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The Performance of Concrete Tile and Terracotta Tile Roofing Assemblies Exposed to Wind-Driven Firebrand Showers

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Abstract

Concrete tile roofing assemblies (flat and profiled tile) 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 with an average mass flux of 10 g/m^2s at a wind speed of 9 m/s. The purpose of these scoping experiments was to determine if firebrands were able to penetrate the tile assemblies and melt the sarking material. Wind-driven firebrand showers were generated using the NIST Firebrand Generator (NIST Dragon) installed inside the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF) in Tsukuba, Japan. No decking was included in the roof support structure as these experiments were intended to replicate Australian construction details. The results, however, are relevant to USA 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. The flat tile terracotta roofing assembly performed best probably 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 transported past the tiles towards the sarking material.

1.0 Introduction

Wildland-Urban Interface (WUI) fires have become a problem of great concern worldwide. There have been significant WUI fires in Australia, Greece, Portugal, Spain, and USA over the past five years [1]. The fires in Australia in 2009 claimed the lives of more than 150 people [1].

The WUI problem can be viewed as a structural ignition problem [1]. For years, post-fire studies have identified firebrands as a significant source of ignition in these fires (see Ref. [2] for a review of many of these studies). The coupling of the NIST Firebrand Generator (NIST Dragon) to the Building Research Institute's (BRI) Full Scale Fire Research Wind Tunnel Facility (FRWTF) in Tsukuba, Japan has made it possible to expose actual building elements to wind-driven firebrand showers. A recent paper has been published that summarizes all of the findings obtained using the NIST Firebrand Generator installed in BRI's FRWTF [3].

Post-fire studies have long identified a building ignition mechanism in which very small (on the order of 1mm) firebrands penetrate under a non-combustible tile roof covering to ignite a building [2]. Although current standards exist (*e.g.* ASTM E108 [4]) to test ignition of roofing decks to firebrands by placing a burning wood crib on top of a section of a roof assembly under an air flow, the dynamic process of multiple wind-driven firebrands landing and then being transported under non-combustible tiles/gaps as a function of time is not taken into account. A recent experimental campaign demonstrated the vulnerabilities of curved ceramic tile roofing (Spanish tile roofing) assemblies to ignition under a controlled wind-driven firebrand attack using the NIST Firebrand Generator. Further details regarding those experiments are provided elsewhere [5].

Recent major bushfires in Australia have led to the establishment of a Royal Commission to examine the suitability of building codes for the construction of houses in bushfire prone areas. With many wildland fires propagated by the spread of firebrands, the resistance of building elements to wind-driven firebrands has become a topic of great interest worldwide as evidenced by papers submitted on this topic from all over the world to the first ever Special Issue devoted to WUI fires in the fire safety science archival literature [6].

The objective of this investigation was to observe the performance of tile roof assemblies using the test method developed by Manzello *et al.* [5] for several types of tile roofing assemblies. Specifically, these scoping experiments were conducted to determine if firebrands were able to penetrate the tile assemblies and melt the sarking material. The outcome of these tests is expected to be of value to both Australian and USA tile manufacturers as well as fire authorities/code officials in these countries.

2.0 Experimental Description

2.1 NIST Firebrand Generator (NIST Dragon)

Figure 1 shows side and front views of the NIST Firebrand Generator (NIST Dragon). A brief description of the device is provided here for completeness and follows prior descriptions very closely [5]. With the exception of the flexible hose, all components of the apparatus were constructed from stainless steel (0.8 mm in thickness). Two propane burners were used to ignite the fuel (tree mulch) to generate firebrands. Recently, an improved Continuous Feed Firebrand Generator has been developed that is capable of generating firebrand showers of unlimited duration [7]. This device was not used for the present experiments because: (1) industry was interested in a direct comparison to the experiment protocols used for the Spanish tile roofing assemblies to those described here, (2) the batch-feed version of the Firebrand Generator, shown in Figure 1, was far less expensive to operate and provided a simple cost-effective tool to determine if further work is required (*i.e.* if firebrand penetration and melting of sarking occurred).

