire-prone areas (Aon Benfield 2016; Kramer et al., 2019). From 1980 to 2021, about 70% of losses due to wildfires in the United States happened in California (Smith, 2020). The rapid development of land in California has outpaced the enhancement of scientific measures to estimate the wildfire risk, evaluate building materials, and provide policy makers with methodical long-term views (Moore, 1981). The California Department of Forestry and Fire Protection (CAL FIRE) took steps to respond to this need in 1982 by introducing the Fire Hazard Severity Zone maps. These maps were then updated in 2007 with three levels of increasing fire hazard severity across California, namely medium, high, and very high. Structures built in the State Responsibility Area (SRA) and high and very high fire hazard severity zones in the Local Responsibility Areas (LRAs) must meet specific building materials, systems, and assembly requirements. The California Building Code Chapter 7A (denoted as Chapter 7A in this document) outlines these minimum requirements (California State Fire Marshal, 2022).

Buildings constructed with fire-resistant materials, such as those built in compliance with the 2007 or newer edition of Chapter 7A, can be less vulnerable to wildfires (Miller et al., 2022). After analyzing survived structures from wildfires in Southern California, Syphard et. al (2017) concludes that buildings with vinyl window frames, stucco exterior construction, dual-paned windows, and tile roofs had a higher survival rate. Recently built structures were more likely to use these materials. However, Knapp et al. (2021) did not find the effects of Chapter 7A–compliant buildings to be statistically significant to the survival rate. This finding could be a result of the requirements of Chapter 7A, which are limited to building materials, systems, and assemblies, while the hazards that local fuel around a building can create is not considered. The hazard intensity from local fuels can vastly vary, which directly influences the performance of different building materials (Caton et al., 2017). To address this issue, California's Board of Forestry and Fire Protection is currently amending the requirements for maintaining a defensible space, 0–30 ft and 30–100 ft, near buildings (Board of Forestry and Fire Protection, 2018). Acknowledging the threat of embers, the Board of Forestry and Fire Protection assembled a group of subject matter experts and stakeholders to update the regulations and include requirements for 0–5 ft (called Zone 0), which is under development. The lack of clarity in Chapter 7A regarding the building features and associated regulations is apparent (Intini et al., 2020); one of which is the requirements for defensible space, specifically 0–5 ft from the building. This will be discussed in detail subsequently. In addition, Chapter 7A provides several prescriptive and performance-based options for compliance of each built environment component addressed in the code. A user could assume that these options provide comparable fire protection, but since a range of ignition-resistant material options can comply, these options do not provide comparable fire protection. Also, as previously mentioned, the enforcement of Chapter 7A is limited to new construction in the SRA and the very high fire hazard severity zones in the LRAs. These provisions are currently not applicable to existing structures unless the local jurisdiction has included such a provision through a locally adopted ordinance.

In response to the need to quantify the performance of different components and provide clear guidance to maintain a defensible space, IBHS published the Suburban Wildfire Adaptation Roadmaps (Insurance Institute for Business & Home Safety, 2021). Fuel management, decks, fences, building shapes, exterior walls, roofs, vents, and eaves are addressed in this report. Individually and collectively, resilient choices in these eight areas reduce the likelihood of ignition that result in catastrophic building loss in a community threatened by wildfire. While there are some actions that are obvious and follow conventional wisdom, other actions are less obvious and require an expert opinion until research can provide more insight. While Chapter 7A provides a range of prescriptive and performance-based options, the Suburban Wildfire Adaptation Roadmaps discriminate the fire performance of individual building components based on their characteristics and fill the gap on defensible space guidance.

Mitigating Wildland-Urban Interface (WUI) fire hazards is often viewed as either a voluntary "every little bit helps" or a "one-size-fits-all" effort (Maranghides et al., 2022a). Yet both approaches leave significant gaps and create a false sense of risk reduction (Maranghides et al., 2022a; Penman et al., 2015). Research shows if a house meets the group of recommendations in the Suburban Wildfire Adaptation Roadmaps, there will be a reduced possibility of ignition compared to a house that does not (Cohen, 2000; Maranghides et al., 2021a). The impact of these recommendations would be greater if all buildings in a neighborhood took these measures.

Mechanisms of Ignition

Buildings are ignited by embers and flames during wildfires. Flying embers and wind-blown, ground-traveling burning debris are by far the most prevalent attack mechanisms threatening structures during a wildfire. CAL FIRE identified embers as the major cause of home loss (Mell et al., 2010). Potter and Leonard (2011) reported that "well over 90% of houses were ignited in the absence of direct flame attack or radiant heat (exceeding 12 kW/m^2) from the main fire front." Hence, embers cause a great deal of damage, whether directly or indirectly.

Direct ignition by embers happens when embers land and accumulate on combustible components of the building and ignite these components or when embers enter the building through openings and ignite interior materials. Small-scale (Richter et al., 2022) and full-scale experimental studies (Cohen, 2000; Davis, 1990; Hedayati et al., 2022; Suzuki et al., 2017) demonstrate that accumulated embers are capable of directly igniting common combustible building components. Embers can also penetrate through openings and ignite the combustibles, such as furniture, inside a building (Quarles et al., 2010; Robertson, 2013).

Indirect ignition by embers occurs when embers accumulate on combustibles near a building and ignite these materials. The resulting flames ignite a component of the building by radiant heat and/or direct flame contact. These spot fires typically have notably lower intensity relative to the main fire front (Potter & Leonard, 2011), but under favorable conditions, these spot fires can spread to nearby structures. It is important to note that only tall, thick flames can radiate sufficient heat to ignite buildings, while smaller flames need to be close or in contact with the building to cause ignition (Himoto, 2022).

After wildfires, unburned tree canopies are commonly found in close proximity to areas destroyed by a crown fire. These unburned areas are commonly referred to as "islands." This pattern contrasts with the damage pattern often seen in floods where areas within the flood zone are contiguously destroyed. Fire spreads when the conditions for combustion—the fire triangle—are met along its path. Combustion requirements in the forest apply equally to WUI fires where structural and wildland fuels are present (Cohen, 2000). Reducing the vulnerability of buildings to embers and flames would result in "islands" of homes and buildings in the WUI within the path of a wildfire.

Although experimental and numerical studies providing information about ember storms in the WUI exist, predicting the path and accumulation position of embers is challenging. During flight, embers follow an unpredictable flight path influenced by building features and environmental parameters. The geometric characteristics of buildings, density of buildings in a community, and characteristics of receptive fuel beds affect ember accumulation, as does the shape of the embers, fuel from which the embers were generated, and local wind patterns, particularly wind vortices (Caton et al., 2017; Hedayati et al., 2019; Nguyen & Kaye, 2021).

