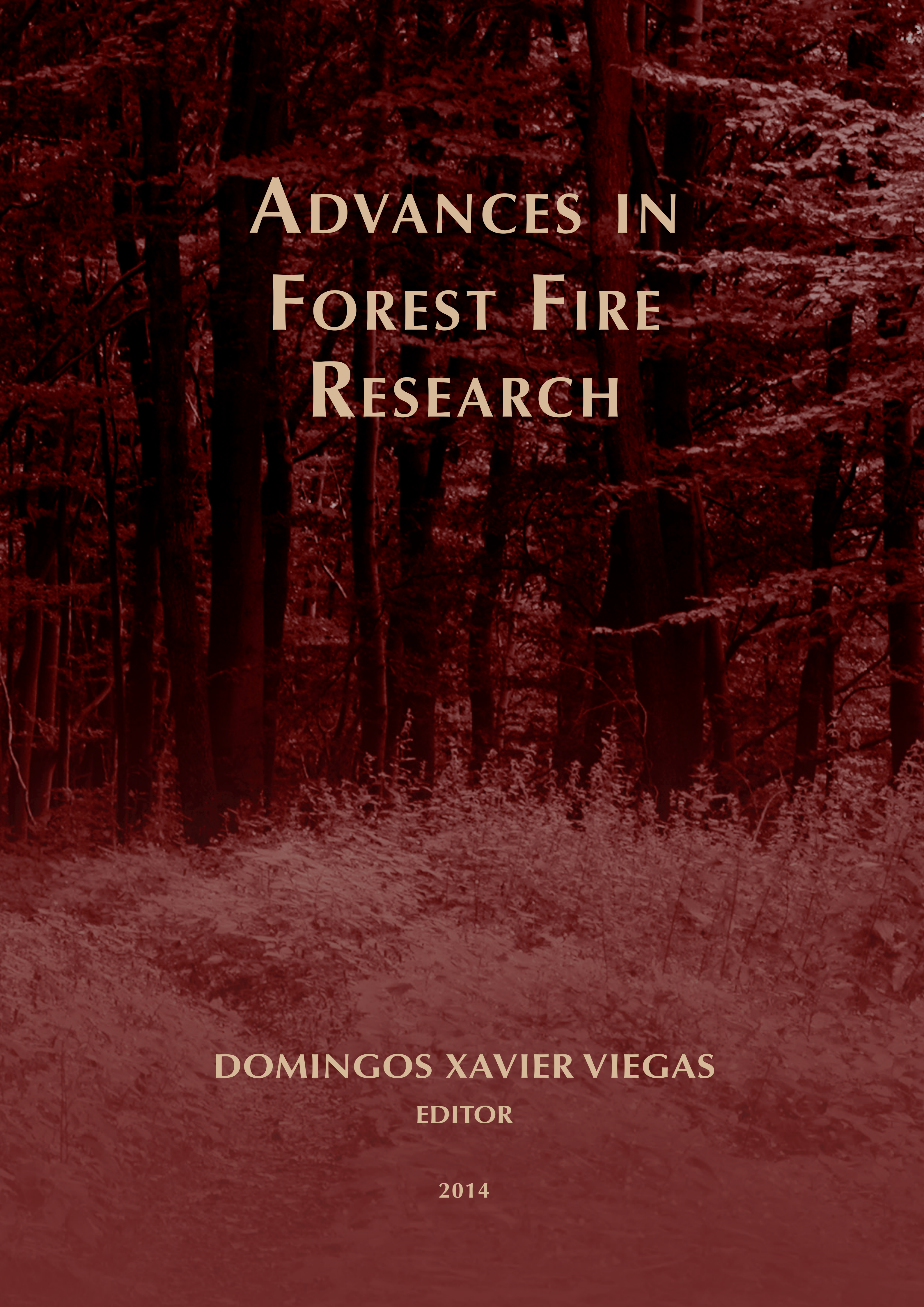

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Hardening structures to resist wildland-urban (WUI) fire exposures

