A Review of Pathways for Building Fire Spread in the Wildland-Urban Interface Part I: Exposure Conditions

Abstract

While the wildland-urban interface (WUI) is not a new concept, fires in WUI communities have rapidly expanded in frequency and severity over the past few decades. The number of structures lost per year has increased significantly, due in part to increased development in rural areas, fuel management policies, and climate change, all of which are projected to increase in the future. This two-part review presents an overview of research on the pathways for fire spread in the WUI. Recent involvement of the fire science community in WUI fire research has led to some great advances in knowledge; however, much work is left to be done. While the general pathways for fire spread in the WUI (radiative, flame, and ember exposure) are known, the exposure conditions generated by surrounding wildland fuels, nearby structures or other system-wide factors, and the subsequent response of WUI structures and communities are not well known or well understood. This first part of the review covers the current state of the WUI and existing knowledge on exposure conditions. Recommendations for future research and development are also presented for each part of the review.

1. Introduction

Even though the term "wildland-urban interface" generates the perception of a problem that is determined solely by geographic location, the WUI problem can also be envisioned as a *structure ignition problem* [1]. If structures are safeguarded against ignition sources, property loss and costs incurred (not to mention potential loss of life) can be avoided. Changing the area around a structure – specifically the surrounding fuel and topography – will affect the exposure conditions that have an impact on the structure. On the other hand, if the pathways to ignition are fundamentally prevented via hardening structures, communities, and surrounding wildland, then the WUI problem can be greatly reduced. A coupled approach of managing landscapes to reduce fire, ember, and radiation exposure conditions, while at the same time engineering structures to resist these exposures, has perhaps the best chance of success. The purpose of this review is to detail the known pathways by which fires can spread into and within a WUI community with the aim of preventing future WUI tragedies via informed decisions in codes, standards, future structure and component design, remodel/renovation of existing buildings, and community planning. Part I of the review focuses on understanding and quantification of exposure conditions, while Part II [2] focuses on the coupled response of components and systems to fire exposure conditions and the effect of mitigation strategies.

Three fundamental pathways have been identified for the spread of fire into and within WUI communities. First, radiant exposure may occur where large flames are close to exposed structural elements. The effect of radiation can often be minimized or eliminated through proper vegetation selection, location and management, and defensible space around structures (the home-ignition zone, HIZ); however, the influence of other nearby structures and their impact on radiant exposure must be taken into account (e.g. conflagrations where fires spread from home to home within a community) [3]. Second, direct flame contact exposure, which occurs when flames from smaller fires are in contact with adjacent structural elements, such as litter or wood piles. This exposure can be mitigated by creating a similar defensible space around structures that is entirely clear of combustible material. Third, fires may spread into and within a WUI community via the transport of firebrands (also called burning embers or brands[1]) generated either by the main fire front, nearby flammable material (e.g. vegetation), or nearby burning structures (e.g. conflagrations) [4]. Protection of structures must therefore incorporate all of these potential sources of ignition, as well as the cumulative effects of fires on nearby surrounding structures within the community. Indirect exposure, specifically exposure from firebrands, deserves particular attention due to recent data that indicates that at least 50% of ignitions, if not more, are due to firebrands [5].

While the underlying ethos of fire spread is known, quantitative knowledge of the effectiveness of specific approaches for risk mitigation and prevention within WUI communities is not well known. Spearheaded by the California fire season of 1985, a joint initiative by the National Fire Protection Association (NFPA) and the USDA Forest Service (USFS) highlighted the WUI problem and generated initial research into the problem [6, 7]. As a result, several research projects were begun to study the radiative exposure of building assemblies to large wildland fires. Over the past decade, the fire science community has come to further recognize the WUI problem specifically, and several organizations have devoted considerable resources to investigation of the additional processes of low-intensity flames and firebrands. While a significant body of work exists on the transport of firebrands [8, 9], quantitative ember exposure, ignition properties, and vulnerabilities of structures to embers has only recently been studied [10]. Different frameworks for wildfire risk assessments are available [11, 12], but the existing frameworks only allow qualitative predictions of radiative exposure. Significant assumptions are made when using many of these tools, such as ignoring firebrands and assuming that fires will only occur under ordinary fuel and weather conditions, when realistically it is only the most extreme fires (high winds and low humidity) that challenge current methods of fire control [3].

The National Institute of Standards and Technology (NIST), the USFS and the Insurance Institute for Business & Home Safety (IBHS) have devoted their resources to identifying clear vulnerabilities of WUI structures to low intensity fires and firebrands, including vulnerabilities in the roofing components, eaves, vents, wood piles, mulch, fences, decks, etc. [3, 4, 13, 14]. Many fundamental studies have also been conducted which aid in our understanding of ignition of fuel beds by firebrands [15–17]. The development of devices capable of simulating a shower of firebrands, such as the NIST Firebrand Generator, referred to as the NIST Dragon [10], as well as several detailed post-fire investigations [13, 18–21], have been particularly significant in developing an understanding of quantitative ember exposure and the effect of the arrangement of homes and layout of communities (land-use planning) [20, 22].

2. The Wildland-Urban Interface Problem

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

The definition of what community areas are WUI often encompasses a comparison of the housing density and location of surrounding wildland [23]. According to the Federal Register of the United States, the WUI "exists where humans and their development meet or intermix with wildland fuel" [24]. They go on to designate three types of communities in the WUI. First, an interface community occurs where structures directly abut wildland fuels. Second, an intermix community occurs where structures are scattered throughout a wildland area. Finally, an occluded community is defined as one that has an "island" of wildland fuels, in the form of a park or canyon, within a broader urban landscape. The WUI can be defined as encompassing all of the above communities, as the risks remain virtually the same. Many studies have worked to define this interface boundary and map it; however, this will not be a focus of this report and can be found elsewhere [25–27].

Fires in the WUI are not a new problem, but perhaps just a problem that has been more recently forgotten. During the same week as the Great Chicago Fire in 1871, the Peshtigo Fire killed between 1500 to 2500 people and burned around 0.6 million hectares, completely destroying twelve communities [28]. Comparing that to the Great Chicago Fire, which killed about 300 people and burned down only 855 hectares, shows the extent to which these events differed. Despite the tragic toll of the Peshtigo fire, it is rarely mentioned, while the anniversary of the Great Chicago Fire is still used as a catalyst for NFPA's Fire Prevention Week every year [29]. The Peshtigo Fire and subsequent wildland and WUI fires between 1896-1910 served as catalysts for the "fire exclusion" movement – a push for fire control and suppression of wildfires, largely led by the USFS [30].

Despite this long history of fire suppression of in the United States, the frequency and severity of wildland fires has continued to increase, especially recently. There has been an increase in WUI fires worldwide, particularly in Brazil, Australia, China, Russia, the United States, and the Mediterranean [31]. Large WUI conflagrations in the United States, such as the 1991 Oakland Hills Fire, the 2012 Waldo Canyon Fire, and the 2003, 2007 and 2014 San Diego Firestorms, have served as constant reminders of the threat large wildland fires pose in the WUI. An illustration of this problem is presented in Figure 1, which shows the number of structures lost per year to wildfire in the United States from 1999-2013 as well as the number of homes lost to Australian bushfires in the last 100 years [32]. In Russia in 2010, nearly 150 structures and settlements were damaged as a result of WUI fires [31]. Figure 2 shows the number of fires and acreage burned per year in the United States from 1985 to 2014. Despite stagnant or decreasing numbers of fires per year, there is a clear increase in the size of fires seen. Recent data shows that 3% of the wildland fires in the United States are now responsible for 97% of the area burned [33]. Following decades of intense wildfire suppression policies, large areas of unburned fuels have built up in the wildland and contribute to the growing size and intensity of wildland fires. Known as the fire paradox, wildfire suppression, which was meant to eliminate large and damaging wildfires, has in turn ensured the inevitable occurrence of these fires [34].

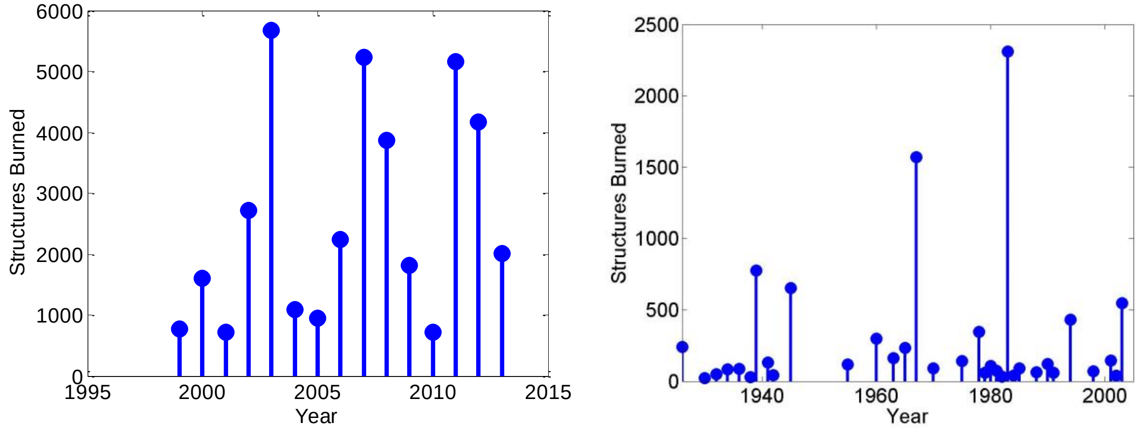

Fig. 1 Historical data on structures burned per year in wildfires in (left) the United States from [35] *and (right) structures burned in bushfires in Australia over the last 100 years from* [32]. *Note the scales and years presented are different due to data available in each country*

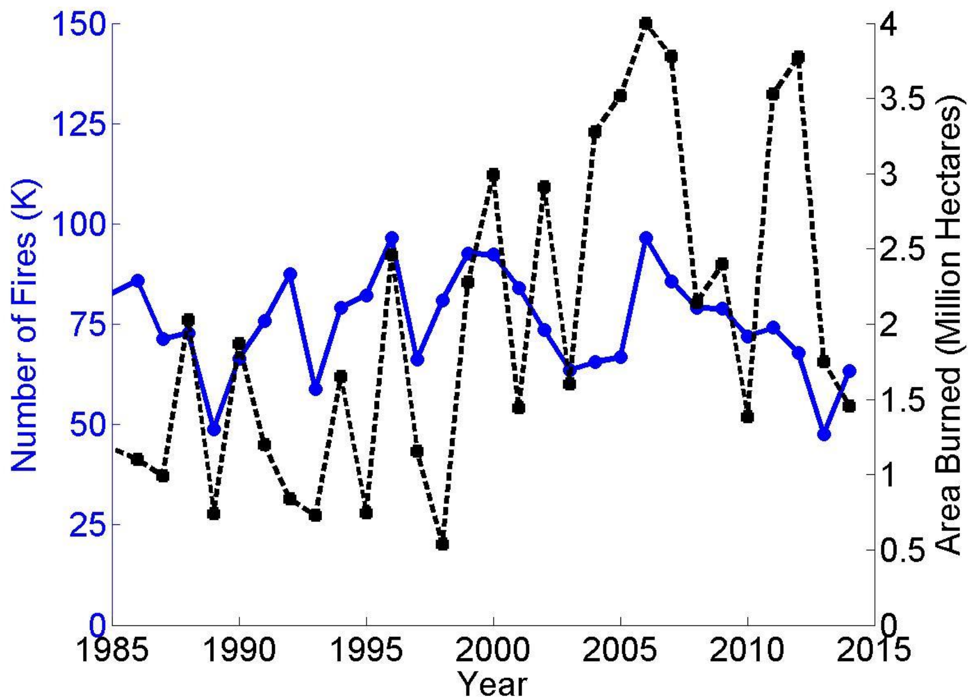

Fig. 2 *Annual number of fires (10^3) and area burned (million hectares) by year. Rising firefighter effectiveness and other factors steadily lowered the number of acres burned until the 1990s, when a slight rise was followed by a sharp increase in the 2000s due to fuel buildups and worsening fire weather conditions* [36]

According to some studies in the United States, around 30 million hectares of national forest land meet high priority for treatment of fuel buildup in WUI areas. Additionally, a mass movement from urban residences to rural communities has increased the size of the WUI. This transition has increased the number of at-risk homes significantly. In 2000, WUI development was estimated to cover 46.5 million hectares, an expansion of 50% from 1970 [37]. In the western United States, 50% of future housing development is estimated to occur in the WUI [38], highlighting a massive increase in future WUI lands. With only 14% of the interface developed, firefighting costs are now between $630 million and $1.2 billion per year. It is projected that if 50% of the interface were to be developed, the cost would range from $2.3 billion to $4.3 billion per year. These costs could make up nearly the entire annual budget of the USFS, which was $4.5 billion in 2008; as a result, improved land-use planning is critical [38]. Figure 3 shows the annual cost of firefighting to the federal government in the United States between 1985 and 2014, which increased from nearly half a billion dollars a year to more than two billion a year in the late 2010's. Note, this figure only accounts for federal fire suppression costs, which by some estimates are only 32% of wildfire protection funding on federal lands [39]. Several billion dollars are additionally spent on other wildfire related costs, such as preparedness, fuel reduction, and emergency funds.