The bottom panel in Figure 1 displays the procedure for loading the Norway Spruce (*picea abies Karst)* tree mulch into the apparatus. Norway Spruce (*picea abies Karst)* was chosen because it belongs to the *Pinaceae* family, which includes such species as Ponderosa Pine (*Pinus Ponderosa)* and Douglas-Fir *(Pseudotsuga menziesii)*; a common conifer species found in the USA, Japan, Australia, and elsewhere. The mulch for the Firebrand Generator was produced from 6.0 m tall Norway Spruce trees.

The mulch pieces were deposited into the firebrand generator by removing the top portion of the apparatus The mulch pieces were supported using a stainless steel mesh screen (0.35 cm spacing). Two different screens were used to filter the mulch pieces prior to loading into the firebrand generator. The first screen blocked all mulch pieces larger than 25 mm in diameter. A second screen was then used to remove all needles from the mulch pieces. The reason for this filtering procedure is described below. The mulch loading was fixed at 2.8 kg.

After the Norway Spruce tree mulch was loaded into the Firebrand Generator, the top section of the Firebrand Generator was coupled to the main body of the apparatus (see Figure 1). The blower was then switched to provide a low flow for ignition (1.0 m/s flow inside the duct measured upstream of the wood pieces). The two propane burners were then ignited individually and simultaneously inserted into the side of the generator. Each burner was connected to a 0.635 cm diameter copper tube with the propane regulator pressure set to 344 kPa at the burner inlet; this configuration allowed for a 1.3 cm flame length from each burner [5]. The Norway Spruce mulch was ignited for a total time of 45 s. After this period, the fan speed of the blower was increased to 2.0 m/s for the flow inside the duct, measured upstream of the wood pieces. The principle behind the operation of the apparatus was rather simple; after ignition, the mulch would begin to burn and the density decreased at which point the low air flow passing through the support mesh was able to loft the burning mulch and force it to exit the device as firebrands at low velocity. The timing and fan blower speed timing was developed to produce glowing rather than flaming firebrands. [5].These procedures were used to generate a continuous flow of glowing firebrands for approximately six min duration. Manzello *et al.* [5] have shown that the firebrands produced using these filtering and ignition procedures generate firebrands with mass up to 0.2 g and surface area up to 1000 mm^2. This is within the range of firebrands generated from burning conifer species (Douglas-Fir and Korean Pine Trees) [8-9].

2.2 Fire Research Wind Tunnel Facility (FRWTF), Building Research Institute (BRI), Japan

The NIST Firebrand Generator was installed inside the test section of the FRWTF at BRI (see Figure 2) in Japan. The facility was equipped with a 4.0 m diameter fan used to produce the wind field and was capable of producing up to a 10 m/s wind flow. The uniformity of the wind flow velocity distribution was verified using a 21 point hot wire anemometer array. The array was translated across the entire 15 m test section to map out the flow distribution. The flow was uniform (within 10 %) across the entire length of 15 m test section [3].

