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Firebrand generation data obtained from a full-scale structure burn

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Abstract. A full-scale, proof-of-concept experiment was conducted to investigate firebrand production from a burning structure. In this experiment, researchers from National Institute of Standards and Technology (NIST) were invited to set up instrumentation and collect firebrands using an array of water pans during a structure burn-down. The size and mass distribution of firebrands collected from the burning structure was compared with those measured from vegetation as well as historical firebrand investigations and found to be larger and broader than those of prior studies from historical firebrand investigations.

Additional keywords: mass distribution, size distribution, WUI fires.

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Introduction

Large outdoor fires that present risk to the built environment are of concern to many countries throughout the world. In particular, wildfires that spread into communities, commonly referred to as wildland–urban interface fires (WUI), are a significant problem in Australia, Europe and the USA. Although it is accepted that WUI fires are an important societal problem, little understanding exists on how to contain and mitigate the hazard associated with such fires. This is due, in part, to the fact that WUI fire spread is extraordinarily complex and presents the next frontier in fire safety engineering.

From a pragmatic point of view, the WUI fire problem can be seen as a structure ignition problem (Mell *et al.* 2010). Ignition-resistant structures under WUI fire exposure were listed as one of the major recommendations in the GAO 2005 report 'Technology assessment: protecting structures and improving communications during wildland fires' (GAO 2005), and was the subject of a Homeland Security Presidential Directive (HSPD 2004). In spite of these facts, little effort has been spent on understanding the processes of structure ignition in these fires.

Post-fire studies support the observation that firebrand exposure has a significant role in the spread of disastrous WUI fires (Barrow 1945; Wilson and Ferguson 1986; Abt *et al.* 1987; Gordon 2000; Maranghides and Mell 2010). In addition, full-scale crown-fire exposure experiments and post-fire studies indicate that radiant heat transfer from forest fires may be significantly less important as a WUI fire building-ignition mechanism than previously assumed (Blanchi *et al.* 2006; Cohen and Stratton 2008; Foote *et al.* 2011). Although the topic of firebrands in general has been extensively studied for more than 40 years (Koo *et al.* 2010) and the phenomenology of WUI fire spread in particular has been observed for decades, the problem of disastrous WUI fire losses is widely perceived to be getting worse (Foote *et al.* 2011). Post-fire damage studies have suggested for some time that firebrands are a significant cause of structure ignition in WUI fires; yet for over 40 years, firebrand studies have focussed on understanding how far firebrands fly or spotting distance (Tarifa *et al.* 1965; Tarifa *et al.* 1967; Muraszew and Fedele 1976; Albini 1979, 1983; Tse and Fernandez-Pello 1998; Woycheese 2000; Knight 2001; Himoto and Tanaka 2005; Anthenien *et al.* 2006; Wang 2011). These studies do not assess the vulnerabilities of structures to ignition from firebrand attack and are of no use to develop ignition-resistant structures.

Recently, Manzello (e.g. Manzello *et al.* 2007*a*, 2008*a*, 2008*b*, 2010, 2011) developed an experimental apparatus, known as the National Institute of Standards and Technology (NIST) Firebrand Generator (or NIST Dragon) to investigate ignition vulnerabilities of structures to firebrand showers. The NIST Firebrand Generator is able to generate a controlled and repeatable size and mass distribution of glowing firebrands. The experimental results generated from the marriage of the NIST Dragon to the Building Research Institute's (BRI) Fire Research

Wind Tunnel Facility (FRWTF) have uncovered the vulnerabilities that structures possess to firebrand showers for the first time (e.g. Manzello *et al.* 2008*b*, 2010; 2011).

To date, the firebrand sizes generated by the NIST Dragon have been adjusted to coincide with those measured from full-scale tree burns and a real WUI fire (Angora) (Manzello *et al.* 2007*b*, 2009; Foote *et al.* 2011). The Angora Fire firebrand data are believed to be the first such information quantified from a real WUI fire. Little data exist with regard to firebrand size distributions from actual structures or WUI fires (Vodvarka 1969, 1970; Babrauskas 2003). It is believed that the structures themselves may be a large source of firebrands, in addition to the vegetation. Yet, owing to such limited studies, it cannot be determined if firebrand production from structures is similar to that of vegetation, or if firebrand production from structures is a significant source of firebrands in WUI fires.