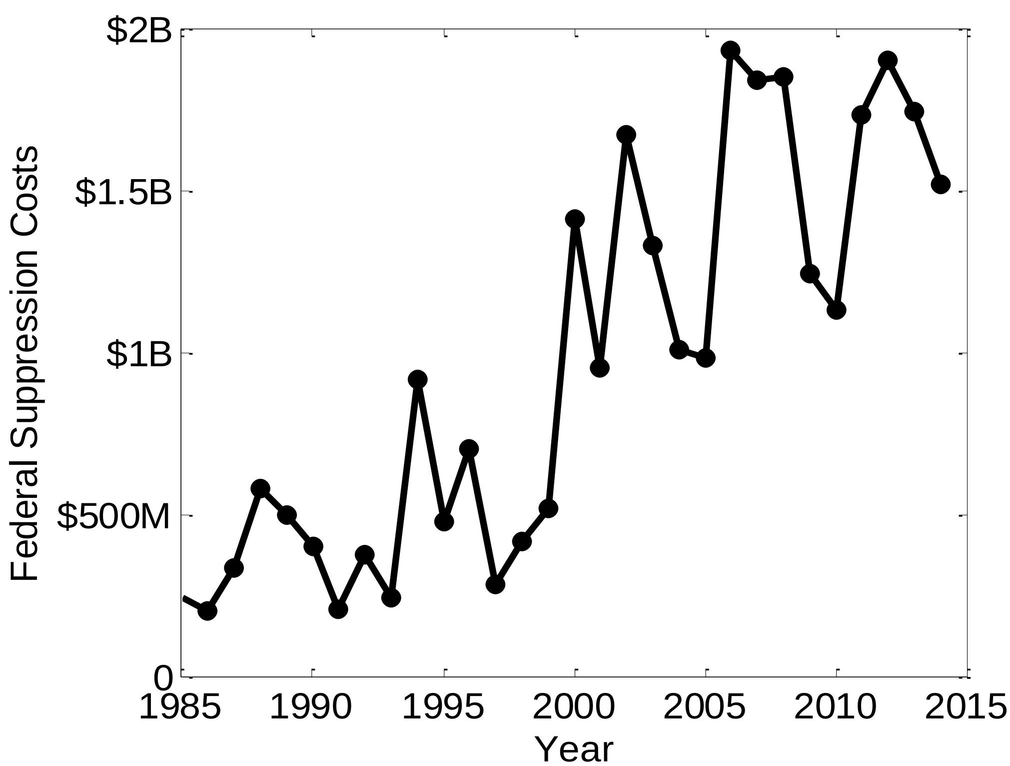

Fig. 3 *Federal suppression costs per year from 1985–2014. With increasing WUI development and areas burned by WUI fires, the federal suppression costs of the United States is predicted to continue to increase with the possibility of maxing out the entire annual budget of the USFS*

With the advent of more extreme fires becoming the norm, a different thought process than that used for traditional structural firefighting techniques and risk assessments. A WUI fire disaster depends on the exposure of vulnerable homes to uncontrollable, extreme fire behavior. If the number of burning and vulnerable homes overwhelms the local fire protection capability, fire protection effectiveness is reduced and many homes are left unprotected. A WUI fire disaster can be avoided, even during extreme wildfire conditions, if homes are ignition-resistant [23]. In a study of bushfire-related home losses in Australia, it was found that nearly all losses occurred during extreme fire danger conditions, namely low humidity and high winds [40]. In structural firefighting, the assumption for most occupancies is that the structural design of the building, passive fire protection systems, and automatic fire protection systems will provide sufficient protection for the occupants to escape and for the fire department to enter the building to provide full extinguishment. In large WUI fires, the fire department cannot be relied upon to provide full extinguishment because many buildings burn down due to firebrand ignition tens of hours after the main fire line has passed. Firebrands and other smoldering debris slowly transition to flaming from innocuous sources that are difficult to identify, while the main fire front threatens new homes and communities miles away. Firebrands can also be transported several kilometers ahead of the front depending on atmospheric conditions, resulting in a large area affected by either firebrands, spot fires, or the main fireline. No firefighting crew has sufficient resources to cover such a large area [41]. A different theory or approach to firefighting and structure protection must be envisioned to prevent future large-scale losses. Current strategies for exterior fire protection in the WUI (e.g. homeowner checklists, mesh coverings for vents) pale in comparison to those developed for use within buildings (e.g. fire sprinklers, smoke detectors, fire retardant materials). One strategy is to provide protection by limiting the pathways by which firebrands or other fire sources can penetrate a property or community, a method which Part II of this review will discuss [2].

There are many ways to reduce WUI ignitions beyond direct structure protection. Local laws addressing defensible space, ingress, egress, and water supply can create a safer environment for firefighters, resulting in more structures being saved [38]. Many of these issues are already covered in existing codes and standards; however, they could be improved with further knowledge including case studies and research [42–44]. Data needed for quantitative risk analysis, such as wildfire exposure conditions or the reaction of components to these conditions, is severely lacking [12].

As protection of property in the WUI has now become an increasing firefighting priority, firefighters are constantly endangered while striving to protect structures. In 2013, 97 firefighters died while on-duty. Of these, 28 of the deaths occurred at ten separate wildland fires. An average of four wildland firefighters have died annually in the United States at wildland fires or prescribed burns in the years 2002-2012. Most recently, the Yarnell Hill Fire in Arizona, USA killed nineteen members of a hotshot wildland firefighting crew, and huge media attention was focused toward the problem of safe WUI firefighting [45]. This event was the largest single loss of life for firefighters since the September 11, 2001 terrorist attacks on the World Trade Center in New York [10]. Community planning needs to include firefighter safety: access to safety zones, adequate egress, etc. [46].

Despite the discussion of fire statistics in the United States, significant fires have occurred worldwide in recent history. Some of these events include the 2009 Black Saturday Fires in Victoria, Australia, which resulted in the deaths of 173 people and the destruction of over 2000 homes [47]; several fires in the Mediterranean, including fires in Portugal, France, and Spain in 2003 [48], as well a string of fires in 2005, 2006, and 2007 [48]; a major WUI fire in the town of Valpariso, Chile, which killed 15 people and destroyed over 2900 homes [49].

While there still exists a large void in knowledge as to how future climate change might alter global wildland fire activity, most estimates suggest that severely altered fire regimes may increase fire activity in some regions, but reduce it in others [50]. Fire management policies may have to shift in the future as climate, rather than human intervention, plays a stronger role in driving fire trends than it has over the past two centuries [51]. In the western United States in particular, a significant increasing trend in the number and size of wildland fires has been found between 1984-2011, with fires increasing by a rate of seven fires per year and 35,500 hectares burned per year. These changes were most significant for southern or mountain ecoregions, where drought was a significant source of increased fire severity [52]. While climate change may be a significant driver in making the wildland fire problem worse in some regions, proper forest management practices, such as prescribed burning, may help to combat the problem by both reducing the intensity of eventual fires and limiting net carbon emissions. Wiedinmyer and Hurteau [53] estimated that 18-25% reductions in CO_2 emissions are possible in the western United States – with as much as 60% in specific ecosystems – by proper prescribed fire use and management practices.

3. Exposure Conditions

Fundamentally, ignition is the process by which a sustained combustion reaction is initiated [54]. In WUI fires, a solid element is typically heated until the solid fuel releases enough flammable vapors to ignite with or without a spark (piloted or auto-ignition), releasing sufficient heat to sustain the flow of flammable pyrolysis vapors from the solid. Often there are enough flaming sources in the vicinity of a large wildland fire to assume that piloted ignition will occur for worst-case hazard analyses. Exposure conditions are often studied to assess what thermal insult they can impart to building materials to cause them to ignite. Typically this thermal exposure is described in terms of a heat flux (rate of heat transfer, kW/m^2) and time to ignition, assuming sustained exposure to a certain heat flux [55]. Three primary categories, radiant exposure, direct flame contact, and firebrands, can be used to describe the types of fire exposure typically imparted to structures in the WUI.

3.1 Radiant Exposure

Exposure of structural elements to radiant heating is probably the most well-studied exposure condition in wildland fires. A significant body of literature is available on means of calculating radiant exposure from a fire [56, 57], and radiant ignition of a solid fuel has been understood theoretically [58] and practically [54, 55] for some time. Therefore, most early research on the WUI focused on radiant exposure to structures.

Radiant emissions from a fire to a structure or other fuel are easy to estimate; however, a precise calculation, even with advanced numerical tools, is difficult to achieve. In its simplest form, the heat flux per unit area from a gray-body fire separated from a target fuel can be expressed as

$$\dot{q}''_{rad} = F_{12}\epsilon\sigma\left(T_f^4 - T_0^4\right), \qquad (1)$$

where ϵ is the emissivity of the body, σ Stefan-Boltzmann's constant, T_f the flame temperature, T_0 the ambient temperature, and F_{12} the view factor between some assumed shape of the flame and the target fuel. Of course, in order to solve this equation some relatively drastic assumptions must be made, most notably an assumption for the shape of the flame and its emissivity. The fire protection literature has a lot of experience with these calculations [59, 60], with notable correlations tested under a wide range of conditions from pool fire sources. While they are not exact calculations, they have been at least moderately successful at predicting heat fluxes from crown fires [61]. Tables for view factors between differently-shaped objects can be found in the heat transfer literature [62].

Before the 1980's, there was little data to support quantitative findings on the amount of radiant exposure possible from an approaching wildland fire. Initial studies after this time utilized simplified models to determine the radiant exposure possible between an approaching wildland fire and a simulated wooden siding of a home [1, 11, 61, 63–65], in order to assess worst-case separation distances. These computational models over-estimated the radiant heat flux that would come from an approaching crown fire, which was assumed to be a worst-case scenario, to incident wood panels [65]. Laboratory experiments produced results that the model was able to predict [61]. These calculations estimated that approaching fires with very long flame lengths (e.g. crown fires) could ignite homes at most up to 40 m away. Beyond this distance, radiant ignition was deemed not possible, even from the most intense crown fire. More recent models of ignition of thermally-thick materials have also been performed, incorporating the movement of the flame front toward an exposed area over time [66].

Testing by Cohen et al., as part of the International Crown Fire Modeling Experiments [67, 68], exposed wooden wall segments to full-scale, active spreading crown fires with deep flame zones. The wall segments experienced both radiative and convective heating, as well as short-range ignitions from firebrands [11]. The derived flux-time correlation identified two primary ignition criteria for wood: a minimum critical heat flux of 13 kW/m^2 and a critical heating dosage level which accumulates over time [11]. Interestingly, actual crown fires only transferred heat sufficiently to ignite half of the wood panels at 10 m, where high radiant heat fluxes up to 150 kW/m^2 were observed. No panels at 20 m or beyond ever ignited and heat fluxes at these distances never reached above 20 kW/m^2, often a limiting heat flux for ignition of wood (though still enough to cause severe burns to human skin) [11, 69]. Although the experimental conditions were not those that are presented in extreme wildfires, due to differences in weather, fuels, and topography, these experimental fires were fully-involved crown fires with significant flame lengths and radiation. In essence, this experiment signaled that unless flames or firebrands ignite close to a structure, the structure is not likely to ignite [1].