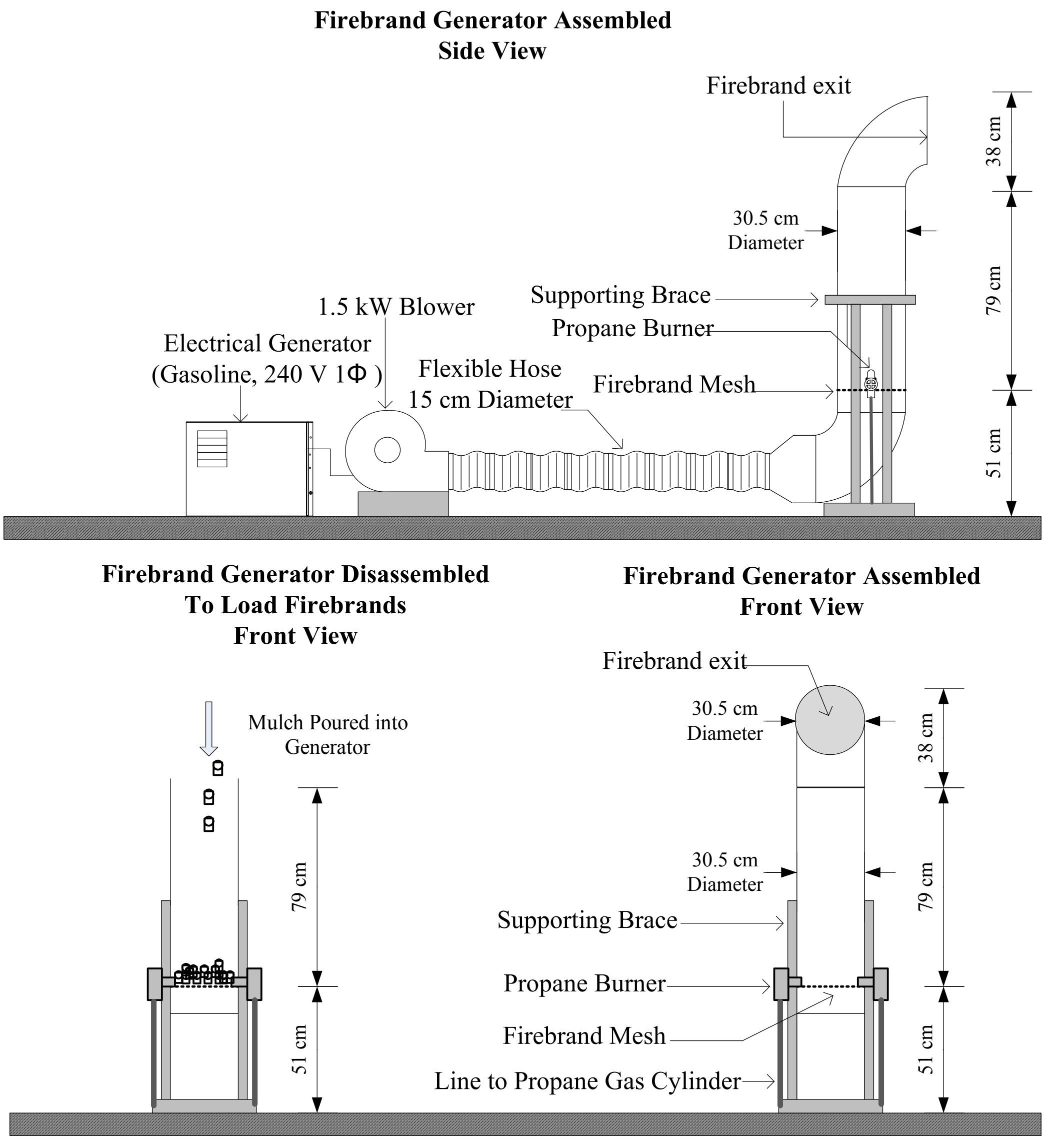

Figure 1. Schematic drawings of the NIST Firebrand Generator (NIST Dragon). The Top Panel Shows the Side View of the Assembled Firebrand Generator and the Bottom Panel Shows Front Views of the Firebrand Generator Disassembled to Load Firebrands (left side of panel) and the Assembled Firebrand Generator (right side of panel).

To determine the average total firebrand mass flux generated by the NIST Firebrand Generator, experiments were conducted to collect the generated firebrands from the device using an array of water filled pans. Water was necessary to quench combustion of the generated firebrands [5]. The firebrands were subsequently removed from the water pans, dried, and the total mass generated over 6 min duration from the device was determined; more details regarding the drying procedure are available elsewhere [5]. Based on these measurements, an average total firebrand mass flux of 10 g/m^{2}s was directed by the NIST Dragon at the roofing assemblies at a wind speed of 9 m/s. It is important realize the all the generated firebrands that depart the mouth of the NIST Firebrand Generator do not land on the surface of the roofing assemblies. The average total firebrand mass flux arriving at the roofing assembly was estimated from video records to be 0.3 g/m^{2}s. Approximately 60 % of the firebrand mass generated from the Firebrand Generator arrived at the roofing assembly surface