Buildings can be affected by multiple sources of ignition during a wildfire, including radiative heat transfer from flames, convective heating from wind-blown plumes, continuous or intermittent flame contact, and localized heating from spot fires near the building (Himoto, 2022). This complex thermal exposure requires systematic fuel management and home hardening strategies to bend down the risk curve. In the WUI, ember-caused spot fires can use vulnerable homes as fuel to grow beyond a local threat into tall flames and lead to extreme fire behavior threatening neighboring homes. While it may be possible to identify the likely ignition pathway in an ember storm for an isolated house, chaotic ember accumulation patterns in communities make it nearly impossible to identify a single vulnerable component for a home in a community. Accepting these complexities of ember-caused ignitions, hardening the home and its immediate surroundings against all known ember vulnerabilities requires a systematic, all-inclusive hardening approach in the entire community. If all components of a home in a community are hardened against embers, the odds of a house becoming engulfed in tall, thick flames and radiating substantial heat to its surroundings are reduced. This allows the first responders to address spot fires early and prevent the spot fire from growing into a suburban conflagration.

Mitigations That Matter

A home is a system of components. To mitigate the risk of wildfire, all components vulnerable to embers and flames must be mitigated systematically. The available literature about the vulnerability of each component is discussed subsequently.

Roof

Wind patterns near buildings heavily influence ember distribution patterns and accumulation locations. Because roofs are a large, elevated surface with complex geometry and a range of slopes, they are prone to ember accumulation during ember storms. The regions on the rooftop where embers reach stability and rest are also a complex function of roof geometry, particularly roof valleys. Roof valleys are often covered with organic debris, which is particularly susceptible to ignition from embers (Nguyen & Kaye, 2021).

The vulnerability of roofs to ember storms is well studied. Several retrospective studies have reported a statistical correlation between wood roofing and building losses due to ember exposure (Davis, 1990; Foote et al., 2011). Moore (1981) reported that out of 1,850 homes, 50% of homes with wood roofs within 30 ft of burning vegetation ignited while only 24% of homes with fire-resistant roofs ignited in the 1961 Bel Air Fire in Southern California. Foote (1994) found the degree of flammability of the roof had a significant impact on home survival where homes with nonflammable roofs had a 70% survival rate compared to 19% for homes with flammable[1] roofs. After the 1991 Oakland Hills Fire in California, it was estimated that each burning home with a non-fire-retardant-treated wood shake roof contributed to the ignition of ten other homes (Bryner, 2000).

Standard test methods such as ASTM E108 (American Society for Testing and Materials, 2020) and UL 790 (Underwriters Laboratories, 2022) evaluate the fire performance of different roofing materials. In 2020, IBHS released a report on the vulnerability of different roofing materials and roof geometry and updated the report in 2021 (Insurance Institute for Business & Home Safety, 2021).

Roof: *As a large, elevated surface with complex geometry and a range of slopes, roofs are prone to ember accumulation and eventually ignition if the roof is not fire resistant. A Class A roof covering reduces this vulnerability.*

Gutters and Downspouts

Gutters are a prime location for leaves and pine needles to accumulate, which can expose the edge of the roof to direct flames during wildfires (Sindelar, 2011). Figure 1a shows a defended home in the Camp Fire (2018) in Butte County, California, where the evidence suggests that embers ignited debris in the gutter and caused damage to the roof deck. Likely due to intervention from first responders, the damage was contained to the gutter and roof edge and did not spread to the rest of the home. IBHS's research highlighted a similar vulnerability for gutters, as can be seen in Figure 1b. Note that the time it takes for the vinyl gutter to melt and fall might exceed the required time to ignite the roof deck.

a b

Figure 1. Direct flame contact to the edge of the roof caused by ignited debris in the gutters during ember storms (a) in the Camp Fire (2018) in County, California (home defended by first responders), and (b) a vinyl gutter melts off a house during testing at the IBHS Research Center.

[1] *There is no clear definition of flammability in this study. It's likely limited to non-fire-retardant-treated wood shakes.*

Frequent clearing of gutters of all debris would reduce this vulnerability. A noncombustible gutter is an excellent choice when the fascia board is not covered with a metal drip edge. Recent testing by IBHS shows noncombustible gutters provide protection for fascia boards or rafter tails, depending on the construction type, against flames. Figure 2 shows photographs taken during experiments at the IBHS Research Center evaluating building-to-building fire spread. In this test, half of the fascia board was covered with a metal gutter and half of it was not covered. The uncovered portion ignited, which caused some damage to the building's roof deck. Figure 2b compares the covered and uncovered parts of the fascia board after the test. In another test, a vinyl gutter was exposed to a flame source 20 ft away. The vinyl gutter melted and exposed the fascia board to flame contact about 10 minutes after ignition, shown in Figure 2c.

a b

c

Figure 2. A noncombustible gutter can provide protection for the fascia board if a metal drip edge is not installed. (a) shows fascia board ignition during the experiment and (b) shows the fascia board condition after the test. In (c), a vinyl gutter deformed due to radiant heat/intermittent flame contact and fell off.

Gutters and Downspouts: *In gutters, leaves and pine needles accumulate, providing embers with a susceptible fuel bed. Gutters should be kept clean with a noncombustible cover to limit debris accumulation. Noncombustible gutters also shield the fascia board from flame exposure.*

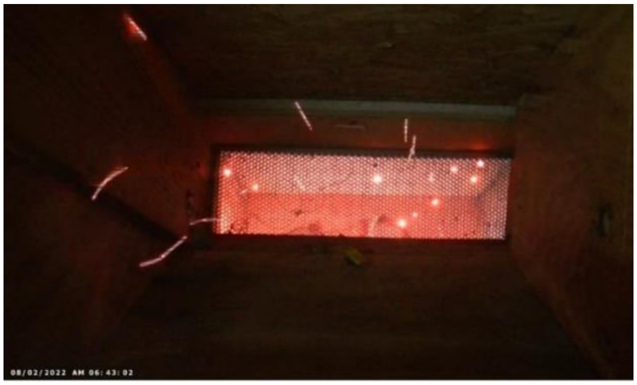
Vents

Unless a home has been built with an unvented design, unconditioned areas (e.g., attic and crawl spaces) must be ventilated to avoid elevated moisture and temperature conditions. Since 2016, Chapter 7A has required new vents to be resistant to embers and flames as tested by ASTM E2886 (American Society for Testing and Materials, 2014); this requirement will be added to the International Wildland-Urban Interface Code in 2024. Recent full-scale tests at IBHS show that ASTM E2886–compliant vents do not allow large embers to pass through. The embers collected behind these vents were small and incapable of igniting combustibles in the attic, as seen in Figure 3a.