Collaboration between the Northern California Fire Prevention Officers (NORCAL FPO, a section of California Fire Chiefs Association, CALCHIEFS) and NIST offered an opportunity to expand and enhance understanding of burning materials emanating from structures. To this end, a full scale, proof-of-concept experiment was conducted to investigate firebrand production from a burning structure. Once the firefighter training exercises were completed, a burn-down of the structure was conducted by the Dixon and Vacaville Fire Departments. As the structure burned, firebrands were collected using an array of water pans positioned over a range of distances, downwind from the structure. A very brief (two-page) summary was reported in a recent conference (Suzuki and Manzello 2011). The current paper provides a full description of this experiment for the first time. Primary benefits of this study are for the improvement of building materials and assemblies that can mitigate threats posed by firebrands (enabling the NIST Dragon to produce distributions commensurate with burning structures), and improvements to fire behaviour predictive models for WUI fire planning.

Experimental description

The structure used for the experiments was a two-storey house located in Dixon, California. This structure was made mainly from brick and wood and prepared for training. Fig. 1 shows three pictures of the structure from outside; two of them show the structure before preparation and one after preparation. All utilities were secured and the water heater and other closed tanks were removed. All glazing assemblies were also removed and plywood was mounted in a fashion to allow rapid ingress, egress, ventilation and hose movement. Further details are provided in the Incident Action Plan (IAP) (IAP 2010).

The weather was mostly sunny with a high temperature of 25°C and wind speed of 20.8 km h^{-1}, which was almost constant, from the south-west during the burn. Fig. 2 shows the first-floor plan for the burned structure. Debris piles were used to ignite the structure. It took ~2 h after ignition for complete burn-down (see pictures shown in Fig. 3). A large amount of water was applied with hoses onto the structure several times to control the fire because the house was located in downtown Dixon. The influence of applying water on firebrand generation from a structure is discussed below. Firebrands were collected

Fig. 1. Pictures of burned structure from outside: (*a*) view from east side; (*b*) view from north side and (*c*) prepared for burning.

by using a series of water pans placed ~4 m (north to north-west) from the structure and on the road ~18 m downwind (north-east) of the structure as shown in Fig. 4. These locations were selected to collect firebrands not only downwind, but also around the structure with less effect of wind. Each pan was 49.5 cm long by 29.5 cm wide by 7.5 cm deep. After deposition into the water pans, the firebrands were filtered from the water using a series of fine mesh filters. Firebrands were dried in an oven at 104°C for 4 h. The mass and size of each firebrand were measured by a precision balance (0.001-g resolution) and using digital image analysis.

Results

After finishing the structure burn, the pans were collected by the firefighters and the firebrands were separated from the water using filters. Examples of firebrand images are shown in Fig. 5. This image was converted to an 8-bit greyscale image. Image