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Abstract

Wildfires that spread into communities, referred to as Wildland-Urban Interface (WUI) fires, have destroyed communities throughout the world. In the USA, over 46 million homes in 70,000 communities are at risk of WUI fires [1]. Historically, fire safety science research has spent a great deal of effort to understand fire dynamics within buildings. Research into how to potentially mitigate the loss of structures in WUI fires is far behind other areas of fire safety science research. This is due to the fact that fire spread in the WUI is incredibly complex, involving the interaction of topography, weather, vegetation, and structures. Since the best way forward to address the WUI problem is the hardening of structures [2], the technical basis for improved test standards and fire and building codes are being developed. This paper provides a brief description of the NIST Dragon technology, recent application of the technology to various building assemblies and mulch, and closes with a series of research gaps that must be addressed to be able to design building components to resist firebrand ignition from WUI fire exposures.

Keywords*: Wildland-Urban Interface (WUI), firebrands, ignition*

1. Introduction

Wildland-Urban Interface (WUI) fires continue to burn in the USA, and are rapidly getting worse, with attendant increased economic costs [1]. Some recent examples include the Bastrop Complex Fire in Texas in 2011, the Waldo Canyon Fire in Colorado in 2012, and fires in Arizona, Colorado, and California, in 2013. Firebrands are generated as vegetation and structures burn in these fires. While firebrand showers are responsible for a majority of structure ignitions in WUI fires (see any number of post-fire investigation reports over the past 60 years; for example Foote [3]), there exist no scientifically-based standard laboratory test methods to evaluate individual building component's resistance to ignition from wind-driven firebrand showers. Without standard laboratory test methods, it is impossible to evaluate and compare the performance of building elements ability to resist firebrand ignition. It cannot be overstated that current understanding of building component type to WUI exposure is still mainly predicated on *anecdotal* evidence. As a result, the limited WUI fire and building codes and standards in practice lack scientific rigor and, when implemented, it is not clear if these provide any benefit to structures in the path of hazardous WUI fires.

Before test standards are developed, full-scale experiments that systematically evaluate individual building component vulnerabilities to ignition to firebrand showers are required. It is critical to understand the full-scale assembly performance when exposed to wind-driven firebrand showers since weak points in a given assembly can be investigated. In turn, this will lead to determining the necessary scale of building component mock-ups that can be used in standard laboratory test methods. As wind is a critical component required to transport firebrand showers observed in actual WUI fires, and wind plays a major role in whether ignition is observed, full-scale experiments must be able to consider the influence of an applied wind field to understand such ignition vulnerabilities.

The Fire Research Division at NIST has embarked on research to begin to determine the vulnerabilities of structures to firebrand showers using the NIST Dragon coupled to a full-scale wind tunnel at the Building Research Institute (BRI). The BRI facility (Japan) has been used since it is the only facility in the world to examine or study the behaviour of building component under wind-driven firebrand showers. Most recently, the NIST Dragon technology was improved to allow for the generation of continuous firebrand showers, as opposed to the original batch-feed Dragon (as described below). With this technology, it is now possible to systematically ascertain building component vulnerability to wind-driven firebrand showers of any duration [4-6]. The Dragon technology directly feeds into the NIST developed WUI Hazard Scale [7]. While beyond the scope of this paper, the WUI Hazard Scale attempts to provide a framework to quantify expected WUI fire exposure, and assign severity scales, for a given parcel and community. The vision is to establish a basis for the levels of hardening (ignition resistance) needed for buildings and communities to protect against exposure from WUI fires. As a result, with the Dragon technology, it will be possible to expose any type of building assembly to different levels of (radiative and convective) heat transfer and firebrand flux, thus enabling design of structures by tailoring fire resistance to the fire exposure and the hazard.

This paper provides an overview of the NIST Dragon technology, recent application of the technology to various building assemblies and mulch, and identifies a series of applied and fundamental research gaps that must be addressed to be able to begin to design building components to resist firebrand ignition from WUI fire exposures.