However, older and inadequately protected vents can provide a pathway for fire and specifically for wind-blown embers to enter the building (Caton et al., 2017; Manzello et al., 2007; Quarles, 2017; Quarles & Gorham, 2019). Installing vents with metal mesh screens is an accepted mitigation strategy to prevent large embers, depending on the mesh size, from entering buildings (Hakes et al., 2017). Sharifian Barforoush and Du Preez (2022) identified eight different mechanisms when embers interacted with mesh screens: passing, stopping, splitting, shattering, pausing, bouncing, slipping, and wandering. Sharifian Barforoush and Du Preez report that, except for some long needle-shaped embers, the 1/16-in. mesh screen was highly effective against both large and small embers; Figure 3b demonstrates how embers could pass through unprotected vents in their experiment.

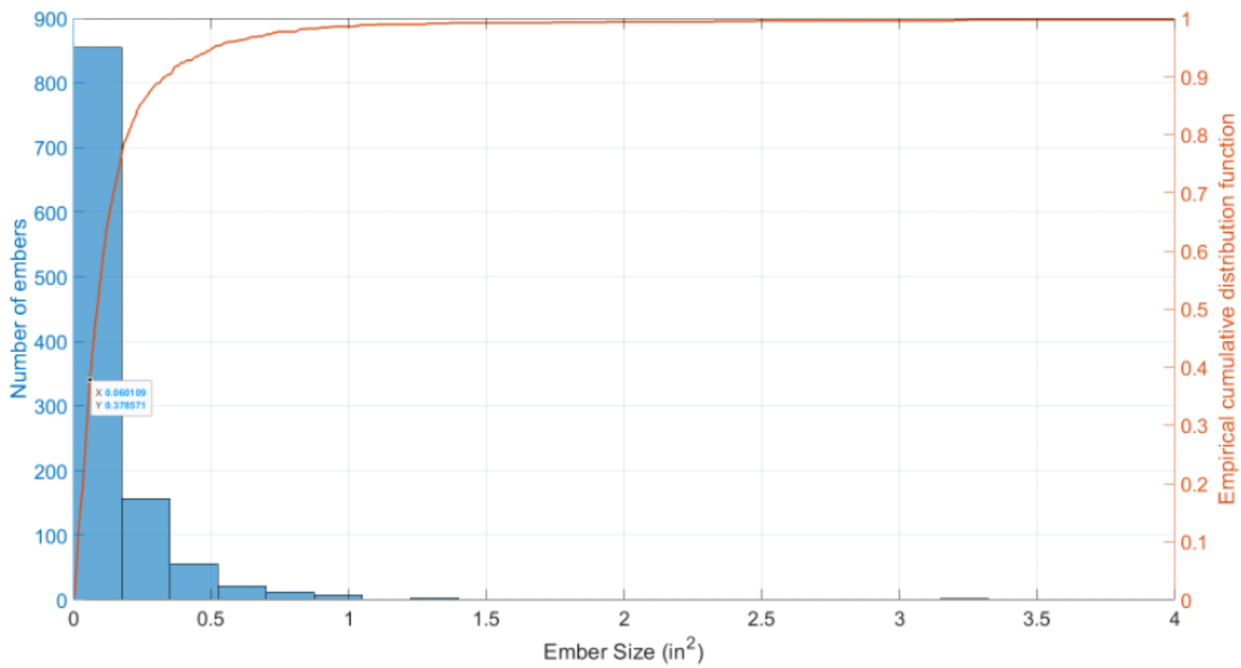
The mesh screen protecting a vent opening should be large enough to allow proper ventilation for the building, but small enough to keep larger embers from entering. The surface area of embers depends on several factors, including wind speed and type of fuel from which the ember originated. During a Joint Fire Science Program–funded research project between University of North Carolina at Charlotte, University of Maryland, IBHS, and other collaborators, the ember (firebrand) production from different structural and vegetative fuels was investigated (Bahrani et al., 2020; Hedayati et al., 2019; Hedayati et al., 2020). The results showed that the mass and size of embers followed a right-skewed distribution. The histogram and cumulative density function for pine tree embers are shown in Figure 3c. Common mesh screen sizes for commercially available vents are 1/4-in. and 1/8-in. The opening size of a 1/8-in. mesh screen is about 0.06 sq in. This point is highlighted on the graph in Figure 3c, which shows that about 38% of the embers were smaller than 0.06 sq in. Manzello et al. (2011) also reported that smaller mesh size reduced the ember penetration ratio, defined as the number of embers leaving from the mesh and the number of embers arriving at the mesh for a given time interval.

When considering defensive measures, it becomes apparent why vents need to be protected. Firefighters can suppress small flames and burning components when they see the fire, but when embers enter through vents, the house is ignited from the inside. When the fire begins inside the house, first responders have little chance of suppressing the fire because the fire can become large before it is visible from the exterior.



a

b



c

Figure 3. (a) Embers get stuck on the outside of an ASTM E2886–compliant vent until they become small enough to penetrate through during building separation tests at IBHS and (b) embers passing through the vents when no mesh is used (Sharifian Barforoush & Du Preez, 2022); image used with permission. (c) Size distribution of embers from pine trees.

Vents: *Vents, including dryer vents, are exposed to flames and embers. Protect the vent from flames by choosing vents made of a noncombustible material. Vent openings must be protected with a 1/8-in. or finer noncombustible mesh screen to prevent large embers from entering the house and igniting it from the inside. Similarly, dryer vents should have a noncombustible louver or flap.*

Vertical Ground Clearance

Wind-blown objects, embers, and debris tend to accumulate at the base of a wall following a change in the wind flow (Manzello et al., 2011). These wind-blown debris are often lower-density fine fuels that can be easily ignited and expose the building cladding to short flames (Manzello et al., 2012b). The importance of ground clearance to reduce ignition potential of a home has been reported in post-event investigations (Quarles et al., 2013).

Full-scale experiments at IBHS (Quarles et al., 2023) and the Fire Research Wind Tunnel Facility in Japan demonstrated that accumulation of embers at the base of an exterior wall can ignite cladding wall is in contact with embers and debris (Manzello et al., 2011; Manzello et al., 2012a; Nazare et al., 2021; Suzuki & Manzello, 2017). Manzello et al. (2017) exposed corner assemblies to embers with different types of mulch at the base with 102 mm (4 in.) and 203 mm (8 in.) vertical noncombustible clearance. At a 203 mm vertical clearance, the Japanese cypress mulch and pine bark nugget mulch ignited the corner assemblies, but the shredded hardwood mulch did not ignite the corner assembly. At a 102 mm vertical clearance, the Japanese cypress mulch ignited the corner assembly.

Figure 4. Ember accumulation at the base of the wall causing ignition (a and b) at the IBHS Research Center, (c) in the post-Camp Fire (2018) investigation in Butte County, California, and (d) at the base of a wall in the Glass Fire (2020) in Napa and Sonoma Counties, California, which did not have the opportunity to grow because of a noncombustible vertical clearance.