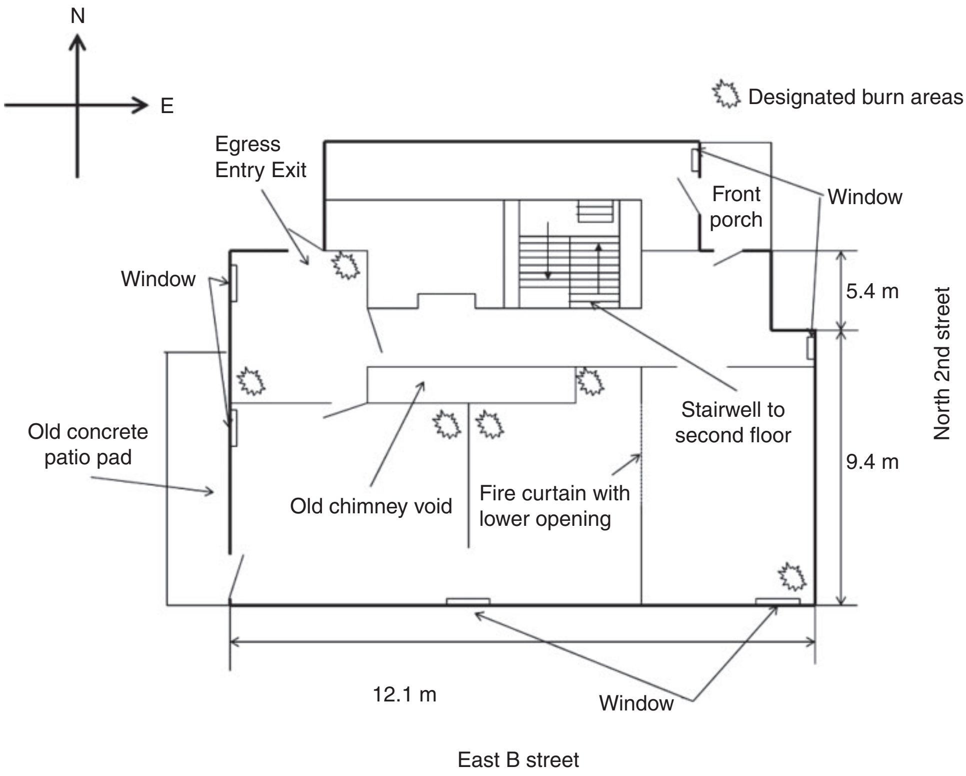

Fig. 2. First-floor plan of burned structure.

analysis software was then used to determine the area of a firebrand by converting the pixel area using an appropriate scale factor. It was assumed that deposited firebrands would rest flat on the ground and the projected areas with the maximum dimension and the second-largest dimension of three dimensions were measured (for cylindrical or flat-shaped firebrands respectively).

Fig. 6*a* and 6*b* shows the size and mass distribution of firebrands at two different places, one ~4 m from the structure and 18 m downwind from the structure. Fig. 6*a* has all the firebrand data, whereas Fig. 6*b* represents data for firebrands less than 15 cm^2 for a detailed comparison. Fig. 6*a* and 6*b* shows that the size and mass distribution of firebrands at the two locations were similar. All the firebrands collected from the burning house were less than 1 g and almost 85% of the firebrands collected 18 m from the structure and 68% of the firebrands collected 4 m from the structure were less than 0.1 g. It is also important to note that one firebrand had a large projected area of 80 cm^2, almost 10 times as large in projected area as the other firebrands (mass of 0.5 g). This firebrand was thought to be burned from roofing paper owing to its large projected area compared with its weight.

Fig. 7 shows the size distribution of firebrands collected from the burning structure. In total, 139 firebrands were collected from the two locations: 89 firebrands from ~4 m from the structure and 50 firebrands 18 m downwind from the structure. Most of the firebrands, 95% of those from 18 m downwind from the structure and 96% of those from ~4 m from the structure, had less than a 10-cm^2 projected area. A firebrand with 80-cm^2 projected area from Fig. 7*a* as well as another firebrand with 22-cm^2 projected area from Fig. 7*b* were eliminated in order to show the size distributions of firebrands with less than 10-cm^2 projected area clearly. It was observed that the size distribution of firebrands ~4 m from the structure was slightly broader than the one from 18 m downwind from the structure.

Comparison with previous studies

Babrauskas (2003) and Koo *et al.* (2010) provide a review of existing research on firebrands. Empirical and experimental research on firebrand size distributions is very limited. As few studies on firebrand generation from actual structure burns have been examined so far, research on firebrand data from tree burns (Manzello *et al.* 2007*b*, 2009) and burn pattern in WUI fires (Foote *et al.* 2011) is also reviewed and compared here with the present study in addition to research on firebrand data from structure burns (Vodvarka 1969, 1970; Yoshioka *et al.* 2004).

Manzello *et al.* (2007*b*, 2009) measured the mass and size distribution from burning trees. In that work, an array of pans filled with water was used to collect the firebrands that were generated from burning trees. The firebrands were subsequently dried and the sizes were measured using callipers, and a precision balance was used to determine the dry mass. The results are compared in Fig. 6*a* and 6*b*. The size and mass distribution of firebrands collected in the present study were observed to have some similarity to the ones from vegetation as well as some differences. The firebrands in this study were observed to have a large projected area for similar mass classes. In addition, a bigger firebrand with more than 50-cm^2 projected

Fig. 3. Pictures of a structure during the burn: (*a*) 30 min after ignition; (*b*) 45 min after ignition; (*c*) 1 h 15 min after ignition and (*d*) 2 h after ignition.

area was found in this study whereas all the firebrands in Manzello *et al.* (2007*b*, 2009) had less than 40-cm^2 projected area.