2. NIST Dragon Technology

The NIST full-scale Continuous Feed Firebrand Generator (NIST Dragon) consists of two parts: the main body and continuous feed component (**see Figure 1**). A brief overview is provided of the device; the interested reader is referred to recent review articles [5-6]. The feed system is connected to the main body and is equipped with two gates to prevent fire spread from ignition chamber back to the wood supply reservoir. A blower is connected to the main body and the purpose of the blower, described in more detail below, is to vary the combustion state of the generated firebrands from either glowing combustion or flaming combustion. The feed system consists of a pneumatic cylinder coupled to a cylindrical container where wood pieces, that will be ignited to produce firebrands, are stored. The pneumatic cylinder is contained inside a metal sleeve. Inside the metal sleeve, the sliding rod of the pneumatic cylinder is connected to a plate that allows the volume of wood contained within the sleeve to be varied. This volume can be set precisely to allow a specific mass of wood to fall into this volume. When the air pressure was applied, the sliding rod of the pneumatic cylinder moves forward, forcing the wood pieces that have fallen by gravity within the volume of the metal sleeve to the first gate, where they are then dropped into second gate that leads to the Dragon where they are ignited (see **Figure 1**). Douglas-fir wood pieces machined to dimensions of 7.9 mm (H) by 7.9 mm (W) by 12.7 mm (L) are used to produce firebrands. Firebrands generated from combustion of these wood pieces in the NIST Dragon have been shown to be consistent with sizes measured from full-scale burning trees, as well as size distributions obtained from actual WUI fires [6]. The number flux and mass flux of generated firebrands may be adjusted by varying the feeding rate of wood pieces into the device.

An operational parameter that is also varied is the blower speed. When the blower is set to provide an average velocity below 3.0 m/s measured at the exit of the Dragon when no wood pieces were loaded, insufficient air is supplied for combustion, and this results in a great deal of smoke being generated in addition to firebrands. At blower velocities above 3.0 m/s, smoke production is mitigated, and many of the firebrands are in a state of flaming combustion rather than glowing combustion. When firebrands contact ignitable fuel beds, they are typically in a state of glowing combustion, not open flaming. It is possible for firebrands to remain in a flaming state under an air flow, and it is reasonable to assume that some firebrands may still be in a state of flaming combustion upon impact. The purpose of this device is to simulate firebrand showers observed in long-range spotting and therefore firebrands in a state of glowing combustion are desired. Yet, the NIST Dragon is also capable to generate showers of flaming firebrands as well.