As the fires tested by Cohen et al. were under a limited set of relatively mild conditions, continuing work is being done to instrument more wildland fires. Several studies, primarily conducted by the USFS in large wildland fires, both prescribed and uncontrolled, have used instrument packages to measure radiant heat fluxes, among other quantities [70–75]. They have measured peak irradiances beneath crown fires of 200–300 kW/m^2, 100 kW/m^2 for surface fires, and 132 kW/m^2 for shrub fuels. All of these studies have focused on wildland rather than WUI fires.

Recently, Kuznetsov et al. tested cylindrical pine wood samples under static and decreasing radiant heat flux. They found that surface temperatures of the wood samples reached critical values faster under variable heat flux, and thus ignited more quickly than under static conditions. Heat flux in wildland fires is often variable, not a constant value [76].

In order to determine radiative heat fluxes, flame lengths and fire intensity can first be determined using standard fire behavior modeling tools from the wildland fire community (e.g. Rothermel [77]). These tools can be used to determine radiant heat fluxes for different exposure conditions of fuel, topography, weather, humidity, etc. and different separation distances [65]. These calculations often give the farthest distance flammable vegetation should be located near the home. More information on material available to estimate clearing distance will be covered in section 3.2.1.

3.2 Direct Flame Contact

Very little work is available in the literature about direct flame contact specifically applied to the WUI; however, there is a broad base of traditional wildland fire literature, which describes flame lengths of vegetative fuels under various ambient conditions[2]. A study by Grishin et al. compared the effects of direct flame contact from a propagating grassland fire on fences and uniform wooden shields. They found that fences sustained less damage than uniform shields, when they were exposed to flames and heat fluxes up to 8.4 kW/m^2. They noted that the uniform wooden shields were exposed to the flames longer, because the gaps in the fence allowed flames to continue propagation across the grassland [31].

Porterie et al. have studied the thermal impact of a fire plume on a structure using a computational fluid dynamics (CFD) model, by modeling a concrete structure and a gas burner set to a heat release rate found from vegetative fuels. They studied the combined effect of radiation and convection over a 150 s time period and found that the combination (rather than just radiation) caused increased structure temperatures, as well as a plume that flattened against the structure in 5 m/s winds. Temperatures reached a maximum of 350 K in the concrete; however, the authors predicted that in a similar situation, temperatures would reach 460 K in wood, given the different thermal properties. Nonetheless, this temperature is below the auto-ignition temperature of wood, indicating that direct flame contact or firebrand impact is necessary to cause structural ignition [78].

Direct flame contact is not typically considered a direct source of ignition of a structure when brush and other wildland fuels are cleared away. It can be a secondary source of ignition from nearby burning material, including vegetation and non-vegetative combustible materials (mulch, wood pile, etc.). Heat fluxes by direct flame contact can be as high as 50-70 kW/m^2 for laminar flames [79] or 20-40 kW/m^2 [80] for turbulent flames, sufficient to ignite components of a structure [54]. As the size of a flame source increases, materials are exposed to similar heat fluxes over a larger area. This result was found for studies that showed that increased burner sizes did not result in increased heat fluxes [81]. While these heat fluxes are very high and can produce short ignition times, flames must directly contact building or structural materials long enough to cause ignition.

3.2.1 Fire Behavior

The steady rate of spread (ROS) of a wildland fire is a relevant parameter for WUI purposes, both because it signals the rate at which a fire will spread toward a community through wildland fuels, and also because the ROS can be related to the fireline intensity and flame length of the fire at the moment of arrival. The fireline intensity (kW/m), comparable to the heat release rate per unit length used in fire science, can be determined from the steady ROS via Byram's correlation. This quantity is derived by multiplying the ROS by the heat content of the fuel and the fuel load

[2]Some codes and standards, such as the California State Fire Marshal standards associated with the California Building code Chapter 7A, have a flame contact exposure component [194].

consumed in the flaming front [82]. Fireline intensity can then be related to the flame length via correlations by Byram for surface fuels [82] and Thomas for crown fuels [83]. Flame lengths can be useful in estimation of radiant heat fluxes from approaching fires [84]. It should be noted that it is difficult to interpret flame length values for deep fuel beds.

Pastor et al. provide a review of the development of fire spread models, including surface, crown and ground spread, as well as spread by spotting [85]. Morvan et al. also review of fire behavior models used and developed in Australia, Canada, and Europe. They also identify research needs, particularly concerning conducting experimental fires under a greater range of conditions, and creating a link between empirical and physical models [86]. Both reviews highlight different equations and correlations that can be used, in addition to Byram's, mentioned above.

Several numerical modeling tools are available to calculate the relevant fire behavior parameters. BehavePlus can calculate one dimensional fire properties such as ROS, fireline intensity, and flame length [87]. FlamMap is available to spatially calculate these values over a geolocated map [88]. FARSITE can then calculate these parameters temporally to provide predictions of fire spread [89, 90]. All of these tools are available through the USFS[3].

Other modeling tools are available in other countries. In Canada, most models use the Canadian Forest Fire Danger Rating System (CFFDRS) and its Fire Behavior Prediction System (CFBPS) [86, 91], which is based on significant fundamental work by Van Wagner [92]. In Australia, models are based on McArthur for grasslands [93, 94] and eucalypt forests [95] in their fire rating danger system (FDRS). These models mainly consist of purely empirical correlations of observed fire behavior at field scale, with data augmented by well-documented wildfires. Cheney and Sullivan more recently replaced the MacArthur grassland FDRS as the preferred tool for grassland fires [96]. Sullivan has presented an extensive review of available models for wildland fire spread worldwide, including physical and quasi-physical models [97], empirical and quasi-empirical models [98], and numerical simulation tools [86, 99].

Despite a wide availability of literature on the fire behavior of traditional vegetation under a range of conditions, these models are almost all semi- or fully-empirical approximations of observed phenomena fitted to specific fire conditions. Without a firm physical basis of fundamental heat transfer and combustion processes that drive spread, these models may break down under untested conditions, in particular under extreme fire conditions [100]. For safety reasons, these extreme conditions cannot be tested during large experiments, such as prescribed burns, despite the fact that extreme fires (high winds, high fuel loads, and low moisture contents) are responsible for the majority of devastating wildland and WUI fires.

Additionally, risk mapping can be used in conjunction with models to determine high risk areas and communities that can be affected severely by wildland fires. In the report on the Fire Paradox project, Lampin-Maillet et al. outline a risk mapping method that combines vegetation and housing density, to come up with a risk map used for mitigation work [48]. Further risk mitigation methods are discussed in Part II of this paper [2].

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[3] http://www.firelab.org/.

While the rate at which a fire spreads is generally determined from correlations, a special effect in steep terrain with canyon walls, sometimes called eruptive fire behavior, has also been documented in the literature [101]. This effect, similar to the trench effect found in urban fires (particularly the 1987 King's Cross fire in London), can extend flame lengths significantly, cause flames to attach to the surface, and increase rates of flame spread up to six times or more [102–104]. While several models are available to describe this effect [101], these models are designed for firefighter safety, rather than WUI design. Nonetheless, community designers should keep this effect in mind when designing placement of structures or escapes, as large inclined canyons with significant fuel loads could cause enhanced flame lengths and rates of spread that are not properly accounted for in other models.

Models seem to be unable to predict thresholds of fire spread, such as the initiation, acceleration, or cessation of fire spread [105], which becomes significant when modeling potential effects of firebreaks. Syphard et al. has indicated it would be useful to have a fire model which accurately determines effectiveness or size of needed fuel break, but such models are unavailable [106, 107]. Finney et al. have highlighted these and many other problems with current models [100] and recently presented new theories on how fire spreads to resolve some of these discrepancies [108, 109]; however, until the results of this and other work are finished, current models should be used with the understanding that their results are limited, but provide the best estimates of fire behavior available today. It is important to remember that these models have been developed for steadily-spreading wildland fires, not for fires spreading through WUI communities. In WUI communities, there are various structures that contribute to the fuel load and modify winds that may affect spread parameters [110], although investigation by NIST has indicated that rates of spread in the WUI are lower than in surrounding vegetative fuels [20].

3.3 Firebrands

Firebrands are thought to be one of the primary sources of ignition in the wildland-urban interface. During wind-driven or very intense fires, so many firebrands are produced and transported that they are often called firebrand "showers", "storms," or "blizzards," and they can ignite spot fires far downstream of the main fire front. Firebrands present hazards in the WUI because they can either directly ignite components of vulnerable structures or can ignite nearby vegetation and other combustibles, which can subsequently ignite the structure via radiant heating or direct flame contact [111]. There does not appear to be a consensus on the percentage of ignitions caused by embers, primarily because it is difficult to determine after-the-fact what caused each individual home or structure to burn down during a fire. In the Grass Valley fire, 193 of 199 homes destroyed were thought to have ignited due to indirect contact, i.e. firebrand attack, as the areas around homes were untouched [19]. In more detailed investigations, such as the Witch Creek and Guejito fires, firebrands were found to be a major threat to homes, estimated to be responsible for as high as two thirds of losses [12]. Ignition from firebrands depends on the conditions of the fire. This paper will review existing knowledge on the generation, transport, and physical mechanisms of transition to flaming, while Part II of the review will cover specific vulnerabilities of structures to firebrand ignition [2].

Detailed knowledge of firebrand production, transport, and ignition may be able to assist future prevention efforts. Modeling ignition of structures, perhaps statistically, may be a possible application of further knowledge of firebrands. To use firebrand data in ignition models, statistical information on firebrands generated from both vegetation and ignited structures, potential transport distances for the brands, and the probability they will ignite structures, vegetation or other nearby flammable material must be assembled. For now, worst-case scenarios must become the focus of all risk modeling efforts, as the most extreme fires are the ones causing WUI disasters. Using worst-case scenarios for modeling WUI fires will require information about firebrands under high winds and high fire intensities. Characterizing this worst-case firebrand flux, how far embers can travel, and their likelihood of igniting different materials is needed as a first step to inform these risk modeling efforts. Reviews by Babrauskas [81], Koo [41] and Manzello [10] should be referenced for further information beyond relevant details provided here.

3.3.1 Firebrand Production

Numerous studies have now been conducted focusing on the generation of firebrands from vegetation, full structures, structural components, and a few actual WUI and wildland fires. These studies tend to focus on the size, distribution, and flux of firebrands generated by the fire by collecting them at various locations downstream. This information may someday be useful in modeling fire spread in the WUI, particularly because fire models often make assumptions about the size and shape of firebrands. These assumptions are used to predict transport of firebrands, but may not represent what actually occurs [41, 112].

A summary of studies on firebrand production is provided in Table 1. This table shows that existing firebrand production studies have been conducted on a number of wildland and structural fuels under limited fuel moisture content (MC), relative humidity (RH), and environmental conditions. For example, the studies in Table 1 did not consider the combined effect of radiation and wind (a realistic condition for fuels during a wildland fire) on ember production and related characteristics, but have started to bridge the gap and provide knowledge of processes occurring in a repeatable and documented way.