Firebrand size distributions from experimental building fires are also presented for comparison (Vodvarka 1969, 1970; Yoshioka *et al.* 2004). Vodvarka (1969) measured firebrand deposition by laying out 3×3-m sheets of polyurethane plastic downwind from five separate residential buildings burned in full-scale fire experiments. Three of the structures were standard frame construction with wood siding. The fourth was asphalt siding applied over sheet rock that covered the original shiplap. The fifth structure was a brick veneer over a wood frame. The total number of firebrands collected from these structure fires was 4748. Very small firebrands dominated the size distribution, with 89% of the firebrands less than 0.23 cm^2.

Vodvarka (1970) measured the fire spread rate, radiant heat flux, firebrand fallout, buoyancy pressures and gas composition from eight separate buildings. Firebrands were collected by laying out sheets of polyurethane plastic downwind from three of eight experiments. Two of the buildings were all-wood construction, and one was cement-block construction and had wooden floors and asphalt shingles over wood sheathing. In total, 2357 firebrands were collected. More than 90% of firebrands had less than 0.90-cm^2 projected area and 85% of them had less than 0.23-cm^2 projected area. Only 14 of them had more than 14.44-cm^2 projected area in three experiments.

Yoshioka *et al.* (2004) measured the size and mass of firebrands from a real-scale wooden house in BRI's FRWTF. Two different pans, both 1×1 m, were placed 2 m from the house to collect firebrands: one was filled with water (wet pan) and the other had no water (dry pan). The total number of firebrands collected in their study was 430, 368 from the wet pan and 62 from the dry pan. It was found that 83% of firebrands in the wet pan were between 0.25- and 1-cm^2 projected area whereas 53% of those from the dry pan were between 0.25- and 1-cm^2 projected area. Only 1 of 308 in the wet pan and 4 of 62 in the dry pan had more than 4-cm^2 projected area. It was pointed out that the reason why the dry pan had fewer firebrands with projected area between 0.25 and 1 cm^2 than the wet pan did was that firebrands burned out in the dry pan.

Foote *et al.* (2011) examined the size distribution of firebrand exposure during the Angora Fire, a severe WUI fire in California, USA, in 2007. In that study, a trampoline, which was exposed to wind-driven firebrands during the fire, was collected for analysis. The burn areas of the round trampoline base were assumed to be generated from firebrands and measured by digital image analysis. The trampoline section that was analysed had an overall area of 10.5 m^2 with 1800 burn holes. The single largest hole in the trampoline base had a 10.25-cm^2 burned area. It was pointed out that more than 85% of the burned areas from firebrands were less than 0.5 cm^2 and more than 95% of them were less than 1.0 cm^2. In addition to the trampoline data, burn patterns on building materials and plastic outdoor furniture were observed at 212 individual locations on or near numerous Angora Fire buildings. A large majority of these firebrand indicators were less than 0.40 cm^2, with the largest being 2.02 cm^2 or 0.64×3.18 cm. Most of the burn patterns on building materials consisted of shallow scorch or char marks

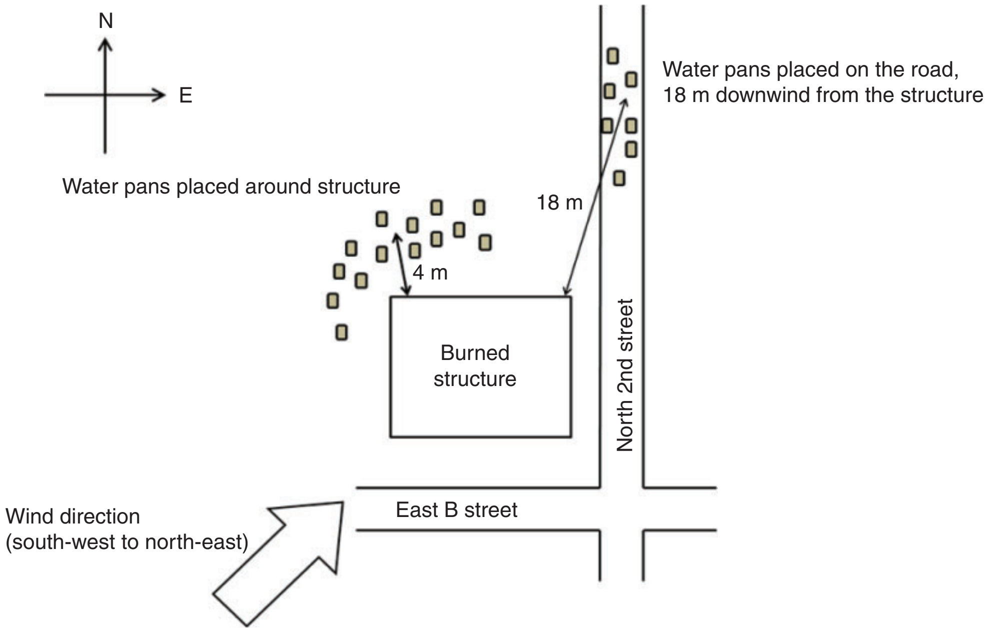

Fig. 4. Location of water pans.