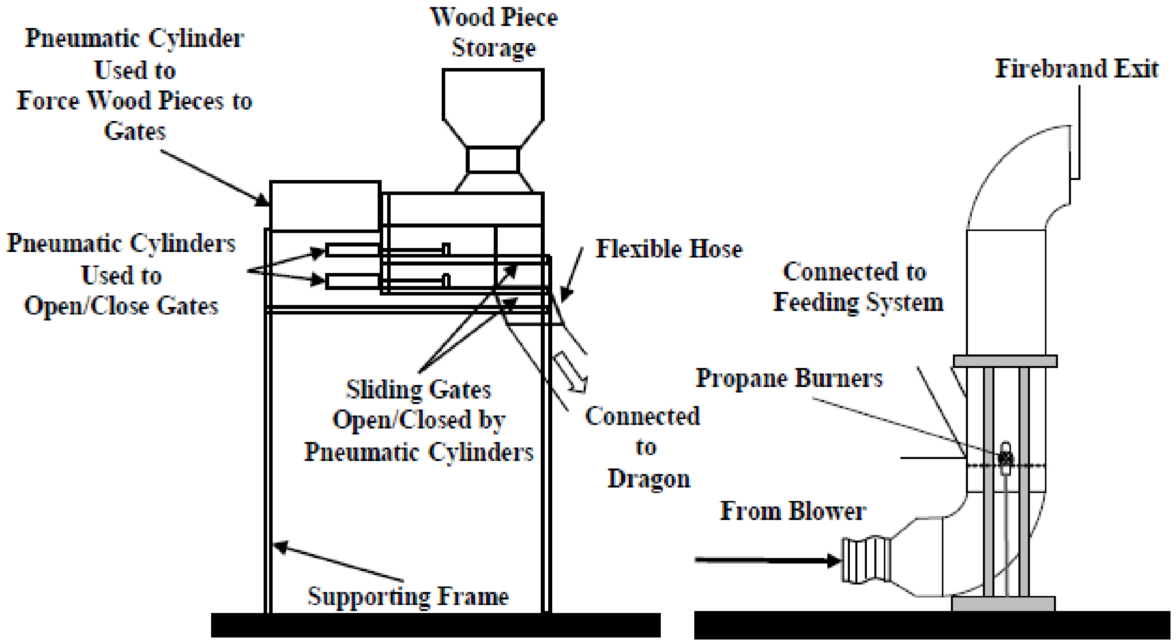

Figure 1Schematic of Full-Scale Continuous Feed Firebrand Generator

3. Current Knowledge Gaps – Applied Research Gaps

3.1. Decking Assemblies

In WUI fires, wood decking assemblies have been observed to be an ignition vulnerability based on post-fire damage surveys conducted by NIST and elsewhere. The California Office of the State Fire Marshal (OFSM) adopted the test method known as State Fire Marshal (SFM) STANDARD 12-7A-4 [8]. The SFM test method is intended to determine the response of decks to firebrand exposure and is very similar to the ASTM E108 [9] roofing test Namely, a firebrand is simulated by placing a burning wood crib (either Class A, B, or C firebrand) on top of a section of a deck assembly under an air flow. Class A is intended to represent the most severe firebrand exposure as it represents the largest crib size (30.48 cm x 30.48 cm x 5.715 cm). The dynamic process of multiple firebrands bombarding decking materials as a function of time is not taken into account in this standard test method. In addition to not simulating a dynamic firebrand attack, no attempt is made to relate the size and mass of the firebrand used in this standard to actual firebrands produced from burning vegetation and structures. There is no evidence to suggest that this test is a 'worst-case' firebrand exposure for decking assemblies.
Recent experiments using the NIST Dragon have demonstrated the dangers of the dynamic process of continual, wind-driven firebrand showers landing onto decking assemblies for the first time [9]. For each wood decking assembly type tested (cedar, Douglas-fir, and redwood), the accumulation of glowing firebrands resulted in flaming ignition of the deck boards. It was also observed that ignition of the deck boards produced smoldering ignition in the support members under the decking assembly (**see Figure 2-3**). Additional experiments must consider more wood types as well as composite (wood/plastic) decking assemblies to determine its performance when exposed to continuous wind-driven firebrand showers. These experiments should be compared to experiments using protocols outlined in SFM STANDARD 12-7A-4 [8]. Finally, it is important to determine whether decking

assemblies, once ignited, can result in a fire spreading to adjacent building components. Therefore, future full-scale experiments are required to address the questions:

- Is the current decking test method that uses Class A firebrand exposure adequate?
- If decking assemblies are ignited, are they capable to ignite adjacent building components?

Figure 2. Picture of the underside of the decking assembly (cedar); overall view [10].

Figure 3. Detail of the underside of the decking assembly (cedar). The ignition process was observed to spread to the wood supporting members [10].

3.2. **Roofing Assemblies**

As indicated above, the ASTM E108 [8] roofing test is used to evaluate ignition of roofs to firebrands by placing a burning wood crib on top of a section of a roof assembly under an air flow, yet, similar to decking assemblies, the dynamic process of multiple firebrands landing under ceramic tiles/gaps as a function of time is not taken into account [6]. Post-fire studies have identified a building ignition mechanism where small firebrands penetrate under non-combustible tile roof coverings [6]. Experiments conducted using the NIST Batch-Feed Dragon has provided experimental confirmation of this ignition mechanism for ceramic tile roofing assemblies (see **Figure 4** and [11] for more details).