Table 1 *Summary of fire ember production experiments*

Author	Fuel	Test Conditions
Tarifa et al. [8]	Wood (pine, oak, spruce, aspen, and balsa), charcoal, natural pine cones and pine brackets	Indoor; wind 0-40 m/s, MC 2%-25%, individual firebrand study
Vodvarka [113, 114]	Wood-frame structures (3 wood siding, 1 asphalt siding, and 1 brick veneer)	Outdoor; wind 0.4-3.1 m/s, temp. 23-31°C, RH 50-70%
Waterman [115]	Roofing (wood, asphalt, and cement-asbestos singles; roll and build-up roofing; and no covering)	Indoor; in a test chamber (internal pressure from an aircraft engine)
Muraszew et al. (1975-1976)	Wood (birch, white pine, and ponderosa pine), and natural fuels (bark plates, pine cones, limb wood)	Indoor; wind 0-11 m/s, temp. 29-32°C RH 10-55%
Clements [116]	Broadleaf tree leaves, pine needles and cones, moss, bark and fronds	Outdoor; with a vertical wind tunnel
Ellis [117]	Eucalypt bark in Australia	Indoor; wind 0 to 20 m/s, MC 7%-13%
Woycheese [9, 118, 119]	Balsa, light balsa, Western red cedar, Douglas fir, red oak, redwood, and walnut	Indoor; wind 0-7.2 m/s
Yoshioka et al. [120]	Wood crib and wooden house (with outer wall siding and slate roofing)	In a large wind tunnel, 2.0-4.0 m/s

Manzello et al. [121, 122]	Douglas fir, Korean pine	Indoor; wind 0-7.2 m/s, MC 10-50% for fir and 10-80% for pine, ember generator
Suzuki et al. [123–125]	Residential building components (wall and corner assemblies) and a full-scale structure	Indoor; wind 0-9.8 m/s, MC about 10%
Rissel and Ridenour [126]	Bastrop Complex Fire in Texas consisting of loblolly pine and understory plus, potentially, structure-generated firebrands	Actual WUI fire measured by burned areas on trampolines
Foote and Manzello [127]	Angora fire in California with white fir and Jeffrey pine with a heavy understory surface fuel loading	Actual WUI fire measured by burned areas on trampolines

For vegetative fuels, controlled laboratory tests were performed by Manzello et al. [122] to collect firebrands off of 2.6 to 5.2 m tall Douglas fir trees at NIST. This work presented a framework for the collection and description of firebrands, ultimately classifying them by mass distributions after collection in water pans. The majority of these collected firebrands were found to have a mass less than 0.3 g, with the distribution of larger brands falling off steeply, as shown in Figure 4. The average firebrand size for the 2.6 m Douglas fir tree was 3 mm in diameter and 40 mm in length. The average size for the 5.2 m tree was 4 mm in diameter, with a length of 53 mm. Firebrands with masses up to 3.5 to 3.7 g were observed for the 5.2 m tall tree. The trees did not produce firebrands without wind if the moisture content was greater than 30%. All firebrands were cylindrical in shape, and the surface area appeared to be directly related to the mass of the brands [122].

Later experiments performed by Manzello et al. [121] at the Building Research Institute (BRI) in Japan investigated Korean pine under varying wind and moisture conditions. Trees were all 4 m tall, and the moisture content was varied between 10 to 100% on a dry-mass basis. Collected firebrands were cylindrical in shape, similar to experiments on Douglas fir [122]. The average firebrand size was 5 mm in diameter and 40 mm in length. The mass distributions collected are shown side by side in Figure 4.

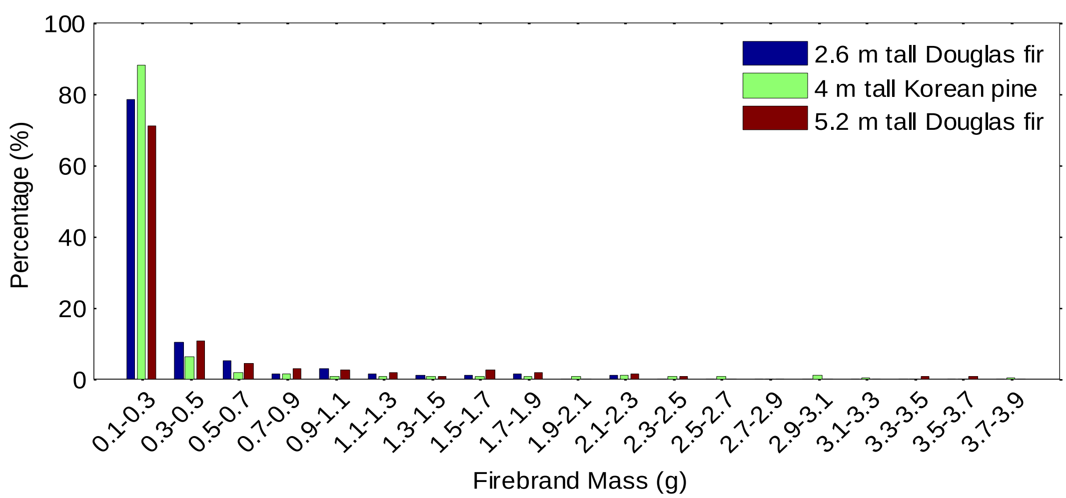

Fig. 4 *The mass distribution of collected firebrands from 2.6 m tall Douglas fir, 4 m tall Korean pine trees, and 5.2 m Douglas fir trees from Manzello et al.* [121, 122]

The distributions of firebrands from structures and vegetation have been presented in terms of both mass and projected surface area [125]. It is useful to determine a relationship between these two quantities because it is easier to measure either mass or size, not both. In a controlled study by Zhou et al. on square firebrands generated in the NIST Dragon [128], firebrand mass and projected area (as would be seen in a photograph of brands on a surface) were somewhat linearly related. Tohidi et al. [129] presented scaling analyses between firebrand mass and actual surface area, finding that the surface area should be related in power-law form to the mass to the 2/3 power, somewhat different than the linear result from Zhou et al. [128]. The difference may occur because Tohidi et al. [129] focused exclusively on cylindrical brands taken from experiments on pine trees [121, 122], while the controlled NIST Dragon study used wood cubes [128]. As firebrands in real studies may be cylindrical, spherical, or wafer shaped, there may be different relationships based on shape.

Experiments have been performed on burning structures to measure the mass and size distribution of firebrands found downwind. Waterman was among the first to study firebrand generation from structures by burning wood shingle roof constructions on complete homes [115]. Brands were collected via a screen trap and quenching pools under conditions that varied the wind and heights of buildings. As expected, wood shingle roofs were found to be much more effective in producing firebrands than were asphalt shingle roofs, which have a layer of plywood under the shingles. The firebrands collected were mostly disc-shaped [130].

The earliest documented studies of full structures burning were by Vodvarka, who measured firebrand size and transport distances from five full-scale wood-framed house fires [113, 114]. Small firebrands dominated the distribution with 89% of the firebrands smaller than 0.23 cm^2. In two of the building fires, a majority of the firebrands were deposited at a single location downstream, with one sheet used to measure the firebrand distribution receiving over 97% of all deposited brands. The number of brands produced was correlated with the time that the fire started to vent through the roof – earlier venting correlated to more brand production. Most brands found were thought to be from roof components including shingles and tar paper or from portions of burnt wood decking [81].

Yoshioka et al. used a crib fire to ignite a wooden house and collected firebrands from both the crib fire and the house fire at the BRI Fire Research Wind Tunnel Facility (FRWTF). They collected brans in both wet and dry pans at the outlet of the wind tunnel [120]. A later test was performed by Suzuki et al. [125] on a controlled burn of a structure in California. During the test, a significant amount of water was intermittently applied to the structure via several hose streams in order to prevent spread to adjacent structures. They found that the majority of firebrands were produced from the structure during burning, not during the application of water to the structure. The impact of water application on the fire is not known, but it could both increase the number of firebrands due to the momentum of the hose stream impacting the structure, while at the same time reducing the buoyancy of the plume, which would lead to smaller firebrands being lofted. In this test, 95% of the firebrands were collected about 18 m from the structure, and 96% of those collected 4 m from the structure had less than a 10 cm^2 projected area. The results from Suzuki et al. [125] are compared to previous studies by Vodvarka [113, 114] in Figure 5. Future testing on similar structures with and without water application should be performed to characterize the influence of water application on firebrand generation and potentially inform recommendations for WUI firefighting practices.

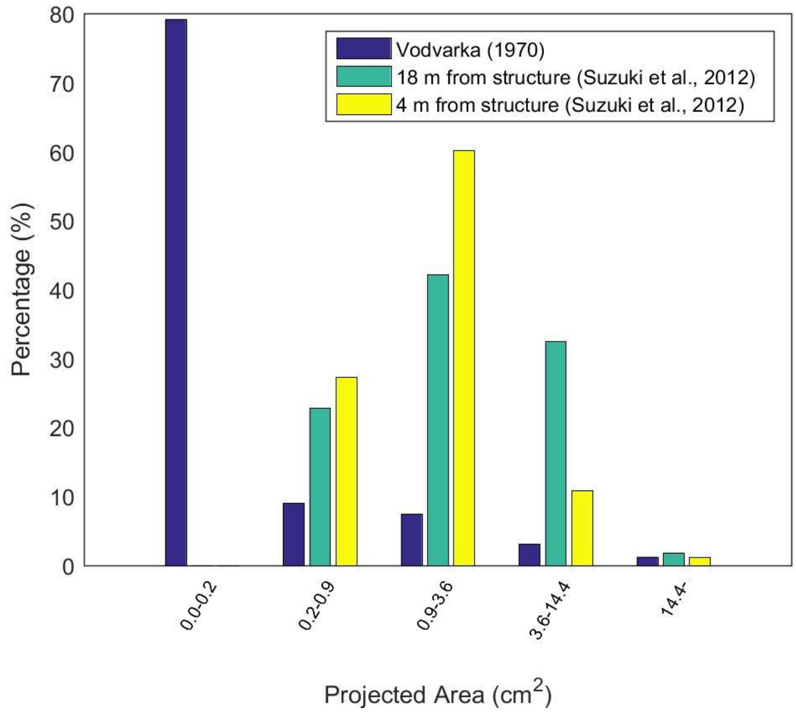

Fig. 5 *A comparison of the projected area distribution of firebrands from structures burning by Vodvarka* [114] *and two collection distances from Suzuki et al.* [125]

In a more recent study, Suzuki et al. burned full-scale structures at the BRI FRWTF with a 6 m/s wind [124]. More than 90% of collected firebrands weighed less than 1 g and 56% weighed less than 0.1 g. The mass distribution was similar to previous studies; however, different firebrand collection strategies (namely wet and dry pans) were shown to induce some small differences between this study and previous studies. This is most likely because a dry pan does not extinguish collected brands, which continue to burn and decrease in area, while the wet pan extinguishes brands on contact.

Suzuki et al. also investigated the combustion of individual structural components to see whether these results were similar to those from full-scale structural burns, perhaps enabling some simplification in the tests necessary to characterize firebrand production [123]. Both individual walls and re-entrant corner assemblies were ignited and firebrands collected in water pans downstream. The results are shown in Figure 6 and compared to other studies of full-scale structure burns [120, 124, 125]. The size distribution is very similar to the range measured from full-scale structure burns. Therefore, valuable information might be garnered from these smaller experiments, though a methodology to do so has yet to be fully established.