This vulnerability has been observed by the authors of this paper in previously unpublished ember exposure tests at the IBHS Research Center. During these tests, the base of the wall segments with wood siding ignited numerous times. From these observations, the authors tested different vertical separation distances between the ground and the base of the combustible cladding to mitigate this, shown in Figure 4b. Direct ignition of the wall occurred only during the no-clearance tests.

Debris piling up against the base of walls during wildfire events can create a susceptible fuel for embers to land on. Depending on the amount of debris, the size and intensity of these small flames can vary. Because a 6-in. vertical clearance was already required for combustible wood siding by the International Residential Code since 2000 for moisture degradation issues, IBHS began recommending a 6-in. vertical clearance to mitigate this ember vulnerability in 2013 (International Code Council, 2000). In Australia, a more conservative 400 mm—or 15 in.—clearance is recommended where a wall meets any horizontal projection including the ground, decks, or roof sections (Queensland Government & Commonwealth Scientific and Industrial Research Organization, 2020). Additional future research is needed to better understand debris accumulation.

Vertical Ground Clearance: *Elevated winds during wildfires cause burning debris to roll and become trapped against walls. When flying embers hit a wall, the embers lose their kinetic energy, fall to the ground, and accumulate at the base of the wall or very close to it. A vertical noncombustible clearance of at least 6 in. at the base of exterior walls limits the exposure to siding from these hot, burning objects.*

Fuel Management in Zone 0

The importance of fuel treatment and management near buildings (e.g., creating and maintaining an effective "defensible space") to minimize the likelihood of flame contact and extended radiant heat exposure to reduce the risk from wildfire has been studied experimentally (Cohen, 2000, 2004), in post-event investigations (Insurance Institute for Business & Home Safety, 2020; Maranghides et al., 2022a), and by scholars active in the public policy arena (Miller et al., 2022). Historically, there have been two defensible space zones: generally described as 0–30 ft and 30–100 ft or to the property line; however, the two zones vary in size in different guidelines (Board of Forestry and Fire Protection, 2018; Dennis, 2003; Federal Emergency Management Agency, 2020). According to Moore (1981), prior to the 1970s, the insurance industry used four levels of "brush clearance," namely 0–30 ft, 30–60 ft, 60–100 ft, and 100+ ft for hazard mapping purposes, which is a similar concept to defensible space. The University of Nevada, Reno's Living with Fire program has advocated for a near-home noncombustible zone since 1991 (Smith & Adams, 1991). Since 2011, IBHS has advocated for dividing the 0–30 ft zone into two separate zones (0–5 ft and 5–30 ft) because of the importance of ember accumulations and ignitions of combustible materials near the building, which create a critical threat to the building from potential small flames. During an ember storm created at the IBHS Research Center, as shown in Figure 4a, the accumulation of embers within the first 5 ft of the building is clear (Quarles et al., 2023). Embers accumulate at the base of the wall and within the first 5 ft from the building. Accumulation of embers in the vicinity of obstacles is also reported by Suzuki and Manzello (2017).

Any combustibles in the 0–5 ft zone are exposed to ember accumulation and potential ignition. Clearing this area of all combustible materials—vegetative and nonvegetative—plays an important role in reducing the likelihood of home ignition. Quarles and Smith (2011) studied the fire behavior of eight different kinds of mulch, namely: composted wood chips, medium pine bark nuggets, pine needles, shredded western red cedar, Tahoe chips, Tahoe chips with fire retardant, single layer Tahoe chips, and shredded rubber. They reported that, "with the exception of the composted wood chips, all of the mulch treatments demonstrated active flaming combustion" and that "shredded rubber, pine needles and shredded western red cedar demonstrated the most hazardous fire behavior"(Quarles & Smith, 2011). The fire behavior of surface fuels like mulch markedly change with wind and slope (Sánchez-Monroy et al., 2019). Hedayati et. al (2018) exposed the cladding of a full-scale building to an 80 kW gas burner for 15 min and monitored the temperature on the wall when the test building was oriented at different angles to the wind. Hedayati et al. report that when the flame was more than 5 ft away from the building, the ignition potential was significantly lower than at closer distances.

Investigations after wildfire events revealed increased vulnerability to the home from nearby combustibles. The investigation performed after the Grass Valley Fire (2008) in San Bernardino County, California, by Cohen and Stratton reported that in most cases, the destruction was not because of high-intensity flames, which are typically thick with large surface area. Instead, Cohen and Stratton found embers ignited the buildings directly or ignited a spot fire near the building where surface fuel touched wood siding (Cohen & Stratton, 2008). In Butte County, California, the National Institute of Standards and Technology's (NIST) post-Camp Fire (2018) report also provided examples where overhanging trees within the 0–5 ft zone could ignite the building (Maranghides et al., 2021a). As shown in Figure 5d from NIST's post-Camp Fire report, a fence was about 6 ft away from the building and branches from a tree extending towards the house appear longer than 1 ft. In other words, the branches were in the 0–5 ft zone and contributed to a pathway for fire. This vulnerability has also been highlighted in the IBHS post-Glass Fire (2020) investigation in Napa and Sonoma Counties, California. In this case, vegetation was observed to provide a pathway for ignition when plants—even in small amounts—touch the building as shown in Figure 5b. The house in Figure 5b was likely defended by first responders during the event.

At this time, little research has been done to understand the flammability of specific plant species and how they create a vulnerability for a home. Without a species-specific understanding of the vulnerability, current field observations and laboratory experiments support no vegetation in Zone 0 until additional research has been conducted.

Vegetation in Zone 0

Vegetative fuel—including dead, organic mulch—can generate a fire pathway when touching a building. As previously mentioned, the accumulation of embers near buildings can ignite these fuels (Manzello et al., 2006; Suzuki et al., 2015). In either scenario, the vegetative fuel can allow flames to reach the building's cladding. As shown in Figures 5a and b, investigations following the Glass Fire (2020) in Napa and Sonoma Counties, California, highlighted this pathway where embers landed in the front yard and ignited the wood mulch. The mulch carried the fire all the way to the home, ignited the hot tub, and damaged the building. Note the landscape barrier, which separates wood mulch with mineral soil. There is no visible damage to the building where the wood mulch is not present against the home. This can also be observed at another home in Figure 5c where the fire stops as the soil covering changes from wood mulch to gravel.

When evaluating available vegetation within the first 30 ft of homes affected by the Witch Creek Fire (2007) in San Diego County, California, it was found that 67% of homes with unmaintained vegetation were destroyed, while only 32% of homes with maintained defensible space were destroyed (Maranghides et al., 2013). Analyzing over 2,000 structures in San Diego County, Syphard et al. (2014) concluded that structures were more likely to survive a fire with an effective defensible space "immediately adjacent" to them. Syphard et al. also reported that reducing woody vegetation cover up to 40% immediately adjacent to structures and preventing vegetation from overhanging or touching structures were the most effective actions.