Figure 4. ***Images of experiments conducted using oriented strand board/ceramic tile (OSB/CT) without bird stops installed [11]. Intense smoldering ignition (SI) was observed within the OSB base layer and eventually flaming ignition (FI) was observed. The wind tunnel speed was 7 m/s and the Firebrand Generator was located 2.0 m from the CT roofing assembly. The dimensions of the roof assembly were 122 cm by 122 cm.***

In addition, concrete tile roofing assemblies (flat and profiled tile; **see Figure 5**) as well as terracotta tile roofing assemblies (flat and profiled tile) commonly used in the USA, Australia, and elsewhere were exposed to wind-driven firebrand showers [12]. The purpose of these *scoping* experiments was to determine if firebrands were able to penetrate the roofing tile assemblies and melt the underlying sarking material. No sheathing layer was included in the roof support structure as these experiments were intended to replicate Australian construction details [12]. The results, however, are relevant to US construction since the same concrete (flat and profiled) and terracotta (flat and profiled) tiles are used in both countries. Underlayment or sarking, in the form of a layer of aluminium foil laminate bonded with a fire retardant adhesive to a polymer fabric, was placed under the tile battens. The results showed that firebrands penetrated the tile gaps and subsequently melted the sarking material for both types of concrete tile roofing assemblies (flat and profiled tile) and the profiled tile terracotta roofing assembly when exposed to wind-driven firebrand showers (**see Figure 6**). The flat tile terracotta roofing assembly appeared to perform better due to its interlocking design. For these tiles, the firebrands were observed to become trapped within the interlocking sections of the tiles and as a result, the firebrands were not able to penetrate past the tiles toward the sarking material. Based on the findings of these experiments, a potential cost-effective mitigation strategy might be to use a continuous underlayment of firebrand-resistant sarking [12].

Figure 5. Concrete Tile Roofing Assembly (profiled tile) Exposed to Wind-Driven Firebrand Showers. The dimensions of each tile were 420 mm long by 320 mm wide. The Height, from the Wind Tunnel Floor to the Base of the Gutter of Roof Deck was 1250 mm [12].

Figure 6. Images of Sarking Placed Under Concrete Tiles (profiled tile) Taken Immediately after the Experiment was Completed. The Tiles have been removed [12].

To further address the issue of wind-driven firebrands, the State of California in the USA mandated the use of a non-combustible mineral surfaced cap sheet under roof tiles [13]. These requirements have never been tested to wind-driven firebrand exposure. A series of open questions remain:

- All roofing assembly experiments conducted by NIST (described above) have made use of the batch feed NIST Dragon. What happens to roofing assembly performance when experiments are revisited with the improved continuous feed Dragon capable of longer firebrand exposures?
- Is the current requirement mandated in California [12] on the use of a non-combustible cap sheet under roof tiles adequate?
- Should the legacy ASTM E108 [9] roofing test be modified to consider continuous wind-driven firebrand exposure to roofing assemblies?

3.3. Mulch Located Adjacent to Structures

Buildings are often surrounded by vegetation that, when ignited, can produce intense, localized firebrand showers, and provide direct flame contact onto building elements, leading to ignition of buildings. The creation of defensible space around structures is a common mitigation strategy, yet in many areas the requirement for the creation of defensible space is either not popular due to resistance to modify the natural environment and landscaping around structures, or not practical due to limited lot/land parcel size. Of particular concern are wood landscape mulches located adjacent to buildings. While there have been some studies of mulch ignition in the literature, none of these studies have investigated the ignition of mulch installed in realistic building configurations exposed to wind-driven firebrand showers; conditions seen in real WUI fires.

Figure 7 displays a typical experiment to expose shredded hardwood mulch beds to continuous wind-driven firebrand showers. In this image, the wind tunnel speed was 6 m/s and the mulch bed moisture content (MC) was 11 % (dry basis). While full details of these results are beyond the scope of this paper (see [14] for full details, it is rather clear that continuous-wind driven firebrand showers are capable of rapidly igniting mulch beds (**see Fig.7**).