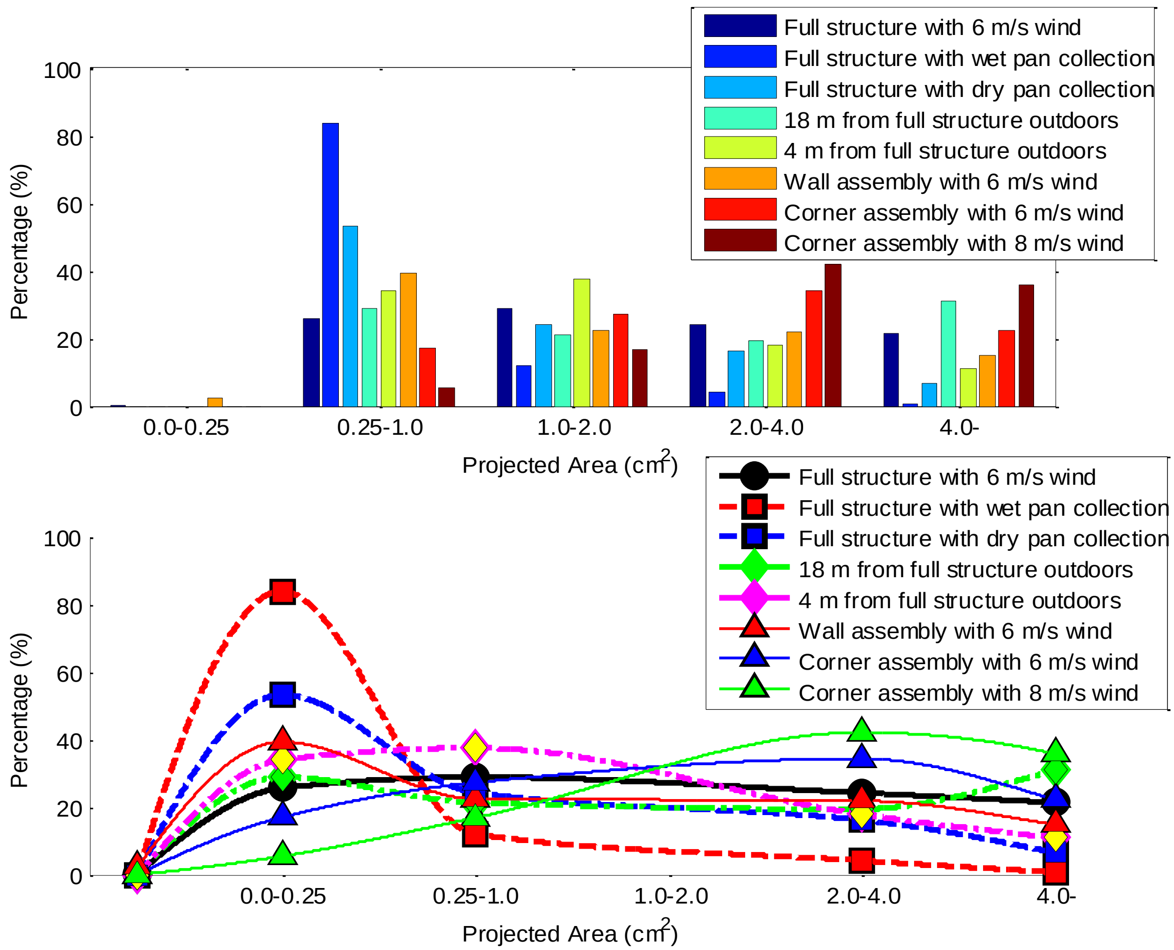

Fig. 6 *Firebrand size distributions from a full structure in a 6 m/s wind by Suzuki et al.* [124], *a full structure by Yoshioka et al. with wet and dry pans capturing brands* [120], *18 m and 4 m from a full-scale structure by Suzuki et al.* [125]

Foote and Manzello examined the size distribution of firebrands during the Angora Fire, a severe WUI fire in California in 2007 [127, 131]. This is the first known collection of firebrand distributions from an actual WUI fire. Fuel mostly consisted of white fir and Jeffrey pine with a heavy understory surface fuel loading [132]. Some fuel breaks were present in nearby collection locations. In the fire, a trampoline, which is a piece of gymnastic equipment that is made of a strong canvas and attached to a frame by springs, was exposed to wind-driven firebrands. It experienced melted "burn holes" from firebrands and served as a representative source for observation of firebrand size and density over an area throughout the passage of the fire (see Figure 7). The trampoline had an area of 1.5 m^2; 1800 burn holes in the trampoline were analyzed by digital photographs. The largest hole in the trampoline had a 10.3 cm^2 burned area, while more than 95% were from firebrands with an area of less than 1.0 cm^2. In addition to the trampoline data, burn patterns were observed on building materials and plastic outdoor furniture at 212 individual locations on or near numerous buildings exposed to the Angora Fire. The largest firebrand indicator was 2.02 cm^2, although a large majority were less than 0.40 cm^2. This study demonstrates how relatively simple methods can be used to extract valuable information from real WUI fires.

A similar approach of studying firebrand production by analysis of trampoline burn patterns was completed by Rissel and Ridenour following the Bastrop Complex Fire in Texas [126]. The fuel consisted of Loblolly pine overstory and yaupon holly understory. The fire burned more than 13,000 hectares and destroyed 1696 structures over approximately 48 hours. These structures were located within the WUI; areas with burned structures included several subdivisions, unmanaged private lands, and 96% of Bastrop State Park. Firebrands were collected from seven locations under a variety of conditions: vegetation and structures up to 30 m from the trampolines, low to high fire intensity, both open and dense canopy cover, and exposure from both heading and flanking fires. Burns under 0.002 cm^2 in the trampolines were indistinguishable and not measured during analysis. 90% of measured holes were less than 0.5 cm^2 in size. Firebrand holes (shown in Figure 7) show a similar size distribution to those measured during the Angora fire.

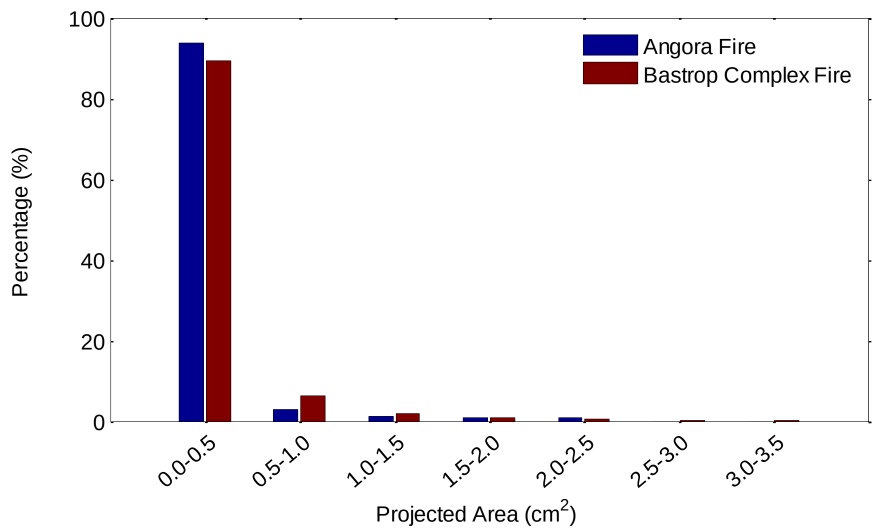

Fig. 7 *Distributions of the area burned measured from holes in a trampoline following the Angora fire* [127, 131] *and Bastrop Complex Fire* [126]

The NIST Dragon has been instrumental in testing many building components, as it is able to continuously produce repeatable size and mass distributions of wind-driven firebrand showers, consistent with previous studies reviewed above [121, 122, 127]. The majority of firebrands produced in the apparatus are less than 0.5 cm^2, similar to results from real WUI fires [121, 122, 127]. The NIST Dragon has been used in Japan at the BRI FRWTF, where experiments can be performed with wind speeds up to 10 m/s in a wind tunnel with a cross sectional area of 4 m by 5 m and a test section length of 15 m [10]. Versions of this apparatus have been produced at IBHS, Underwriters Laboratories (UL) in the United States, and at the Association for the Development of Industrial Aerodynamic (ADAI) in Portugal.

Recent work by Zhou et al. [128] used 12.7 mm cubic wooden particles to create firebrands, and shot them out of the NIST Dragon to characterize the effect of wind on mass and size distributions downstream from a stable point source generating a firebrand shower. They found that the probability distribution function, *f(x)* closely followed a normal or Gaussian distribution,

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (2)$$

where x is the horizontal distance downstream from the outlet of the firebrand generator, μ is the center of the distribution, and σ is the standard deviation of the distribution (i.e. σ^2 is the variance). The distribution was found to fit the number and mass distributions of firebrands deposited downstream from no wind, 6 m/s, and 9 m/s cases, shown in Table 2 for both number and mass distributions. As can be seen from the results, the distribution of firebrands shifts downstream as the wind velocity increases. With increasing wind, additional drag forces will transport particles farther downstream. These results may provide a framework for future studies and help create inputs for computer models needing firebrand generation information.

Table 2 *Firebrand number and mass distributions fitted to a Gaussian curve from Zhou et al.* [128]

Wind Speed (m/s)	**Center of Distribution, μ (m/s)**	**Standard Deviation, σ**
Number Distribution, $f(x)$		
0	1.4	0.61
6	2.69	1.61
9	4.21	2.52
Mass Distribution, $f(x)$		
0	1.35	0.61
6	2.20	1.36
9	3.49	2.30

One recent firebrand collection study conducted in the New Jersey Pine Barrens (USA) aimed to produce a protocol for characterizing firebrand generation in terms of particle mass, size, and origin in the field [133]. These properties were then related to fire intensity. Fuels were classified before the fire into traditional 1, 10, and 100-hour fuels; however, 1-hour fuels were further separated into < 2 mm, 2.01–4 mm, and 4.01–6.35 mm diameter fuels, as it was later found that not all 1-hour fuels combusted. Pine bark and several small shrubs were carefully sampled during tests to see which sizes detached and became firebrands. Firebrands were collected downstream in metal trays filled with water. Some trays were covered with a thin plastic film, while others were left with exposed water. The plastic covering allowed flaming and smoldering brands to pass through, much like the trampoline studies by Foote et al. [127] and Rissel and Ridenour [126]. Smaller brands were observed to “bounce” off the thin plastic film when observed with an IR camera.

After collecting and cataloging data, it was found that branches smaller than 2 mm were consumed, but branches between 2.01–4 mm were only partially consumed, and branches between 4.01–6.35 mm were not consumed at all. These results contradict the assumption that all 1-hour fuels burn completely. This differentiation may result because the original 1-hour class of fuels covered up to 2-hour fuels [82]. Pine bark was observed to detach from trees up to one minute after the fire front had passed, indicating that the fire-induced draft is important for bark-originated firebrand production and transport. 70-89% of brands collected were bark slices, while the rest were brands from cylindrical branches. About 30% of the brands had a mass between 0.010–0.020 g, and very few had a mass greater than 0.10 g. It was interesting to note that collection without the thin plastic film was comparatively weighted toward lower masses (0.005-0.020 g), likely because the plastic film may have expelled low mass brands, whether burning or not.

In Richburg, South Carolina, the IBHS Research Center uses a larger-scale, modified version of the NIST Dragon apparatus. Mulch burning equipment creates firebrands similar to the NIST Dragon, but the facility has the capability of conducting tests at wind speeds greater than 10 m/s [134]. The combination of the large scale, higher winds, and the ability to rotate a building during testing makes the facility unique in its ability to represent the characteristics of natural winds and firebrands occurring during wildfire conditions. The firebrand generating equipment developed for the IBHS Research Center and NIST Dragon has been used in several tests which will be presented for specific building components in Part II of this review [2].

Very few studies have approached the physical generatation of firebrands within a fire. Two recent studies have proposed some potential mechanisms. A study by Tohidi et al. investigated whether firebrand generation experiments in the laboratory (particularly those by Manzello et al. on coniferous trees [121, 122]) would represent full-scale WUI fires [129]. In their scaling analysis, Tohidi et al. propose that firebrands may detach and transport beyond the fire front by two means: their own weight or drag. Vertical drag can be generated by the fire plume and horizontal drag can be generated by wind. These mechanisms were characterized in a firebrand breakoff model defining the critical shear stress for breakage as:

$$\sigma_{max} = \sqrt{\left(\frac{8\rho_{air}C_D U_h^2 \eta^2}{\pi}\right)^2 + \left(\frac{8\rho_{air}C_D U_v^2 \eta^2}{\pi} - 4\rho_{wood} g L \eta\right)^2}, \qquad (3)$$

where U_v and U_h are the vertical and horizontal components of the air velocity, respectively, ρ_{air} the density of the air, C_D the induced drag coefficient on the particle, $\eta = L/D$ the aspect ratio of the cylindrical brand, and g the acceleration due to gravity [129]. This formula presents a simplistic, intuitive framework to which additional analyses can be added.

In a study by Koo et al. [41], larger trees are noted to produce larger firebrands; however, this result has not been corroborated by further investigation by Tohidi et al. [129] of past coniferous tree firebrand experiments [121, 122]. Tohidi et al. characterized the size of each firebrand in terms of two length scales: the cube root of the volume and the square root of the surface area, neither of which correlated with tree height. The lack of correlation with tree height suggested that the size distribution of firebrands may be more dependent on the mechanisms of breakoff and that tree height may only provide an increased, buoyant vertical velocity.