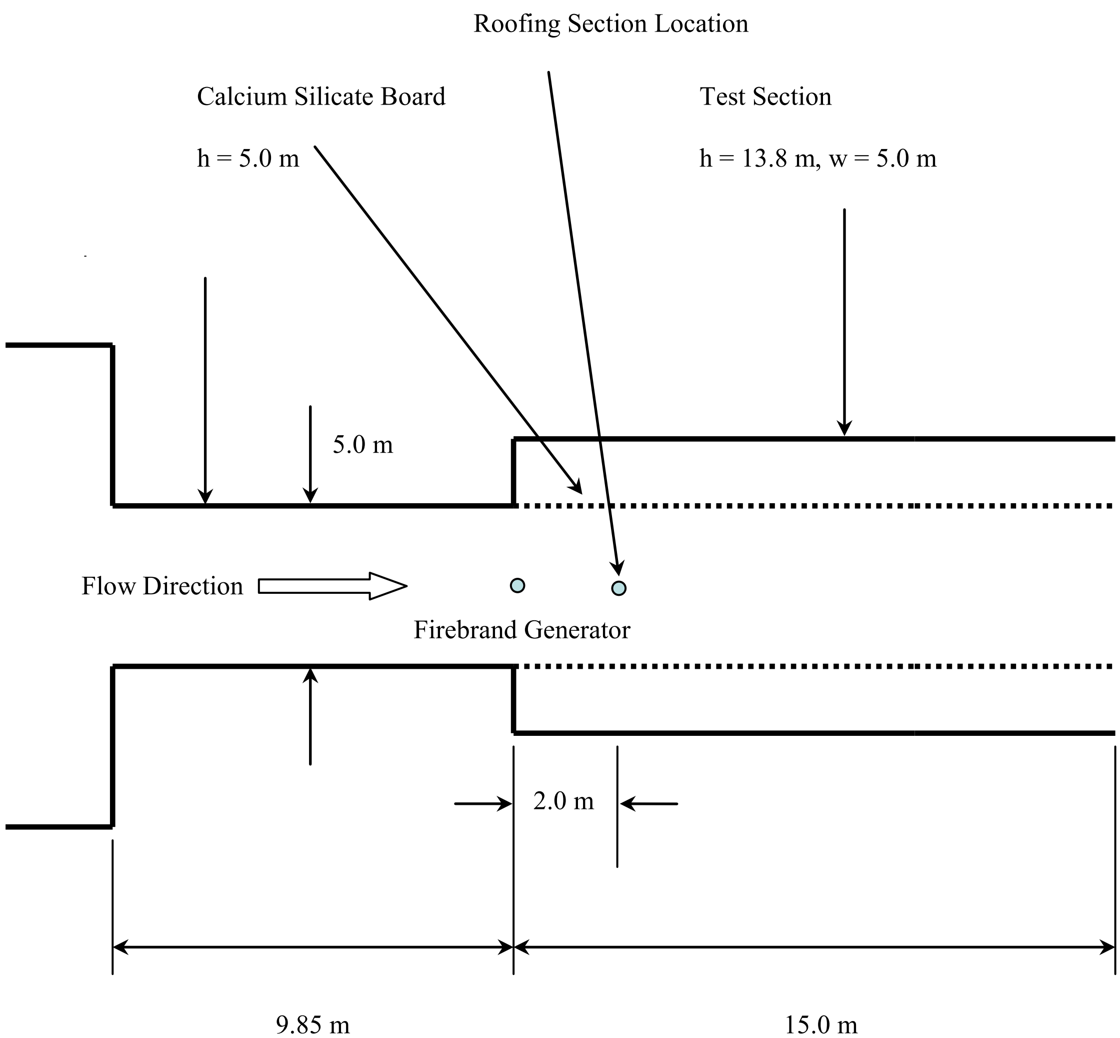

Figure 2. Schematic of BRI's Fire Research Wind Tunnel Facility (FRWTF).