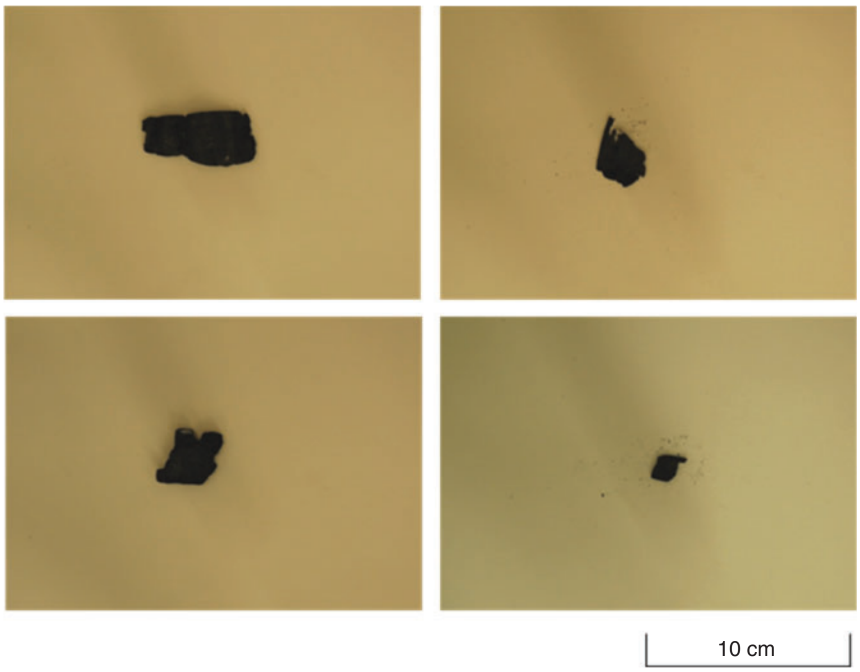

Fig. 5. Pictures of firebrands collected at a burn site.

on wooden or composite lumber decks. No actual firebrands were identified in association with these burn patterns.

In the present study, 139 firebrands were collected from the two different locations. Most firebrands, 95% of those ~18 m from the structure and 96% of those ~4 m from the structure, had less than 10-cm^2 projected area. Fig. 8 shows the comparison between the size distributions of firebrands at both locations and the data for one wooden structure from Vodvarka (1970). Most firebrands were observed to be larger than those from previous studies (Vodvarka 1969, 1970; Foote *et al.* 2011). The peaks of firebrands from burn sites were found to be between 0.9 and 3.6 cm^2 whereas the one from the previous studies was found to be less than 0.23 cm^2. It was found that the size distribution of firebrands in the current study was larger and