Barr and Ezekoye have also investigated breakage and lofting of firebrands and have developed dimensionless parameters to describe the breakage and lofting of brands via a thermal plume [135]. They described the structure of wildland fuels using a fractal model coupled with simple combustion models to produce brand breakage and lofting inputs to future numerical models. They also charred wood and performed three-point bending tests which showed a somewhat linear correlation between flexural strength and density; however, the temperatures used to heat the wood indicate that only charring occurred, whereas smoldering would occur in real fire exposures. Both Barr and Ezekoye [135] and Tohidi et al. [129] couple their models with Monte Carlo simulations that could someday populate inputs to brand transport models.

3.3.2 Firebrand Transport

A large body of work is available in the literature on firebrand transport. It is well known that brands can be transported over a large distance and ignite new spot fires or structures in WUI communities. In order to model the transport of firebrands, many features must be taken into account, including the size and aerodynamic qualities of the brand, winds in both the thermal plume and wind field, and the burning characteristics of the brand which may change its aerodynamic qualities over time.

Several reports of firebrand ignition of homes and communities have been documented over the past several decades. A 1960 Japanese study found spot fires ignited in cities 700 m from the main fire front, indicating that a firebrand was transported to ignite the new spot fire [81]. In modeling the Great Hakodate Fire of 1934, rapid spread rates were attributed to the transport of firebrands, which were later roughly correlated to wind speed [81]. More recently, a NIST report on a community outside San Diego, California affected by the 2007 Witch Creek and Guejito Fires found that firebrands arrived one hour before the flame front, traveling up to 9 km [20]. These firebrands subsequently ignited properties over the following nine hours. The range in which brands may transport to ignite spot fires varies widely depending on the type of fuel. High intensity Australian eucalyptus fires, whose bark sheds and is extremely aerodynamic, have ignited spot fires 19-24 km away on average and up to 30 km in extreme cases [136, 137]. California chaparral has been documented to ignite fires up to 6.5 km away, and mixed conifers can produce brands which ignite new fires up to 21 km away [81, 138].

While firebrands were recognized as a possible source of spreading fires for some time, Clements was among the first to study the aerodynamics of particles as they related to potential brand transport [116]. He studied terminal velocities for components of different vegetation species, as there seemed to be an obvious correlation between the geometry of particles and their lofting characteristics. Muraszew then took the next step of investigating combustion of brands by looking at the time it would take for vegetation, wood cylinders, and cedar shingles to burn [139]. He found that the flaming time, t_{fl}, could be correlated with the volume-to-surface-area ratio (*V/S*) in mm,

$$t_{fl} = 25(V/S)^{5/4}. \tag{4}$$

Muraszew later worked toward developing a more complete model of firebrand transport [140–142], but this model has not been presented.

Tarifa et al. were among the first to fundamentally study burning brands of woody fuels, examining their burning properties, flight paths, and lifetimes through an vertical wind-tunnel apparatus [8]. They studied cylindrical and spherical samples of pine, oak, aspen, spruce, and balsa wood, with initial spherical diameters ranging from 10 to 50 mm and initial cylindrical dimensions ranging from 6 to 15 mm and 18 to 36 mm in diameter and length, respectively. Wind was varied from 0 to 40 m/s, and it was found that brands did not drastically change their shape during burning, nor did moisture content of the brand exert much influence on the brand flight path [8].

A variety of models for firebrand transport were later developed based on Albini's 1979 model for the maximum distance a spot fire could ignite from a single burning tree [143], multiple burning trees, [144], crown fires [145], or wind-driven surface fires [146]. Variables included were: the quantity and surface-area-to-volume ratio of foliage in the burning tree(s), height of the tree(s), the wind field that transports the firebrands, and the firebrand burning rate. No validation data is available; nonetheless, later work [144, 147, 148] has incorporated Albini's model into multiple numerical simulations, including firebrands from a crown fire in FARSITE [89] and adaptions in HIGRAD/FIRETEC [112]. Individual calculations using simplified versions of Albini's can be run on BehavePlus [87, 147, 148].

Pagni and Woycheese [119] significantly expanded on Tarifa's work [8] to develop several models of brand propagation, lofting, and burning. Information was found through a series of tests and by utilizing brand momentum conservation with spherical wooden brands lofted above a symmetric pool fire in a constant horizontal wind. Variations to these conditions were not considered. They found that the dimensionless regression rate of brands depended inversely on both the dimensionless burning parameter and the dimensionless diameter. It was also found that the diameter decreased faster in larger brands than in smaller diameter brands. Finally, drag and gravity dominated the acceleration during lofting for sufficiently large brands [9].

Pagni reviewed eight combustion models for burning brands, including an averaged stagnation-point burning model using the wood's chemical properties [130]. The Baum and McCaffrey model [149] was used for the plume and a constant horizontal velocity driving downwind propagation was approximated. Pagni and Woycheese subsequently applied their own combustion model to determine the maximum propagation distance for disk-shaped brands, which they found to be most common in their studies. Their combustion model identified two stages of combustion of brands: flaming combustion and glowing combustion. Denser wood samples (oak and Douglas fir) produced flaming combustion for a longer duration than other fuels, but were less likely to transition to glowing surface combustion. Complete combustion of any brand rarely occurred without significant, persistent surface combustion on the upwind face of the brand. Wood with a lower density, such as cedar and balsa wood, more readily transitioned from flaming to surface glowing combustion, with flaming combustion ending relatively early in the brand's lifetime. They also noted the effect of the wood grain orientation: an end grain faced the end velocity vector [119].

When Pagni and Woycheese applied their combustion model to determine propagation distance for differently shaped brands, they determined that the maximum propagation distance occurred for disk-shaped brands. Analytic equations for brand thickness and propagation height lofted from large, single fire plumes were determined as a function of time for different heat release rates, wind speeds, and brand properties [9]. Using their model, they found that brands released from greater heights will typically be smaller in size and completely combust in air, whereas brands released from lower elevations will typically be larger, but will result in shorter propagation distances [118].

Other models, such as those by Wang, have integrated previous models and observations for brand production, lofting, and ignition into a statistical form that can be used when modeling [150]. Baum and Atreya recently developed a new model for firebrand combustion used to determine the duration of burning and the ultimate transport distance during lofting. They considered several different shapes and determined an analytical solution for quasi-steady burning [151]. Ellis studied the characteristics of a 'stringybark' type eucalypt, messmate, which can cause spot fires approximately 3 km from a fireline and is considered responsible for driving fire spread in the Black Saturday fires in Australia. He found that these bark firebrands may reflame during flight, or when removed from an airflow, potentially increasing the likelihood of ignition on landing [152].

Numerical studies on the distribution of cylindrical firebrands from burning line fires [153] and disc-shaped brands from burning trees [154] have also been performed. These models focus on the combustion model of firebrands, including both pyrolysis and char oxidation, tracking the brands after they have been released at different locations from a potential fire. A dual distribution of embers was found in both cases, with larger embers falling in a state of flaming combustion near the fire front, followed by a distribution of smaller embers landing further away in a glowing state of combustion. For firebrands generated by line fires, the normalized mass of firebrands landing in a flaming state correlated with the flight time, normalized by $\rho_{w0}\tau_{f0}$ in a flaming state, and $\rho_{w0}D_{f0}^{5/3}\tau_{f0}^{-1/6}$ in a charring state, where ρ_{w0} is the initial density of the brand, τ_{f0} the initial thickness, and D_{f0} the initial diameter. The parameter $\rho_{w0}\tau_{f0}$, along with the char content of the brands, worked well to distinguish which brands would land in one region versus another [154]. The parameter $\rho_f^{w0}\tau$, where ρ_f^{w0} is the initial firebrand density and τ the brand thickness, determined whether disc-shaped brands emanating from burning trees fell in a flaming or glowing state. For brands that remained longer in the thermal plume, the distance covered upon landing was independent of particle diameter and correlated with $I^{0.1}U_{wind}^{0.9}\left(\rho_f^{w0}\tau\right)^{-0.2}$, where I is fire intensity. The distance a firebrand travels from a burning tree therefore varies almost linearly with increasing wind speed, but varies weakly with increasing fire intensity, being independent of fire diameter or position within the canopy upon release [153].

Table 3 *Summary of firebrand lofting and transport experiments and models adapted from Koo et al.* [41]

Authors	Experiment	Firebrand model	Plume and wind model
Tarifa et al. [8]	Burning firebrands in wind tunnel	Sphere and cylinder with combustion	Inclined convective plume [155], given launching height in constant horizontal wind
Lee and Hellman [156, 157]	Particles in vertical plume generator [157]	Spheres with combustion [156]	Turbulent swirling natural convective plume [157]
Muraszew and Fedele [136, 139, 140, 142]	Burning firebrands in wind tunnel and fire whirl in vertical channel [139]	Statistical model [141]	Fire whirl [142]
Fernandez-Pello et al. [158–160]	-	Sphere with combustion [158] Disc, cylinder, and sphere [160]	Given launching height [159], McCaffrey plume [149, 160] in constant boundary layer wind
Albini [144–146, 161]	-	Cylinder with combustion [136]	Launching height from flame structure analysis in constant horizontal wind
Woycheese and Pagni [9, 41, 118, 119]	Burning firebrands in wind tunnel	Non-dimensional model with combustion [162]	Baum and McCaffrey plume model [149]
Himoto and Tanaka [163]	-	Disc without combustion	Given launching height in turbulent boundary layer
Porterie et al. [153]	-	Small world network model, Disc with combustion	Steady state crown fire [78].
Koo et al. [41, 112]	-	Disc and cylinder with combustion	HIGRAD/FIRETEC wildfire model [164, 165]
Sardoy et al. [154]	-	Disc with combustion	Buoyant line plumes in stratified crossflows
Wang [150]	-	Sphere with combustion	Baum and McCaffrey plume model [149] with Rayleigh form pattern [166]
Baum and Atreya [151]	-	Prolate and oblate ellipsoids with combustion	Potential flow model
Zhou et al. [128]	Cubic firebrands released from NIST Dragon. Gaussian distributions fitted	-	-

3.3.3 Firebrand Ignition of Fuel

One of the most complex and stochastic processes to understand in WUI fire spread is the ignition of recipient or "target" fuels by firebrands. Despite many years of study on the topic [167], it is not yet possible to formulate the ignition potential of fuels *a priori* based on both firebrand and target fuel properties. Nonetheless, a framework for studying this phenomena has appeared in the literature and takes into account the known sensitivity of ignition time to firebrand size/mass and target fuel properties, such as density and moisture content.

Many variables contribute to the process of target fuel ignition after a firebrand lands, including the physical dimensions of the firebrand, properties of the material, and ambient weather conditions [81, 130]. Depending on these variables, an ignited recipient fuel may start glowing combustion and then die out, just smolder, or transition from smoldering to flaming and grow into a larger fire. Understanding the effects of each of the above variables on the ignition process is important in order to develop a physical model for firebrand ignition; however, we do not yet have a predictive framework capable of repeatedly describing this ignition process, even statistically. The known processes which have been suggested to contribute to ignition will be described below, following a review of systematic experiments.

Early experiments were performed by Dowling in Australia to determine the cause of ignition of wooden bridge members due to firebrand impact [168]. Burned wooden cribs were used to generate 7–35 g of multiple firebrands and test their ability to ignite large pieces of lumber with a 10 mm gap. He found that 7 g of firebrands were sufficient to produce smoldering ignition of the wood within the 10 mm gap. It was not mentioned whether the brands were smoldering or flaming upon deposition.

Manzello et al. studied ignition of shredded mulch beds by up to four glowing cylindrical or disc-shaped firebrands [16, 169, 170]. Disc-shaped firebrands could ignite the mulch beds with only half the mass needed for cylindrical brands to ignite identical mulch beds. This result suggests that contact between the brands and mulch beds (conductive heat transfer) is a critical process. Manzello et al. also highlighted the increased ease of ignition with increasing numbers of firebrands, further motivating the need to study accumulation of brands, rather than just individual particles.