2.3 Concrete Tile and Terracotta Tile Roofing Assemblies

A custom assembly was constructed to mount the tile roofing assemblies. In all experiments, the tile roofing assemblies were mounted 2.0 m downstream of the NIST Firebrand Generator (see Figure 2); the same location as used by Manzello *et al*. [5]. In these experiments, no decking was included in the supporting structure as these experiments were intended to replicate Australian construction details. Underlayment (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 batten spacing was adjusted depending on the type of ceramic or terracotta tile roofing assembly being tested. A photograph of the custom assembly for the experiments is shown in Figure 3. The sarking (green material) as well as the battens used to support the tiles are clearly visible in the figure. Figures 4-8 display the four types of tile roofing assemblies tested, including two concrete tile roofing assemblies (flat and profiled tiles) as well as two terracotta tile roofing assemblies (flat and profiled tiles). The differences between the flat and profiled tiles are obvious in the images. A 25 degree pitch was used for all roofing assemblies. The overall dimensions of each roof assembly were 1.2 m by 1. 2 m. The flat terracotta tiles had an interlocking design. The tile roofing assemblies were constructed in an attempt to have uniform gaps across the tiles.

Figure 3. Custom Assembly used to Mount the Various Tile Roofing Assemblies. The Sarking (green material) as well as the Battens used to Support the Tiles are Clearly Visible. In this Picture the Batten Spacing was Adjusted for Terracotta Tiles (flat tiles).

Figure 4. 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.

Figure 5. Concrete Tile Roofing Assembly (flat tile) Exposed to Wind-Driven Firebrand Showers. The Dimensions of Each Tile were 420 mm long by 329 mm wide. The Height, from the Wind Tunnel Floor to the Base of the Gutter of Roof Deck was 1250 mm.

Figure 6. Terracotta Tiles Roofing Assembly (flat tile) Exposed to Wind-Driven Firebrand Showers. The Dimensions of Each Tile were 425 mm long by 265 mm wide. The Height, from the Wind Tunnel Floor to the Base of the Gutter of Roof Deck was 1250 mm.

Figure 7. Terracotta Tile Roofing Assembly (profiled tile) Exposed to Wind-Driven Firebrand Showers. The Dimensions of Each Tile were 423 mm long by 265 mm wide. The Height, from the Wind Tunnel Floor to the Base of the Gutter of Roof Deck was 1250 mm.

3.0 Results

A total of four experiments (all under the same wind tunnel speed of 9 m/s) were conducted. WUI fires in the USA and bushfires in Australia have been observed to occur under wind speeds in excess of 20 m/s [10]. A wind tunnel speed of 9 m/s was selected for these scoping experiments, because this is near the upper limit of the FRWTF. A typical experiment is shown in Figure 8 for terracotta tile roofing assembly (flat tile). The results shows that, for both types of concrete tiles (flat and profiled), firebrands were observed to accumulate in the gaps of the tiles. The firebrands continued to burn until they were able to penetrate the tile gaps and the underlayment (sarking) was observed to melt. Figure 9 displays burn patterns present in the sarking for experiments conducted for profiled concrete tiles. The tile gaps are on the order of 3 mm. Penetration of the tile gaps was not a surprise as prior work by Manzello *et al*. [11] observed firebrands penetrating a 1 mm wire mesh.

Figure 8. Typical Experiments Exposing Terracotta Tile Roofing Assembly (flat tiles in this image). The Wind Tunnel Speed was 9 m/s and the Roofing Assembly was Located 2.0 m from the NIST Dragon. The Average Total Firebrand Mass Flux was 10 g/m^2s.

The terracotta tile roofing assembly constructed of profiled tiles (no interlocking) performed similarly to both types of concrete tiles used; namely firebrands were observed to penetrate the tiles and melt the sarking. For the terracotta tile roofing assembly (flat tile), these tiles are interlocked, and it was observed that, after the firebrands penetrated the tile gaps, the firebrands were trapped within the interlocking between the tiles so essentially no penetration was observed onto the underlayment (sarking – see Figure 10).

Figure 9. Images of Sarking Placed Under Concrete Tiles (profiled tile) Taken Immediately after the Experiment was Completed. The Tiles have been Removed.

Figure 10. Photograph of sarking placed under terracotta tiles (flat tiles) taken immediately after the experiment was complete. The tiles have been removed. No firebrand penetration was observed.