Figure 7. Image of 1.2 m by 1.2 m by 51 mm (depth) shredded hardwood mulch bed at 11 % MC exposed to continuous wind-driven firebrand showers. The re-entrant corner, with dimensions of 1.2 m by 1.2 m by 2.44 m high, was lined with gypsum board to investigate the ignition of the mulch bed itself; the ability of the mulch bed to ignite the wall assembly was not considered [14].

- Are wind-driven firebrand showers capable of igniting common wood mulches found in WUI communities?
    - Shredded hardwood mulch was observed to ignite. How about other common mulch types such as pine bark, pine bark nuggets, and pine straw?
- Once ignited, is the wood mulch bed capable of producing ignition of the structure itself?

3.4. **Wood/Vinyl Fencing Assemblies**

Post-fire studies conducted by NIST on the Waldo Canyon Fire in Colorado (2012) suggested that wood fencing assemblies are vulnerable to ignition from firebrand showers in WUI fires, but again there has never been any experimental verification of this ignition mechanism. Fencing assembly ignition has also been observed in Australia [15]. Presently, there is lack of understanding on fence assembly ignition vulnerabilities under wind-driven firebrand exposure. **Figure 8** displays results obtained when exposing redwood fencing to continuous firebrand showers. Redwood fencing assemblies were observed to produce their own firebrands.

- Do fence assemblies, if ignited by wind-driven firebrand showers, transfer or link the fire to the structure?
- Are certain fencing assembly types more amenable to firebrand generation?

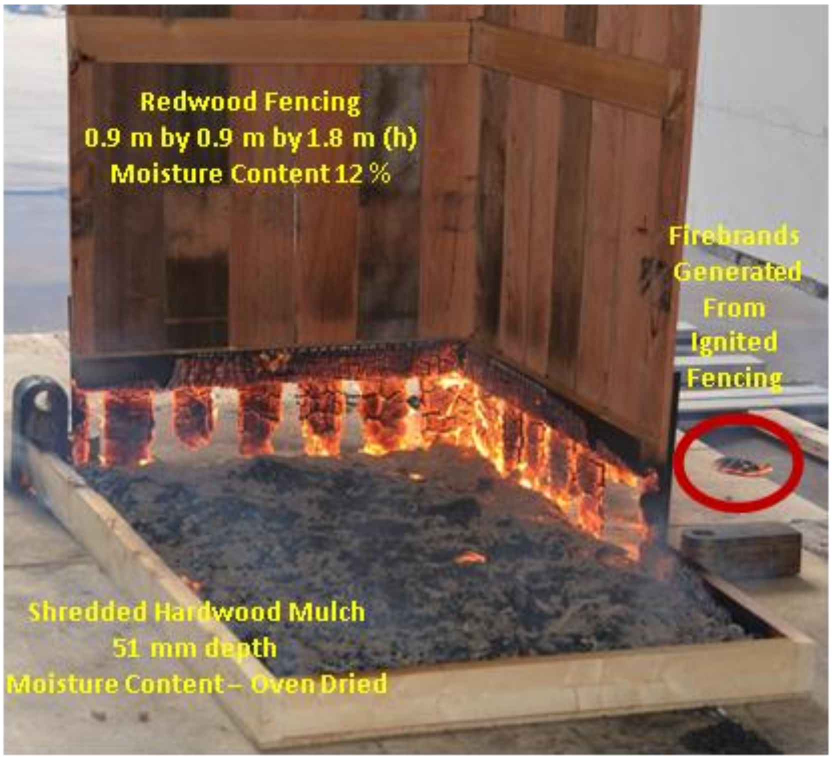

***Figure 8** Redwood fencing (inside corner section), exposed to wind-driven firebrand showers at 8 m/s from the NIST Dragon. The firebrands produced smoldering ignition in the shredded hardwood mulch bed (foreground; depth 51mm), this transitioned to flaming ignition in the mulch, and the redwood fencing was subsequently ignited by the mulch. Shredded hardwood mulch was intended to represent various fuels that are adjacent to fencing in the Wildland-Urban (WUI). As the redwood fence continued to burn, firebrands were generated with large projected area and low mass, and were blown downstream (far right).*

3.5. **Different Wall Siding Types**

Complete lack of understanding on wall ignition vulnerabilities under wind-driven firebrand exposure.