Using Principal Components Analysis (PCA) and Generalized Additive Mixed Models on data from 27 independent forest fires in New South Wales, Australia, Penman et al. (2018) concluded that vegetation touching houses likely caused ignition of the house once that vegetation ignited. It is difficult to distinguish between vegetation touching houses, garden cover, and overhanging vegetation in this study, which was

a

b

Figure 5a-b. *Example of vegetation in small amounts located in Zone 0 creating a pathway for fire spread: (a) Wood mulch provided a pathway for fire to get close to the building and ignite a hot tub during the Glass Fire (2020) in Napa and Sonoma Counties, California; (b) Ground-level plants during the Glass Fire (2020).*

c d

Figure 5c-d. *Example of vegetation in small amounts located in Zone 0 creating a pathway for fire spread: (c) Tree branches overhanging Zone 0 burn during the Camp Fire (2018) in Butte County, California, and provide a pathway for fire to reach a home (Maranghides et al., 2021a), used with permission; (d) Low-intensity surface fire (ember caused) stopped as it met gravel during the Glass Fire (2020), view from the deck to the backyard.*

an uncertainty source in their PCA analysis. While Gibbons et al. (2012) reported similar results, Wilson and Ferguson reported that vegetation very close to the siding and touching the roof did not increase the destruction rate of buildings (Wilson & Ferguson, 1986). As a caveat, Wilson and Ferguson focused on vegetation in contact with the roof rather than any other components.

Analyzing pre- and post-fire aerial imagery and connecting the results to the insurance claims data, ZestyAI concluded that if the first 0–5 ft around buildings were maintained to a light vegetation density, the likelihood of destruction was about 2 times lower compared to buildings with high density vegetation in the first 0–5 ft (Arrowsmith et al., 2021). The report goes on to say, “having heavy vegetation, more than 50% coverage, (including brush, trees, and shrubs) immediately around the home can nearly double the chance of destruction.”

Given the challenging nature of predicting wildfire occurrence and growth, homeowners often have little to no time to prepare for an approaching wildfire. Therefore, consistent maintenance of Zone 0 is required when a wildfire is not threatening.

Vegetation in Zone 0: *Wind carries debris and embers during wildfires, which settle near homes as the wind slows down and interacts with the structure. Combustibles should be kept at least 5 feet from homes to minimize the risk of short flames to the homes and to provide no fuel for embers to land on. A well-maintained Zone 0 with no combustibles also acts as a fuel break to stop surface fires approaching the home and reduces the likelihood of home ignition.*

Fences in Zone 0

Structural fuels, fences, and decks in contact with or within 5 ft of the main building can also provide a pathway for fire to spread. Laboratory tests and post-event investigations (Butler et al., 2022; Insurance Institute for Business & Home Safety, 2020) show the vulnerability of combustible fences, as seen in Figure 6a-d.

Figure 6. Examples of combustible fencing providing a pathway for fire to the house, damaging the noncombustible siding and eave (a and b) in the Glass Fire (2020) in Napa and Sonoma Counties, California, defended; (c) in the Camp Fire (2018) in Butte County, California, defended by first responders (Insurance Institute for Business & Home Safety, 2020); and (d) at the IBHS Research Center where the arrows indicate the direction of fire spread.

Fences in Zone 0: *Combustible fences provide a path of fuel for fire to reach a home. Even for homes with noncombustible cladding, flames from a burning fence can threaten vulnerable components such as eaves and nearby windows. Installing a noncombustible fence inside Zone 0 breaks the path of fire to a home.*

Attached Decks

Attached decks are another structural fuel that can exist in Zone 0. Dossi et al. (2022) recently introduced a Wildfire Resistance Index for buildings in California and Portugal. For buildings in California, Dossi et al. reported that building features, such as vent screens and decking material, are highly correlated to the damage level of the building, and protecting these features increases the survival likelihood of the building. Once ignited, decks can expose a building's cladding (siding), exterior wall components such as windows and doors, and the under-eave area to flames and radiant heat, as shown in Figure 7. In a wildfire, decks are typically exposed to embers on their top surface and flame impingement on the underside (Hasburgh et al., 2017; Leonard, 2019; Manzello & Suzuki, 2019; Meerpoel-Pietri et al., 2021). Given that the majority of homes in a wildfire ignite due to embers, if the underdeck area is clear of combustible materials, the risk of flame impingement to the underside of the deck is reduced, except for decks built on a slope. Keeping the underdeck area clear of combustible materials is especially important for low elevation decks where the maintenance of the underdeck area is troublesome, and in the case of ignition, flames can reach the joists and ignite them. Without an underdeck flame impingement, the only threat to the deck is from embers accumulating on the deck surface, where embers typically accumulate in the between-board gaps on the joist or at the corners where the deck assembly meets the siding (Manzello & Suzuki, 2014, 2019; Quarles & Standohar-Alfano, 2018).

Hedayati et al. (2022) reported that the substructure of the decks plays a major role in its vulnerability to flame impingement from below. Once the joists ignite due to the initial flame impingement exposure, the joists can burn for an extended period and continuously expose the bottom side of the deck boards to flames. Hedayati et al. reported that boards above a joist did not burn intensely if the joist wasn't engulfed in flames.

Attached Decks: *Deck assemblies (walking surfaces, joists, and posts) are vulnerable to embers and flames. Embers can fall between deck boards and ignite the joists beneath or combustibles in the underdeck area. The odds of underdeck flame impingement are minimized if the underdeck area is well-maintained with no combustible materials. Where decks are low to the ground, enclosing the underdeck area with 1/8-in. or finer noncombustible mesh reduces the likelihood of debris and ember accumulation. A solid walking surface limits the ignition potential of the deck joists as no embers can reach them; this means the joists are unlikely to become a pathway for fire to reach the home (Hedayati et al., 2022). To best reduce the odds of deck ignition, choose a noncombustible deck assembly (including joists, railings, posts, and walking surface).*

Fuel Management Beyond Zone 0

While Zone 0 is designed to minimize the threat of localized fires from embers and creeping fires (Ascoli et al., 2018), the area beyond Zone 0 also plays a role in protecting the structure in a wildfire. A structure with fire-resistant or noncombustible materials is more likely to withstand a creeping fire than a fire with tall flames (Maranghides et al., 2022a; Syphard & Keeley, 2019). Moreover, suppression efforts by first responders are more effective if they can enter the parcel without risking their safety (Penman et al., 2015). With effective structural and vegetative fuel management beyond Zone 0, the threat of tall, thick, high-intensity flames frequently resulting from flying embers is reduced.