4.0 Discussion

A series of scoping experiments were conducted to expose concrete and terracotta tile roofing assemblies to wind-driven firebrand showers with an average mass flux of 10 g/m^{2}s at a wind speed of 9 m/s. The firebrands were generated using a batch-feed version of the NIST Firebrand Generator, which provided about 6 min of firebrand showers. In all experiments, the tile roofing assemblies were placed 2.0 meters downstream of the firebrand generator. The results showed that firebrands can penetrate a profiled terracotta tile roofing assembly and a (flat and profiled tile) concrete tile roofing assembly and melt the underlying sarking material. For a flat terracotta tile roofing assembly, these tiles are interlocked, and it was observed that, after the firebrands penetrated the tile gaps, the firebrands were trapped within the interlocking between the tiles, so essentially no firebrand penetration to the underlayment was observed.

These experiments were conducted with the roofing assemblies installed by the manufacturer. This may be a best-case scenario because in realistic applications the gaps between tiles may change with time due to earthquakes, settling of the structure, aging of the roof, or other possible reasons. Manzello *et al*. [5] simulated this effect and observed greatly reduced performance of roofing assemblies as compared to well-aligned Spanish tile roofing assemblies. In these experiments, the sarking material was observed to melt, yet full penetration of the sarking material by glowing firebrands was not observed. This is important because penetration by burning firebrands could ignite materials below the sarking, such as fine fuels found in attic spaces, as shown by Manzello *et al*. [11]. In addition, it was also not possible to conduct experiments for wind speeds larger than 10 m/s. Wind speeds in excess of 20 m/s, however, have been observed in real WUI fires and bushfires [10]. Manzello *et al*. [12] quantitatively showed that the surface temperature of glowing firebrands increased as the applied airflow was increased. In that work, building materials were observed to ignite under higher applied airflows, as compared to no ignition observed for lower applied airflows. Specifically, firebrand temperatures were observed to increase from 550 °C at an applied wind speed of 1.3 m/s to 675 °C when the wind speed was increased to 2.4 m/s [12]. The duration of an actual WUI fire firebrand attack may be longer than the one simulated in this study, which would result in the tile roofing assembly being exposed to a greater number of firebrands, increasing the probability that a greater number of firebrands would deposit under the tiles. If the wind speed was higher, the temperature of the firebrands could be higher as compared to the present experiments, providing even more favorable conditions to melt and ultimately penetrate the sarking by melting the thin aluminum foil backing of this material (as Al has a melting temperature of 660 °C and glowing firebrand temperatures have been shown to exceed that [12]).

5.0 Summary

Concrete tile roofing assemblies (flat and profiled tile) 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 with an average mass flux of 10 g/m^{2}s at a wind speed of 9 m/s. The purpose of these scoping experiments was to determine if firebrands were able to penetrate the tile assemblies and melt the sarking material. 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. The flat tile terracotta roofing assembly performed best probably 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 transported past the tiles towards the sarking material.

Based on the findings of these experiments, a potential cost-effective mitigation strategy would be to use a continuous underlayment of firebrand-resistant sarking. Clearly, full-scale experiments are required to observe vulnerabilities of structural components to wind-driven firebrand showers and, yet bench scale test methods afford the capability to evaluate firebrand resistant technologies such as firebrand resistant sarking. The bench scale Dragon's LAIR (Lofting and Ignition Research) facility, described in detail elsewhere [13], is a unique experimental platform to evaluate sarking material performance to wind-driven firebrand showers. Once promising technologies are identified, full scale tests, similar to those described in this paper, could be conducted to test the performance to provide firebrand resistant tile roofing assemblies.

6.0 Acknowledgements

This work was funded by the US Tile Roofing Institute (TRI). TRI partnered with the Roofing Tile Association of Australia (RTAA) and sent two RTAA members to Japan to construct all the roofing assemblies used in these experiments. As these experiments were not covered under the BRI/NIST agreement, BRI's FRWTF facility was rented for this work. The assistance of Dr. Yoshihiko Hayashi in arranging the rental is appreciated. The technicians of the NIST's National Fire Research Laboratory (NFRL) are acknowledged for preparing the shipment of the NIST Dragon to Japan.

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