- Are test standards [16] that exist for direct flame impingement adequate?
- Once ignited, are certain combustible siding types more likely to generate firebrands?

4. Translating Full-Scale Experimental Results to Laboratory Test Standards

As needed physical understanding is being collected from the full-scale experiments, work is required to develop reduced-scale test methods that will be able to reproduce results of the full-scale experiments above. The specific exposure ranges (*e.g.* duration of firebrand flux) will be determined as further understanding of WUI fire exposure develops. It is important to understand that is a significant challenge.

As mentioned, a very important characteristic of the NIST Dragon is that the firebrand size and mass produced using the device can be tailored to those measured from full-scale tree burns [17-18], and actual WUI fires [19], which are in stark contrast with the size of firebrands referenced in existing test standards and wildfire protection building construction recommendations. In collaboration with the California Department of Forestry and Fire Protection (CALFIRE), NIST quantified firebrand distributions from a real WUI fire (2007 Angora Fire) [19]. Specifically, digital image analyses of burn patterns from materials exposed to the Angora Fire were conducted to determine firebrand size distributions. The firebrand size distributions reported were compared to firebrand size distributions from experimental firebrand generation using the NIST Dragon, as well as historical firebrand field studies. The most salient result reported in [19] was the documentation of the consistently small size of firebrands (<0.5 cm^2) and the close correlation of these results with the sizes of experimentally generated firebrands from the NIST Dragon. The Texas Forest Service has used this methodology to collect firebrand size distributions from the recent Texas Bastrop Complex fires in 2011, as well, and reported similar findings to the 2007 Angora fire; significant numbers of very small firebrands were produced [20].

- More information of this type is clearly needed from actual WUI fires - this is an important challenge for future WUI fire research.
- Other than the Angora Fire and Bastrop Fire data sets, which are limited, no other information on firebrand distributions from actual WUI fires is available.

Rapidly deployable instrumentation packages that can be placed in the path of WUI fires to collect information on firebrand fluxes generated in *actual* WUI fires are needed. The authors have developed such a system to quantity heat flux from WUI fires and the concept was vetted in prescribed fires, but this methodology must be extended to collect needed firebrand flux [21] from actual WUI fires. It is difficult to simulate the range of WUI fuels (*e.g.* structures) and wind speeds in prescribed fires, and as a result, using only firebrand data from prescribed fires will not give meaningful data from actual WUI events. Prescribed fires are, however, a useful place to test a conceptual firebrand flux instrument package.

5. Fundamental Research Needs

As indicated above, much applied research is needed to be able to begin to consider designing structures to resist firebrand ignition in WUI fires. Yet, it is important not to overlook fundamental research needs that are an integral part of this problem as well. Important fundamental needs also link WUI research to materials science research, as better fundamental ignition data will lead to enhanced, firebrand resistant materials. Specifically, these needs are:

- Fundamental understanding of ignition of building elements by firebrands, answering questions such as:
  - What is the mechanism of ignition of building elements by firebrands?
  - How does firebrand accumulation influence the heat flux applied to adjacent ignitable materials?
  - How does wind influence accumulation as well as the burning and heat transfer from accumulated firebrands to an ignitable material?
- Forensic analysis of firebrands collected from WUI fires, answering questions such as:
  - What are firebrands comprised of?
  - Is it possible to determine the source of firebrands from burned samples?
    What types of firebrand materials have a greater potential of igniting materials (vegetative and building elements)?

6. Summary

Research into WUI fires, and how to potentially mitigate the loss of structures in such fires, is far behind other areas of fire safety science research. This is due to the fact that fire spread in the WUI is incredibly complex, involving the interaction of structures with topography, weather, and vegetation, and other structures [6]. While WUI research is challenging, this paper attempts to delineate a series of current research gaps in order to be able to begin to harden structures to firebrand showers, an important aspect of WUI fire exposure.

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