Vegetation Beyond Zone 0

Reducing the threat of tall, thick, high-intensity flames can typically be achieved by creating discontinuity between trees and bushes in both the horizontal and vertical directions. Statistical analysis of post-event investigations reveals that vegetative fuels located near buildings add to the vulnerability of the structure. The Ramsay et al. (1987) post-Ash Wednesday Bushfire analysis reported that the amount and type of vegetation near houses was an important factor in their damage state. Houses were more likely to have survived when they did not have dense vegetation around them. Cohen and Butler (1996) modeled radiative heat transfer from burning vegetation and concluded that vegetation thinning within 40 m (131 ft) of a building mitigates ignition. Analyzing post-fire data collected in Southern California, Miner (2014) concluded that reducing vegetation density by 25% is sufficient to reduce the risk. Miner also mentioned that in the short term, the most important action is to remove flammable vegetation adjacent to or overhanging homes. Gibbons et al. (2018)analyzed about 500 homes affected by Southern Australia bush fires and reported that removing vegetation close to homes is "at the forefront of mitigations." The study concluded that removal of shrubs and trees upwind of the house reduces the risk of house loss more effectively than removing trees very close to the house. Samora-Arvela et al. (2023) analyzed post-fire investigation data in Portugal and reported that the presence of trees and bushes within a radius of 30 m (98 ft) from the buildings was the most important determining factor in the degree of damage or destruction of the buildings.

Post-fire investigations show mixed findings on the vulnerability of trees near buildings. Numerous examples of destroyed buildings surrounded by green trees show that nearby trees do not always increase the vulnerability of a structure (Candian Broadcasting Corporation, 2018). Nonflammable vegetation between the fire and the home can be beneficial to protecting the home from embers and radiant heat (Foote et al., 1991). Conversely, Manzello and Suzuki (2021) show that a noble fir tree can intensely ignite under ember exposure, demonstrating the species-to-species variability in risk.

Vegetation Beyond Zone 0: *It is clear that more methodical research is needed to investigate home vulnerabilities to nearby burning vegetation considering vegetation type and density, horizontal and vertical connectivity, and relative location to the home under windy and sloping conditions. Additional research would define terms such as "low flammability vegetation"(Anderson, 1970), "irrigated vegetation" (Valachovic et al., 2021), and "sparse out vegetation" (Valachovic et al., 2021) used in existing literature. While the vast majority of post-event investigations advocate for the removal of dense vegetation on a parcel, studies like Foote et al. (1991) demonstrate uncertainty and the need for further research. Until additional research is available, the consensus among research groups and practitioners follows the conceptual spacing of vegetative fuels to reduce fire spread. Trees and shrubs beyond Zone 0 should be spaced following a crown-to-crown distance and vertical clearance of 10 ft (Colorado State Forest Service, 2012)* .

Accessory Structures and Outbuildings

Fire spread between buildings can cause widespread damage within a community (Cohen, 1995; Himoto, 2022; Maranghides et al., 2021b; Rehm et al., 2002). The spread rate is influenced by slope, building size, distance between buildings, and wind direction and intensity (Cohen, 1995; Yuan et al., 2022). Because of the complexity of building-to-building fire spread, most efforts to understand this phenomenon are limited to reduced-scale tests (Cicione et al., 2019; Narayanan et al., 2022) or numerical and stochastic modeling (Cheng & Hadjisophocleous, 2009; Huang, 2020; Masoudvaziri et al., 2021). There have been a few experimental studies regarding fire spread between buildings; most of these studies have been based on radiation from flames jetting out through openings during an internal fire (Yuen et al., 2021).

During wildfires, on the other hand, the entire structure could be engulfed in flames, which leads to a drastically different fire behavior. Using some limited field observations, McGuire (1965) developed a theoretical model that calculates building separation based on the size of the buildings and the percent of openings on the building's exterior. McGuire's calculations are based on the ratio of the radiant heat intensity at the receiving surface to that at one or more radiating surfaces. His calculations suggest a 53-ft separation for a structure 10-ft by 25-ft with 100% opening (almost the entire building in flames). Himoto et al. (2018) studied three arrays of mock buildings with dimensions of 3.6-m by 3.6-m (11.8-ft by 11.8-ft). About 260 kg (573 lb) of wood cribs were loaded into the buildings. Buildings were separated by 0.5 m (1.6 ft) within the array, and the arrays were separated by 3.6 m (11.8 ft). Following the first fire, 15 out of 18 model houses were burned due to successive fire spreads that lasted about 50 min with a 1.6 m/s (3.5 mph) ambient wind. A study by Hasami (1997) examined the spread of fire from a heptane and propane burner to one three-story building (13.6-m by 9.1-m by 11.69-m, or 44.6-ft by 29.8-ft by 38.4-ft) and the spread of fire to two two-story buildings (roughly 4.5-m by 10-m by 7-m, or 14.7-ft by 33-ft by 22.9-ft). Approximately 3 m (9.8 ft) separated the burners from the main buildings, and 4.5 m (14.7 ft) separated the main building from the secondary buildings. The results of his tests are not available in English, but because of its relevance, the methodology is covered in this paper. Yuan et al. (2022) examined fire spread in wood buildings and observed that the fire spread from one wood building to three other wood buildings within 30 min of igniting the first. Configurations on both flat ground and an uphill slope show a reverse trend between building distance and thermal radiation.

Note that none of the experiments mentioned above incorporate the effects of wind on building-to-building fire spread. To fill this gap, IBHS committed to studying wind-driven building-to-building fire spread and the first phase of the project—fire spread from approximately 300-sq-ft outbuildings—is currently under investigation. Fire spread from outbuildings to a main structure is a common fire spread mechanism in the WUI, as shown in Figure 8. Preliminary results indicated that a burning shed 30 ft away from the main structure would result in repairable damage to the main structure. Figure 9 shows two of these experiments. This research will be published in 2023.

Accessory Structures and Outbuildings: *When accessory buildings ignite, usually due to spot fires spreading, short local flames transform into tall flames that radiate significant amounts of heat and/or touch nearby buildings. To limit these kinds of exposures, all accessory buildings like sheds and gazebos within 30 ft of the home should be built with the same mitigation measures as the home.*

a b

Figure 8. Example of a shed damaging the main structure on a parcel in the Glass Fire (2020) in Napa and Sonoma Counties, California. In photo (a), a shed was about 6 ft away from the main structure (suppressed by first responders and the homeowner). In photo (b), an attached outbuilding completely burned and damaged the main structure (suppressed by first responders).

a b

Figure 9. Photographs of a wind-driven building-to-building fire spread experiment at the IBHS Research Center showing (a) a burning woodshed positioned 30 ft from the main building and (b) a burning metal shed positioned 10 ft from the main building. In both cases, the open shed door is facing the main building.

a b

Figure 10. In the Glass Fire (2020) in Napa and Sonoma Counties, California, (a) a combustible fence provided a pathway for fire to spread uphill and damage both homes during fire, and (b) a wood fence spread fire and led to a cascade of damage (defended).