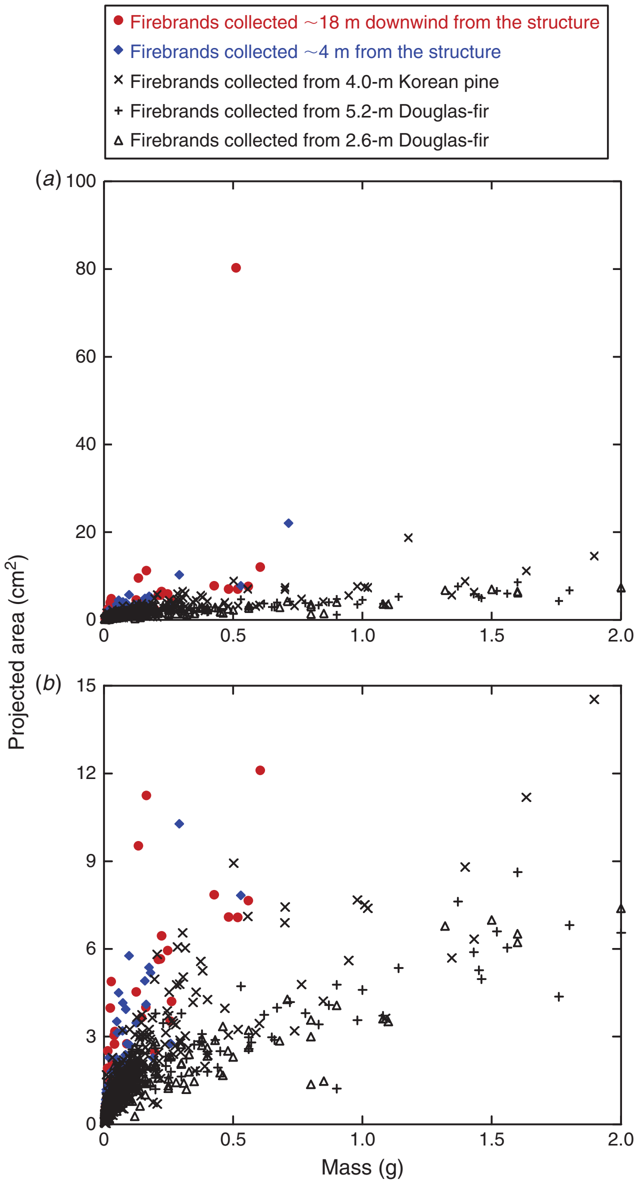

Fig. 6. Mass and size of firebrands collected in this experiment, compared with firebrand data from vegetation: (*a*) mass and size of all firebrands collected in this experiment and (*b*) detailed data of firebrands with less than 15-cm^2 projected area.

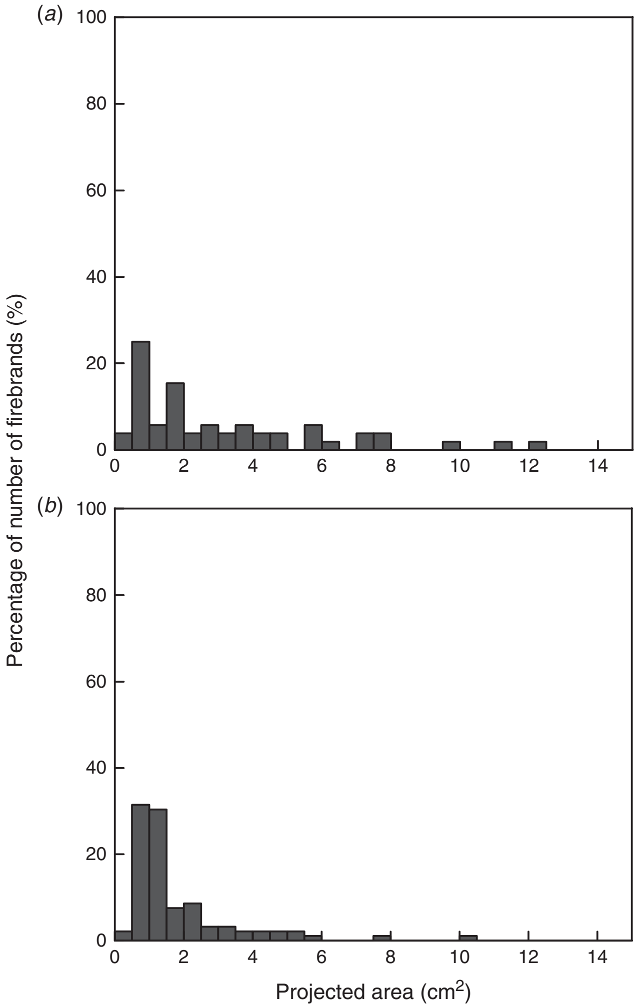

Fig. 7. Size distributions of firebrands from structure: (*a*) firebrands collected around structure and (*b*) firebrands collected from 18 m downwind from structure.

broader than in the previous studies. In addition, no firebrands smaller than 0.3 cm^2 at both sites were found whereas most of firebrands in previous studies were smaller than 0.23 cm^2.

The size distribution data collected in this study were also compared with those from Yoshioka *et al.* (2004) (Fig. 9). Most firebrands collected in the present study at both locations were also observed to be larger than those from Yoshioka *et al.* (2004). More firebrands from the study of Yoshioka *et al.* (2004) had a projected area of between 0.25 and 1.0 cm^2 compared to those in this study. The differences between Yoshioka *et al.* (2004) and the present study are the distances from the structure and wind speed. In order for firebrands to travel far, they need to be larger and to be lofted by a strong wind (Blackmarr 1972; Bunting and Wright 1974; Koo *et al.* 2010). In Yoshioka *et al.* (2004), the wind speed was 14.4 km h^{-1} and pans were located 2 m from the house, whereas the wind speed was 20.8 km h^{-1} and pans were placed 4 and 18 m from the structure in our study. No firebrand smaller than 0.25 cm^2 was found in both studies.