Manzello et al. also performed experiments on common building materials to determine the range of conditions under which glowing firebrands might ignite these materials. Materials tested included oriented strand board (OSB) and plywood, which were oriented in a V-shaped pattern at varying angles to determine how angle, wind speed, and number of firebrands would influence the material's contact with glowing firebrands and its subsequent ignition [171]. It was found that single firebrands were unable to ignite the materials used, even after applying various airflows. Multiple firebrands were able to ignite some materials. It was concluded that the critical angle of interest for ignition was between 60° and 135° for any tested airflow. No ignitions were found below 1.3 m/s for any conditions, signaling that the combined effect of angle and sufficient incident wind are necessary for ignition.

Ellis considered ignition of fuel beds, namely pine needles, due to eucalyptus firebrand impact [117]. Single firebrands that were 5, 15, and 50 mm in diameter (0.7–1.8 g) were deposited in both flaming and smoldering states onto pine needles of varying moisture contents. Flaming brands ignited all pine needles when the moisture content was less than 9%, while glowing brands only ignited the fuel bed when the ambient airflow was increased. More recently, Ellis studied ignition of eucalypt litter fuel beds by flaming and glowing firebrands. He found that ignition probability increased with wind and decreased with fuel MC, but that there was little difference between 1 m/s and 2 m/s winds. He also found that glowing firebrands were sensitive to environmental changes, and further studies need to be conducted to determine how fuel bed characteristics interact with glowing firebrands to change ignition probability [172].

Santamaria et al. looked at the impact of firebrand accumulation on ignition of structural wood in an inclined, V-shaped configuration [173]. Ember loading ranged from 0.2 to 98 g/m^2 with embers having a surface area smaller than 100 mm^2. They performed testing using an electric heater in order to separate the thermal impact on the wood from the smoldering caused by embers. It was found that similar heating rates were reached between the electric heater and embers, but neither ignited the wood samples. Some observation of flaming ignition resulted when a hole broke on the bottom of the apparatus, signaling additional buoyant airflow, known to influence the transition to flaming process.

In a joint effort to study types of firebrands in the Mediterranean, Ganteaume et al. ignited eight types of fuel, including leaves, twigs, bark, and pine cones. They measured the time that it took the material to ignite, flaming duration, and mass loss. They found that evergreen oak leaves had the shortest ignition time, while pine bark had the longest ignition time. Pine cones had the longest flaming duration. They found that brands lost between 70-90% of their initial mass throughout the heating combustion tests [174].

Because most firebrands cease flaming combustion before landing on recipient fuels [8, 16, 169], they often land in a state of smoldering combustion. Therefore, modeling ignition must incorporate a hot object landing with some initial thermal inertia onto a bed of flammable material. Figure 8 depicts some major heat transfer features of this process. In order to ignite a target fuel (e.g. a wooden deck) or a fuel bed (e.g. forest litter), a brand or collection of brands must together be large enough to transfer the heat necessary to initiate smoldering combustion. This heat must be transferred before the brand(s) deplete their supply of flammable material through oxidative reactions, while smoldering, and additional pyrolysis during transition to flaming (mass-loss rate represented by $\dot{m}''$ in Figure 8) [175]. As firebrands are often smoldering upon landing, they continue to generate heat through chemical reactions while resting on the recipient fuel surface, so potential heating comes from (1) the temperature and heat capacity of the brand upon landing, (2) potential heat due to additional exothermic reactions in the brand, and, (3) in the case of smoldering transition to flaming, potential heat due to exothermic reactions in ignited target fuels.

The calculation of heating needs to include the rate of heating and the rate of heat loss. Glowing firebrands will release heat via both convection, $\dot{q}''_{conv}$, and radiation, $\dot{q}''_{rad}$. The effect of convection gives rise to some interesting phenomena. While rates of smoldering and heat release will increase with increasing external winds (to some limit), the winds will also increase the rate of convective heat losses. Heating to the fuel bed will inevitably depend on the contact between the firebrand(s) and the fuel bed, $\dot{q}''_{indepth}$, with the result that looser beds of vegetative fuels will have poor contact, despite otherwise exhibiting more favorable combustion characteristics once ignited. Less dense fuels, as well as dense fuels with significant spacing, such as decking, will have reduced potential for conductive heating due to lower density and poor contact; however, less attenuation will allow for more radiative heating within the fuel bed. Additional supplies of oxygen due to spacing will also aid the heating process, increasing the possibility of transition from smoldering to flaming.

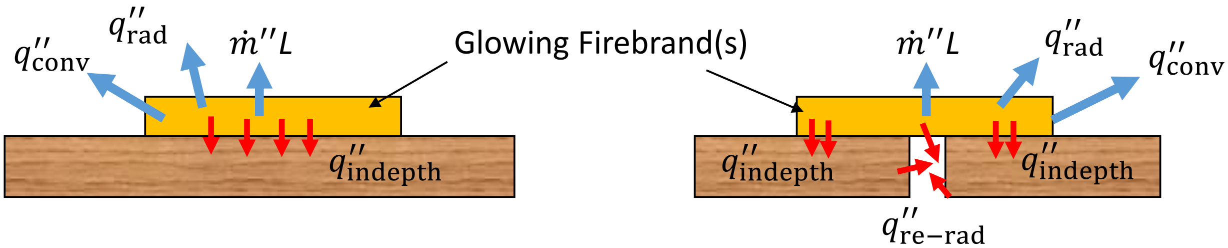

Fig. 8 *Heat and mass transfer processes that cool both the firebrand and target fuel as well as heating processes that provide re-radiation and/or in depth conduction leading toward ignition*

In determining the processes contributing to heating and ignition of recipient fuels, knowledge of temperatures on the surface of deposited firebrands can provide some insight. Recent experiments at the University of North Carolina at Charlotte used a high definition IR camera and a macro lens to examine the surface temperature profiles of glowing firebrands. The firebrands were generated from a mini firebrand generator using 12.5 mm diameter, 57 mm long white birch dowels. Figure 9 shows the surface temperatures of one end of a glowing firebrand. As the spectral emissivity of the charring solid is unknown, an emissivity of 1.0 was used, following previous work by Urbas et al. [176], where IR temperature measurements were validated with a thermocouple. Temperatures in the high temperature region were 800-850°C, in agreement with surface measurements in a cone calorimeter by Urbas et al. [176], but somewhat higher than firebrands subjected to a 1.3 and 2.4 m/s wind by Manzello et al. [171]. If the emissivity is chosen to be 0.7, which is closer to that used by Manzello et al. [171], surface temperatures are 900-946°C, which is higher than Urbas et al. [176] found. More work needs to be done on the mechanisms of heating and cooling on firebrands, including the effect of wind, which has a competing effect of increased surface cooling and surface oxidation.

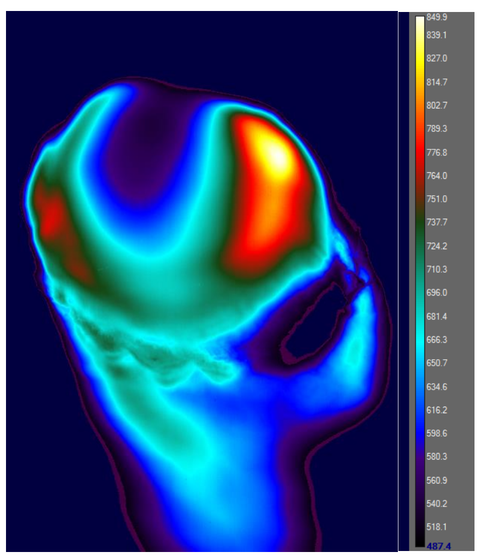

Fig. 9 *Surface temperature profiles of a glowing firebrand using an IR camera*

It has been suggested that the summation of energy stored in a brand (including stored heat and chemical energy) is a possible means of correlating and/or modeling the phenomena of ignition [177]. Recent work with heated particles [178], though, has found a poor correlation between particle thermal energy and time to ignition. A possible approach to modeling the problem is that of an inert or reactive "hot spot" ignition theory, such as that proposed by Gol'dshleger et al. [179, 180]. This theory neglects the energy of the fuel particle, but includes a 1-step Arrhenius reaction of the recipient fuel. This approach may be useful because it can take into account the different sizes of heated particles. Work by Hadden et al. [178] used this theory to determine a critical hot spot radius (i.e. minimum particle radius for ignition, r_{cr}),

$$r_{cr} = \delta_{cr}\sqrt{\frac{k}{\rho A \Delta H}\frac{RT_{p0}^2}{E}\exp\left(\frac{E}{RT_{p0}}\right)}, \tag{5}$$

where δ_{cr} is the Frank-Kamanetskii hot spot parameter, k the thermal conductivity, ρ the density, A the area, ΔH the heat of combustion, R the gas constant, T_{p0} the initial particle temperature, and E the activation energy. δ_{cr} must be solved numerically, but Gol'dshleger et al. [179] provide a simplified expression,

$$\delta_{cr} = 0.4\sqrt{b^2 + 0.25n(n+1)(b + 0.1b^3)}(2.25(n-1) - \theta_0)^2(1 - 0.5\beta\theta_0), \tag{6}$$

where $b = \rho c/\rho_p c_p$, $\beta = RT_{p0}/E$, $\theta_0 = (E/RT_{p0}^2)(T - T_{p0})$, and n is a coordinate system factor (n = 0 for Cartesian, 1 for cylindrical, and 2 for spherical coordinates). The subscript p denotes particle parameters, while other parameters are properties of the fuel bed.

Qualitative agreement between this approach and ignition of a cellulose-powder fuel bed by hot particles has been achieved [178], illustrating the connection between spherical particle diameters and ignition, not thermal energy. The ignition process in experiments, when observed with schlieren, actually shows two types of ignition both in the gas phase: a piloted-type process occurring for the larger and hotter particles and a spontaneous type of ignition for smaller particles. These results are somewhat different than the assumptions made in the theory. For glowing brands on solid fuels, rather than in cellulose beds, the effect of heat losses may be even more significant, due to the lack of immersion between brands and recipient fuel. A recent review of firebrand ignition studies by Fernandez-Pello et al. [15] highlighted the fact that ignition by large, hot metal particles may in fact be dominated by cooling from the particle, since the size of the particle correlates so well with the ignition time. The correlation with only particle size does not well model an actual firebrand and adds complications in achieving an adequate theory. While many studies have focused on individual or multiple discrete brands landing on a fuel bed [16, 169], fundamental studies with piles of small brands landing in crevices or stagnation zones have not been found. This is an important configuration as it is often found over wooden or composite decks [181].

The theory has multiple limitations because it does not take into account ongoing reactions in firebrands, the moisture content of fuels, lack of good conductive contact between fuels and firebrands, radiative feedback, or external radiation. Additionally, the theory is still quantitatively different from experimental observations. Continued improvement of theories is ongoing, and includes ideas such as adding different thermal properties of materials into Gol'dshleger's original theory [167] or using the self-heating theory [81]. Work may apply beyond firebrands, as other hot particles such as sparks from power lines or rifle bullets have also been shown to ignite wildfires [15, 182].

Yin et al. made some initial steps in formulating a thermal-based theory by proposing a correlation between the ignition time of a loose vegetative fuel bed and bed properties, using a heat balance analysis,

$$\sqrt{t_{ig}} \sim \frac{q\sqrt{(\rho_f k)/c_p}}{(\rho Z \Delta H_c)/t_b - h_T(T_f - T_0)}, \tag{7}$$

where t_{ig} is the ignition time after brand deposition, q is the heat required for ignition of moist fuel on a dry-mass basis, ρ_f the initial density of the firebrand, k, ρ, and c_p the thermal conductivity, density and specific heat of dry pine needles in the bed, respectively, Z the height of the brand, ΔH_c the heat of combustion of the brand in a glowing phase of combustion, h_T the heat loss coefficient, T_f the firebrand temperature, and T_0 the initial temperature of the target fuel bed [17]. As can be seen from the correlation, $\sqrt{t_{ig}}$ is correlated linearly with both the heat required for ignition of the fuel bed, q, and, the moisture content of the fuel, assuming the fuel is dead and evaporation is solely due to increase in temperature. The correlation between $\sqrt{t_{ig}}$ and moisture content appears to stay linear for the Chinese pine fuels tested by the authors, as well as lodgepole pine tested by Jolly et al.; however; the correlation constants for the fuels differ, and they were not compared quantitatively with the correlation [183, 184].