Fences Outside of Zone 0

Real-world WUI fires have shown that fences located beyond Zone 0 contribute to fire spread in communities (Insurance Institute for Business & Home Safety, 2020; Maranghides et al., 2013; Maranghides & McNamara, 2016), as can be seen in Figure 10. Australian researchers investigated the effectiveness of noncombustible and combustible fences in preventing bushfire spread. After ignition, the combustible fences ceased to act as barriers and contributed to the fire spread (Johnsson, 2018; Leonard et al., 2006).

In a recent study from NIST (Butler et al., 2022), the vulnerability of fences was examined. This research concluded that when combustible objects burn in close proximity, fire hazards are disproportionately higher. When a fire occurs, surface fuels—such as mulch and vegetative debris—burning close to the fence result in extreme fire behavior. In the NIST study, fires burned along mulch lining the base of a single fence row and parallel fences. An inferno consumed the fence pairs when positioned close together. The single fence row burned more quickly with mulch or debris present at the base than without mulch or debris. Compared with fences where mulch or debris was not located at their base, individual fence rows burned more slowly. According to the report, in a WUI environment, fences should not be built parallel to each other, even within 1 m (3 ft) of each other, as shown in Figure 11. Along with providing fire a conduit, this design introduces severe flame and radiation hazards to the neighborhood.

Debris accumulated between back-to-back fences is rarely removed. Highly susceptible surface fuel trapped in a conduit-like channel is hazardous as it creates ladder fuel. When ignited, fire can rapidly grow and "carry the fire along toward your house in a matter of a few minutes, not hours" (National Institute of Standards and Technology, 2022).

Figure 11. *Fire behavior between parallel fences (a) 0.6 ft apart, (b) 1 ft apart, (c) 1.5 ft apart, (d) 2 ft apart, and (e) 3 ft apart and longer fence (Butler et al., 2022), used with permission.*

Fences Outside of Zone 0: *The combination of trapped debris between back-to-back fences and the fence itself creates an extremely susceptible fuel bed for embers. This construction method should be avoided in the WUI.*

Eaves and Soffits

The under-eave area of buildings—whether vented or unvented—is vulnerable to fire. Eaves are constructed in two basic ways: open eaves and enclosed or soffited eaves. In open eaves, the roof rafters that extend beyond the exterior wall are visible. Open eave construction is typical in the western United

States. In enclosed or soffited eaves, the rafters are protected by a panel. The enclosing panel can be installed horizontally (extending from the roof edge back to the exterior wall) or parallel to the roof slope.

The overhang can protect walls from the rain and sun, but the overhang can also exacerbate wildfire exposure. The eave is susceptible to wind-blown embers and flames if nearby vegetation or combustible siding ignites. A 2008 FEMA guideline (Federal Emergency Management Agency, 2008) states that wider overhangs can be more vulnerable because wider overhangs trap more heat and embers. This is particularly true for buildings on sloping terrain with an open-eave design.

Experimental studies typically use open eaves as a "worst-case scenario," which is usually used to create guidance (Manzello et al., 2012b; Maranghides et al., 2022b). Syphard & Keeley (2019) concluded from a statistical analysis of structure loss in California between 2013 and 2018 that enclosed eaves had a highly significant protective effect compared to no eaves and open eaves as seen in the relative risk ratios. The existence of "temporary fuels" such as vehicles near the building also pose a direct flame contact and radiant heat threat to the eaves. Quarles et al. (2011) exposed soffited and open eaves to flame contact and radiant heat. Quarles et al. reported that open-eave designs that incorporate a fascia board are more vulnerable to direct flame contact exposures compared to soffited-eave designs. However, the open-eave design performed better against radiant heat exposure. It should be noted that most of the post-fire observations about eaves are anecdotal (Quarles et al., 2010) and more research on the vulnerability of eaves from surrounding fuels is needed.

Eaves and Soffits: *The geometry of eaves traps heat from flames and hot gases. While field evidence of ignitions is anecdotal, protecting the eaves with noncombustible soffits mitigates the ignition potential.*

Exterior Wall Covering/Cladding

Exterior walls are vulnerable to flames and radiant heat because of their geometry and area. Reentrant corners, an inside corner to the building, are particularly vulnerable. Ignition of siding can result in rapid fire growth (Green et al., 2022). When siding ignites, the heat can penetrate through the exterior surface to the underlying layers including sheathing and studs.

Investigating flame spread over combustible exterior walls, the Institute for Research in Construction of the National Research Council of Canada concluded that some combustible claddings support "unlimited vertical flame spread" (Oleszkiewicz, 1990). Maranghides and Johnsson (2008) reported that flames jetting out of a window ignited a mock wall assembly 6 ft away—the minimum home separation distance required by some building codes—in 80 sec; these tests were performed with no wind. Post-fire investigations report that fire can also grow on the surface, spreading laterally and specifically vertically, and expose other components on the wall such as windows and under-eave vents to flames, as demonstrated in Figure 12 (Insurance Institute for Business & Home Safety, 2020; Maranghides et al., 2015; Quarles et al., 2013).

Figure 12. *IBHS post-fire investigations show: (a) fire penetration through combustible cladding and vertical flame spread during the Glass Fire (2020) in Napa and Sonoma Counties, California, likely from a burning vehicle; (b) radiant heat damage from surrounding fires (located more than 50 ft away) damaged the vinyl siding, also during the Glass Fire (2020); (c) T1-11 siding ignited due to fire from surrounding vegetation, likely suppressed by first responders during the Camp Fire (2018) in Butte County, California; (d) fire penetration through combustible cladding during the Waldo Canyon Fire (2012) in El Paso County, Colorado (Maranghides et al., 2015); and (e) in the laboratory, the siding of the building ignited during IBHS's full-scale wind-driven building-to-building fire spread tests.*

Exterior Wall Covering/Cladding: *While a 6-in. vertical clearance protects a wall from embers, more action is needed to provide protection from flames. Their geometry makes walls suitable recipients of radiation and flame contact in WUI fires. The spread of flame through walls can be slow, but surface flame spread on combustible siding occurs quickly. This exposes windows and eaves to direct flame contact and can begin the cascade of damage for a home. Noncombustible cladding eliminates the chance of such flame exposures.*

Exterior Glass (Windows, Skylights, and Glass Within Doors)

Windows and other glazing create a discontinuity in the cladding of a building. The cavity and edge effects at the discontinuities cause some inevitable installation vulnerabilities(Jensen, 2013; Manzello & Suzuki, 2021; Šadauskienė et al., 2022). Hence, the entire opening (windowpane[s], window frames, and fasteners) are vulnerable to radiative and convective heating, as displayed in Figure 13. Studies show that a thermal insult results in a temperature gradient between different parts of the window assembly and can cause different types of failure (Cuzzillo & Pagni, 1998; Gao et al., 2013). Double-paned windows are mandatory in many parts of the western United States for energy efficiency purposes. These windows are typically annealed glass and can withstand about 25 kW/m^2 of thermal exposure (Quarles & Gorham, 2020). In comparison to single-paned systems, double-paned systems consistently perform better in terms of fire barrier performance (Shields et al., 2005). If the windowpanes are tempered, the resistance increases to about 40 kW/m^2 (Babrauskas, 2003), which is not an uncommon heat exposure in a wildfire.