A significant difference between this study and prior literature studies was that a large amount of water was applied, intermittently, on the structure during the burn in order to control the fire (owing to the proximity of the structure to other homes). Water application may influence the results in several ways. It was possible that water application would result in a less intense buoyant fire plume emanating from the structure and that would lead to smaller firebrands being lofted. Future measurements without water suppression are needed to answer this question.

Summary

Collaborative work between NORCAL FPO, a section of CALCHIEFS, and NIST was successfully accomplished and a

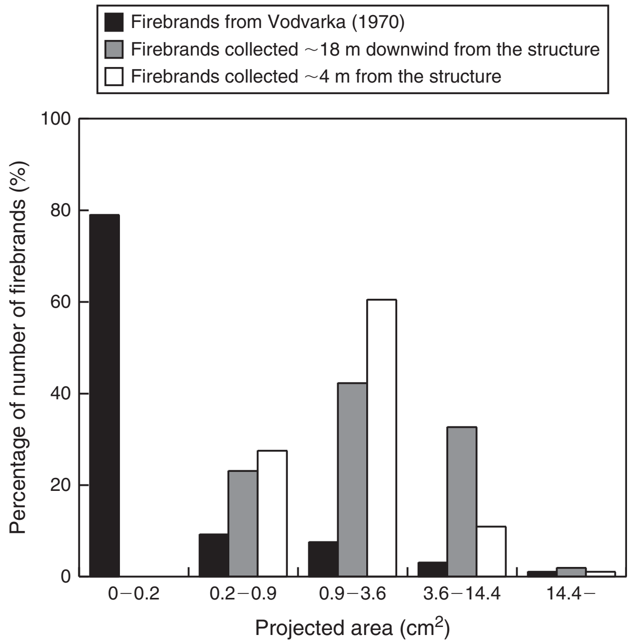

Fig. 8. Comparison between the size distribution of firebrands in the present study and the one from Vodvarka (1970).

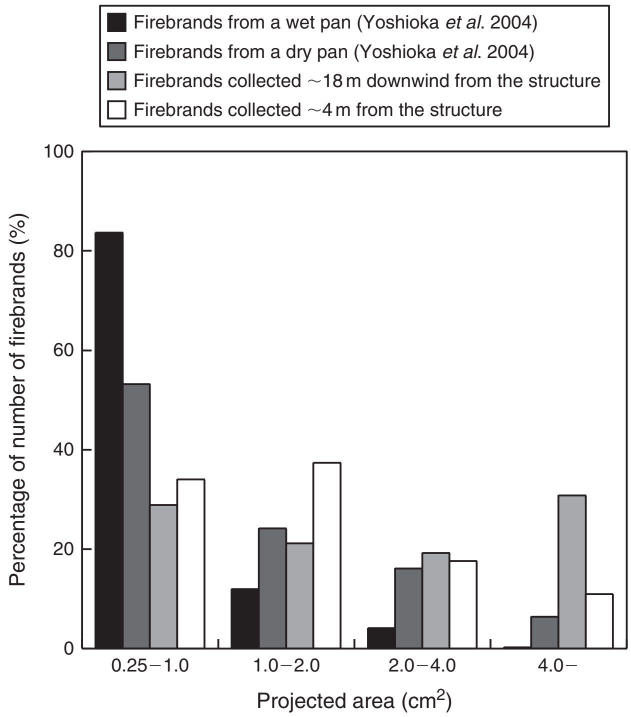

Fig. 9. Comparison between the size distribution of firebrands in the present study and the one from Yoshioka *et al.* (2004).

structure burn-down was completed. During the structure burn, firebrands were collected using a series of water pans. Firebrand data are discussed in this paper. As mentioned above, to control the fire, water was applied. In real WUI fires, most firebrands are produced without water being applied. Even though the situation is different, this study is constructive and serves as a first step to observe firebrand generation from a real structure because there are very few studies that have observed firebrand generation from real structures to date. In this study, the size and mass distribution of firebrands collected at the burn site was larger and broader than those of prior studies.

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