Viegas et al. has also studied firebrand ignition of fuel beds of varying vegetative materials under different moisture contents with no wind [185]. The results of this study showed that fuel bed properties were more influential in the ignition process than brand characteristics. The likelihood of ignition increased with the addition of airflow over the fuel bed, confirming results from previous studies. Wang et al. performed recent experiments with hot metal particles igniting expanded polystyrene foam and found that foam density and thickness had little effect on ignition. Their theoretical analysis proposed that the hot particles acted as both heating and pilot sources, with ignition controlled by a competition between the gas mixing time and particle residence time [186].

Table 4 *Summary of existing studies on ignition of fuel beds*

Authors	Target Fuel	Conditions	Results
Waterman and Tanaka [115]	Urban fuels	External winds, steady and oscillating	Ignition probability increased with winds >2.7 m/s. Oscillating winds decreased the probability of ignition
Dowling [168]	Timber bridges	Brands from burned wood cribs deposited onto 10 mm crevice	7 g of firebrands were able to produce smoldering ignition of the wood
Manzello et al. [16, 169]	Pine needles, shredded paper and cedar shingles	Glowing and flaming firebrands	Single flaming firebrands ignite fuel beds. Multiple glowing brands required to ignite most beds. MC and wind play a critical role
Manzello et al. [171]	OSB and plywood	V-shaped angle, wind speed and number of firebrands varied	Ignition sensitive to mass of firebrands, external wind and angle of crevice
Hadden et al. [178]	Cellulose powder fuel beds	Hot metal particles dropped onto fuel bed	Found a hyperbolic relationship between particle temperature and size
Manzello et al. [187]	Cedar crevices	6 m/s ambient wind	Transition from smoldering to flaming ignition was observed in all loading rates at or above 23.1 g/min, and ignition times decreased for larger loading rates
Viegas et al. [185]	Mediterranean vegetative fuel beds	11 pairs of burning embers	Ignition depended more on fuel bed than ember characteristics, especially MC
Yin et al. [17]	Pine needle beds with different MC	MC between 25-65% of fuel bed, 3 m/s wind, square glowing firebrands	Relationship between ignition time and MC of fuel bed established
Manzello and Suzuki [181]	Western red cedar, Douglas fir and redwood decks	Firebrand mass flux of 17.1 g/m^2s	20% of ejected brands accumulate on decks. Sensitive to density of wood baseboard
Zak et al. [188]	Cellulose powder fuel beds	Hot metal particles dropped onto fuel bed	Expanded results for several different metals
Wang et al. [186]	Expanded PS foam	Hot metal particles	Hot particles act as both heating and pilot sources, with ignition times occurring due to competition between gas mixing and particle residence times
Santamaria et al. [173]	Wood crevices	V-shaped wood crevice with stagnant conditions. Bark brands and charcoal used as brands	Brand heating could be simulated by electric heater. Ignition is still not formulated, but aided by exposure to airflow

4. Discussion

While it is useful to identify vulnerabilities and best practices, protection of WUI communities cannot evolve without more quantitative analyses to optimize protection schemes. Part I of this review has covered most of the existing science related to exposure conditions from WUI fires. In the era of performance-based design, many design choices in the built environment are based upon knowledge of fire behavior and its effects on risk. Such an understanding of wildland fire behavior, coupled with its impact on WUI communities, does not yet exist. Two main areas are necessary to inform risk and hazard quantification: data collection from real fires and expanded fundamental understanding. A statistical representation of data from previous fires, when carefully collected and analyzed, has the ability to inform our understanding of how fires will affect real structures and quantify these effects in a risk model when enough data is gathered. Increased measurements of firebrand "fluxes" would help quantify this missing piece of a possible exposure scale [128]. These risk models can then be used to perform cost-benefit analyses for fire mitigation that optimize resources available and estimate potential impacts of decisions made [3]. The amount of data needed for such an approach is most likely a limiting factor [12]. Fundamental research, on the other hand, has more potential to provide simplified tools for the design of WUI communities. Increased fundamental understanding has the power to limit the level of large-scale experiments and collection efforts needed by providing a means to scale and better understand collected information, which can eventually be used to inform the quantification of risk and hazard.

4.1 Exposure Framework

Several frameworks are available to perform risk and hazard analysis in order to optimize protective strategies or fire management; however, most would be greatly improved with additional information on the response of structures in the WUI to fire [3, 12]. This type of data does not exist; so, for the most part, risk modeling today only incorporates features of surrounding wildland fire behavior (fuel, slope, weather, etc.) and the density of structures [12, 189–191].

Maranghides and Mell laid out what they thought were the missing components, by defining a WUI hazard scale broken up into fire and ember exposure, shown in Figure 10 [12]. While such a defined structure is not necessarily absolute, their description of how most every "box" of possible fire exposure conditions has yet to be studied highlights the lack of data currently available. The necessary step of connecting these exposures to the response of specific structural components will require additional effort. Since all structural components are hazards, it is necessary to include exposure from nearby structures and surrounding fuels, not just those directly intimate with the main structure.

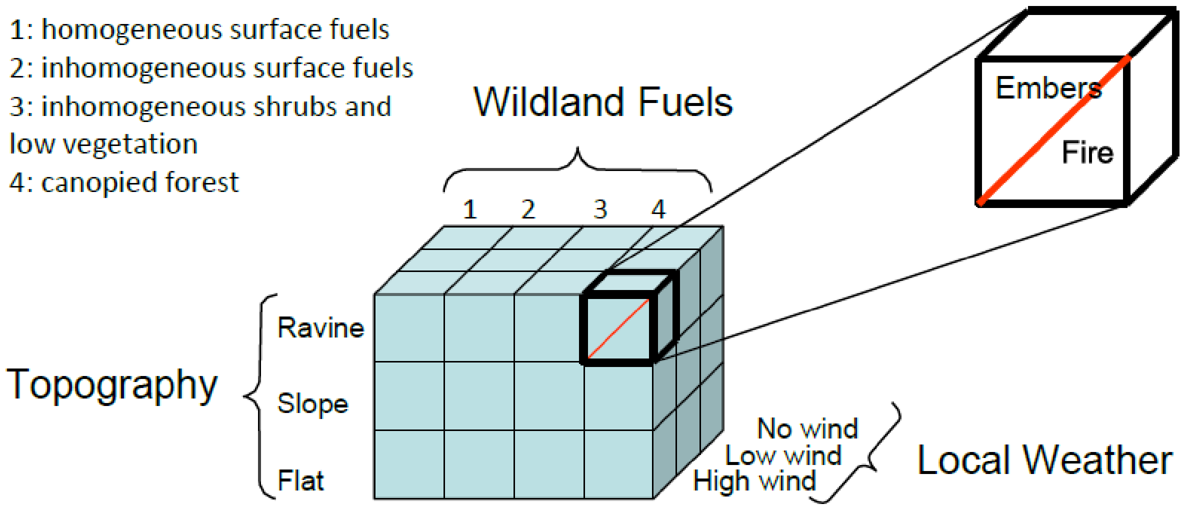

Fig. 10 *Capturing exposure from wildland fuels from Maranghides and Mell* [12]

4.2 Firebrands

Although many experiments have been performed on generation, transport, and ignition from firebrands, there does not yet exist a framework which can be adapted to relatively realistic simulations of real fires. Many studies by Manzello et al. have been instrumental in setting up a framework for identifying vulnerabilities on specific structural components and measurement of the distribution of firebrands from real fires [10]. This work has been a great contribution, illustrating increased involvement from the fire science community. Nonetheless, much work is left to be done. There are many potential fuel types, from large pine stands to Mediterranean chaparral, which may invariably generate different ember fluxes that should be studied and compared. Higher wind speeds have yet to be approached in order to create a more realistic WUI fire situation. Most experiments have been conducted with wind speeds up to 10 m/s, while wind speeds in excess of 20 m/s are often observed during WUI fires [10]. Along with these higher wind speeds, real WUI fires have up to several hours of continuous firebrand generation. Therefore, experiments need to incorporate longer firebrand exposure to simulate actual WUI fires. A framework to couple the observed results does not yet exist.

To further understand ignition from firebrands, testing should consider different elevations and higher velocities of firebrand generation. Testing that includes the combined influence of firebrands and radiative heat flux is another area that should be further investigated as both may be present during WUI fires and some observations on roofing indicate radiation will greatly accelerate transition to flaming [81]. It is also important to couple these results to multiple building components to observe their interaction. Single component testing alone would not have been able to reveal firebrand collection spots, such as re-entrant corners [134], which appear to play a critical role in structure ignition. Important components that need test standards will be discussed in Part II of this review [2].

In terms of firebrand generation, some research has been conducted to measure firebrand production from both vegetation and structures, presented as mass or size distributions collected downstream [123, 124, 127]. Research should continue on collection of firebrands from real and simulated fires, including different vegetation, structures, winds, etc. Very limited research appears in the literature on the actual process of firebrand generation and how it relates to the materials which generate firebrands. If more understanding can be garnered from specific fuel types, perhaps these distributions can be better understood *a priori*.

Lofting and transport of firebrands has been the most-studied aspect of the problem. While there is still work to do, several models exist which are adept at incorporating firebrands and investigating their transport through a fire plume [41, 112, 153, 154] or statistically investigating their transport numerically [189].

The least-understood process is ignition by firebrands. Ignition of a recipient fuel by a firebrand may depend on many characteristics: firebrand properties (i.e. size), ambient winds, fuel moisture content, geometry, whether the brand is flaming or smoldering on landing, and how many brands land in a particular recipient fuel [5]. Little is known about how these characteristics interact and the actual effect they have on how and when ignition occurs. The relative influence of solid-phase chemistry, re-radiation, brand size, configuration, etc. must be determined before better models for ignition can be developed. Some of these studies should focus on denser materials, such as wood or plastic often found on structures in the WUI. Most studies which have taken a closer look at ignition phenomena by firebrands have been somewhat restricted to loose, vegetative fuels [16, 185], which may behave differently than the higher density, varying geometries found on or near structures.

4.3 Wildland Fire Fundamentals

While fire dynamics is a fairly developed field used to analyze the built environment [54, 55], such knowledge is limited or non-existent applied specifically to WUI fires. Tools are available to predict the spread of wildland fires, their intensities, and expected radiative fluxes [87, 89], but these tools are based on assumptions of steady flame spread that have limited or no physical basis [192]. This assumption leaves gaps, as no tool can assess whether a fire will accelerate, decelerate or stop, critical elements when looking at the effectiveness of fire breaks in protecting a community. There is also no way to incorporate the influence of structures or fire suppression using current tools. New tools under development, such as WFDS (WUI Fire Dynamics Simulator), hope to bridge some of these gaps, but still require significant advancement in fundamental understanding of fire behavior to be accurate enough to further enhance knowledge on the problem. Increased research on wildland fire behavior and its coupled effect on structures in the WUI, such as recent numerical efforts [193], could enhance our understanding of structure-wildland and structure-structure interactions. Development of software with a firm technical and scientific basis could be a valuable tool in a WUI community designer's toolbox.

Other research needs include those surrounding firebrands, as discussed above. The mechanisms governing transition from smoldering to flaming combustion are not well-understood. This transition is of particular importance in determining whether ignition of a fuel will occur. Ignition due to flames and firebrands needs to be more completely characterized. Additionally, research on fire behavior and smoke transport is necessary, with the latter affecting health and environmental concerns.

5. Conclusions

Great strides have recently been made to understand several of the fundamental exposure conditions contributing to structure ignition and fire spread through WUI communities. While there are still many gaps, a framework is developing on the basis of these studies to guide future research from the laboratory to field scales. More attention should be paid to connecting work between scales and mathematically fitting results so that they can eventually be placed in risk assessment frameworks. This increased attention to fundamental details will surely pay large dividends; therefore, this type of investigation should not be neglected in the process. It is through the connection of laboratory and theoretical studies, large scale collection efforts, and application of these techniques and measurements of their success to real fires, that we will ultimately make a dent in reducing the WUI fire problem.

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