Cohen (1995) exposed different types of windows to heat flux intensities of 9.3 kW/m^2 , 13.6 kW/m^2, and 17.7 kW/m^2. Cohen reported that annealed single-paned windows and the outer pane of annealed double-paned windows broke at all three heat fluxes. The inner pane of annealed double-paned survived at 9.3 kW/m^2. However, at higher heat fluxes, the second annealed pane of the double-paned windows also failed in 75% of the tests. Both single-paned and double-paned tempered windows survived.

Figure 13. *Vulnerability of windows: (a) glazing collapsed in Neos Voutzas-Mati, Greece (2018) due to the combustion of a pine tree (Peñaloza et al., 2021), used with permission; (b) windows damaged by radiation from a burning fence about 10 ft away during the Glass Fire (2020) in Napa and Sonoma Counties, California, where the arrow indicates the direction of radiation; (c) the outer tempered pane of a window fell out during an IBHS full-scale test; (d) window damage following the Grass Valley Fire (2006) in San Bernardino County, California, due to a burning building about 40 ft away, documented by Stephen L. Quarles.*

IBHS's recent findings show that the tempered outer pane of a double-paned window fails after about 10 min of exposure to the heat of a burning shed 30 ft away, and therefore it is necessary to have both panes tempered. The performance of a glazing unit depends on multiple factors including heat intensity, the air gap between the two panes, and breakage behavior of the first pane; these factors are not well understood (Wang et al., 2017).

Exterior Glass: *Windows are vulnerable to flame contact and radiation. Multipaned windows are more resilient by providing multiple layers of protection before flames can penetrate the home. Tempered glass further increases resilience because of its higher resistance to radiation.*

Exterior Doors

Like other parts of the building envelope, exterior doors can be exposed to flames, radiant heat, and embers. NIST's post-Waldo Canyon Fire (2012) investigation in El Paso County, Colorado, reports doors as a frequent damaged component of the building (Maranghides et al., 2015). Maintaining a proper defensible space around the building reduces the potential thermal insults from flames. However, embers can still accumulate at the base of a door and potentially penetrate through the door jamb. IBHS's post-Marshall Fire (2021) investigation in Boulder County, Colorado, showed limited damage to exterior doors due to ember accumulation at the base, as can be seen in Figure 14a. Figure 14b demonstrates ignition of the door jamb due to ember penetration of a home during research experiments at the IBHS Research Center.

a

b

c

Figure 14. *(a) Post-Marshall Fire (2021) investigation in Boulder County, Colorado, showing evidence of ignition from an accumulation of embers and debris at the base of the door; (b) Embers charred the threshold during the Victorian Bushfire (2009) in Australia (Leonard, 2009), used with permission; (c) Embers ignite the door jamb at the IBHS Research Center.*

This highlights the importance of the door assembly rather than the door itself. It should be mentioned that most of the evidence regarding external doors is anecdotal and more research in this area is needed.

Exterior Doors: *Flames are less likely to reach exterior doors if there is proper defensible space around the home. However, wind-blown embers may still accumulate at the base of a door or penetrate small openings around the door and ignite the door jamb. Similar to other components, the entire door assembly should be mitigated. Fire-rated doors are the most practical solution due to the lack of noncombustible door assemblies (door jamb) on the market.*

Bay Windows

Existence of combustible materials, either accumulated debris, plants, or other fuels, adds a vulnerability to bay windows. Similar to low-elevation decks, bay windows trap debris as well as heat and embers due to their geometry. The evidence around bay windows is anecdotal and limited to post-event investigations (Maranghides et al., 2015). In the wake of the Glass Fire (2020) in Napa and Sonoma Counties, California, IBHS investigated this vulnerability. As shown in Figure 15, the vegetation underneath the open bay window was mostly consumed, while the vegetation beyond it was less so.

Enclosed Space Underneath Bay Windows: *The geometry of bay windows traps heat underneath them. While field evidence of ignitions is anecdotal, enclosing this area with noncombustible materials eliminates the risk.*

Figure 15. *Heat trapped underneath bay windows caused the vegetation in this area to burn disproportionally to its surroundings during the Glass Fire (2020) in Napa and Sonoma Counties, California.*

Takeaways

Outdoor fire behavior, especially in the WUI where fuels are more diversified, is a highly complex phenomenon dominated by embers, which attack communities during wildfires. Depending on the condition of the recipient fuels that embers land on, the characteristics of the embers themselves, and environmental conditions, embers can burn out, start small flames, or grow to large flames. Embers, small flames, and large flames all pose different threats to homes. Large flames radiate enough energy to ignite combustible building materials without coming in contact with the building. However, small flames need to be in very close proximity or even touching the building component to ignite them.

Vulnerable homes in the path of wildfires may become fuel for the fire with devastating, long-term impacts on communities. Due to the variety of possible ignition scenarios, a single hardening strategy is not effective at reducing the chance homes ignite. A systematic approach is necessary to harden homes against embers and flames because the mitigations against each are different.

Embers threaten a home directly and indirectly. Embers can start small spot fires near homes, which often propagate and can indirectly ignite a home. To minimize the threat of direct ignition by embers, a properly maintained Class A roof is required. It is necessary for all vents to have a mechanism that minimizes ember entry into the building. The footprint of a home should have a 6-in. noncombustible vertical clearance to limit direct contact between rolling, burning debris and any combustible components of the exterior wall. To minimize the threat of indirect ember ignition, maintained defensible space is needed, with special attention given to the development and maintenance of Zone 0.

Tall flames radiate substantial heat, spread rapidly, and are more difficult to suppress. However, their spread can be predicted more easily. Several factors affect the radiant heat intensity emitted by flames including their height, width, thickness, and the distance between the flame and surrounding fuels. Tall flames require vertically oriented fuel so noncombustible or fire-resistant materials are best suited to limit the possibility of tall flames. Increasing the distance between the potential source and the potential target is another effective way to reduce the spread of fire.

To protect a home from flames, all main vertical surfaces of the home, namely siding, windows, and exterior doors should be held to the highest fire resistance standard. Back-to-back fence rows should be removed. The eaves and area beneath bay windows should be enclosed to minimize heat trapping in these areas. Deck assemblies should be noncombustible or have solid walking surfaces with no gaps.

A tiered system of home hardening developed using the current state of the science in wildfire mitigation includes a foundational systemic protection of a home against embers and an additional layer of systemic protection to guard against vulnerabilities to flame exposure. As IBHS and others continue research, new findings must be considered for updates to this functional 2-tiered systematic approach. While no home is fire-proof, systematically applying known mitigation strategies will reduce the chance a home is lost in a wildfire.

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