Using the NIST Dragon to Quantify Structure Vulnerabilities to Ignition from Firebrand Showers

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Abstract— **Until recently, attempting to experimentally quantify the vulnerabilities of structures to ignition from firebrand showers has remained elusive. The coupling of a two unique facilities has begun to unravel this difficult problem. The NIST Firebrand Generator (NIST Dragon) is an experimental device than can generate a firebrand shower in a safe and repeatable fashion. Since wind plays a critical role in the spread of WUI fires in the USA and urban fires in Japan, NIST has established collaboration with the Building Research Institute (BRI) in Japan. BRI maintains one of the only full scale wind tunnel facilities in the world designed specifically for fire experimentation; the Fire Research Wind Tunnel Facility (FRWTF). The coupling of the NIST Firebrand Generator and BRI's FRWTF is leading to progress in accessing vulnerabilities of structures to a firebrand attack. A brief summary of key results to date using the NIST Dragon installed in the FRWTF are provided in this paper as well as a description of the newly developed NIST Dragon's LAIR (Lofting and Ignition Research) facility. The Dragon's LAIR is the only experimental facility capable of simulating wind driven firebrand showers at reduced scale.**

Keywords-Firebrands; Wildland-Urban Interface (WUI) Fires

I. INTRODUCTION

Structure ignition in the Wildland-Urban Interface (WUI) is a significant international problem with major WUI fires reported in Australia, Greece, Portugal, Spain, and the USA. There have been three significant WUI fires within the past six years in the State of California in the USA. The recent fires in Victoria, Australia in 2009 have resulted in over 150 deaths and more than three thousand destroyed structures.

Evidence suggests that wind driven firebrand showers are a major cause of structural ignition in Wildland-Urban Interface (WUI) fires in the USA and Australia [1-3]. Japan has been plagued by structural ignition from firebrand showers in urban fires. Building codes and standards are needed to guide construction of new structures in areas known to be prone to these fires in order to reduce the risk of structural ignition in the event of a firebrand attack. Proven, scientifically based retrofitting strategies are required for homes located in areas prone to such fires. To meet these objectives requires knowledge regarding the types of materials that can be ignited by firebrands as well as vulnerable points on a structure where firebrands may easily enter.

It is difficult to develop measurement methods to replicate wind driven firebrand bombardment on structures that occur in actual WUI and urban fires. Entirely new experimental approaches are required to address this problem. Past firebrand studies have focused on understanding how far firebrands fly (spotting distance); these studies do not assess the vulnerabilities of structures to ignition from firebrand attack [4-15].

In order to do this, a unique experimental apparatus, known as the NIST Firebrand Generator, has been constructed to generate controlled and repeatable firebrand showers. Since wind plays a critical role in the spread of WUI fires in the USA and urban fires in Japan, NIST has established collaboration with the Building Research Institute (BRI) in Japan. BRI maintains one of the only full scale wind tunnel facilities in the world designed specifically for fire experimentation; the Fire Research Wind Tunnel Facility (FRWTF). The coupling of the NIST Firebrand Generator and BRI's FRWTF is leading to progress in accessing vulnerabilities of structures to a firebrand attack [16-19]. A brief summary of key results to date are delineated in this paper as well as a description of the newly developed NIST Dragon's LAIR (Lofting and Ignition Research) facility. The Dragon's LAIR is the only reduced scale experimental facility capable of simulating wind driven firebrand showers at reduced scale.

II. NIST FIREBRAND GENERATOR (NIST DRAGON)

Figure 1 is a drawing of the NIST Firebrand Generator. A brief description of the device is provided here since a detailed description has been provided elsewhere [16-19]. This version of the device was scaled up from a first-generation, proof-of-concept Firebrand Generator [20]. The bottom panel displays the procedure for loading tree mulch into the apparatus. Tree mulch is used as the fuel source to generate firebrands (details follow below).

The mulch pieces were deposited into the Firebrand Generator by removing the top portion. The mulch pieces were supported using a stainless steel mesh screen (0.35 cm spacing), which was carefully selected. 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 justification for this filtering methodology is provided below. The maximum mulch loading possible with the current Firebrand Generator design is 2.8 kg. The firebrand generator was driven by a 1.5 kW blower that was powered by a gasoline electrical generator. The gasoline electric generator provided the blower with the necessary power requirements.

After the tree mulch was loaded, the top section of the Firebrand Generator was coupled to the main body of the apparatus. The blower was then switched to provide a low flow for ignition. The two propane burners were then ignited individually and simultaneously inserted into the side of the generator. This sequence of events was selected in order to generate a continuous flow of glowing firebrands for up to six minutes duration.

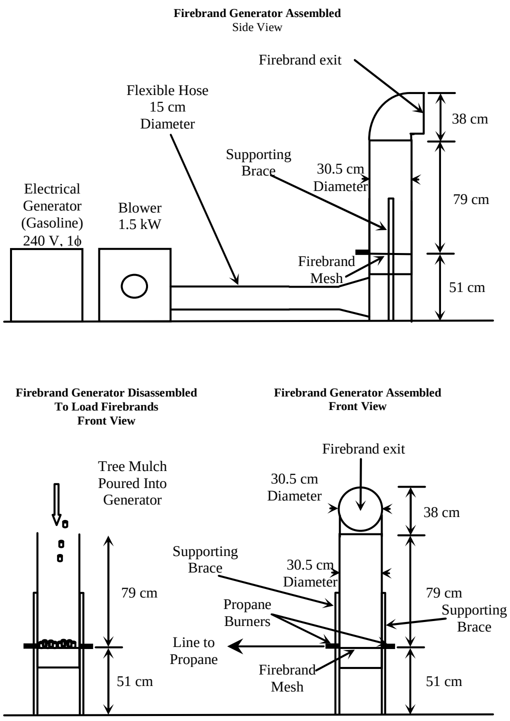

Figure 1 Schematic of NIST Firebrand Generator.

The Firebrand Generator was installed inside the test section of the FRWTF at BRI. Figure 2 displays a layout of the facility. The facility was equipped with a 4.0 m fan used to produce the wind field and was capable of producing up to a 10 m/s wind flow. The wind flow velocity distribution was verified using a hot wire anemometer array. To track the evolution of the size and mass distribution of firebrands produced, a series of water pans was placed downstream of the Firebrand Generator. Depending on the structure vulnerability to be tested, different assemblies were placed downstream of the Firebrand Generator (mock structures, roofing assemblies, etc.).

The Firebrand Generator was designed to produce firebrands characteristic to those produced from burning trees. Prior to designing the Firebrand Generator, Manzello *et. al.* [21-22] conducted a series of experiments quantifying firebrand production from burning trees (see Figure 3). In that work, an array of pans filled with water was used to collect the firebrands that were generated from the burning trees. The firebrands were subsequently dried and the sizes were measured using calipers and the dry mass was determined using a precision balance. Based on the results of two different tree species of varying crown height and moisture content (Douglas-Fir Trees and Korean Pine Trees) burning singly under no wind, cylindrical firebrands were observed to be produced. It was observed that more than 85 % of the firebrands produced from trees were less than 0.4 g [21-22]. Therefore, the filtering procedure for tree mulch used in the Firebrand Generator was selected to produce firebrands with size/mass distributions commensurate to those measured from burning trees.

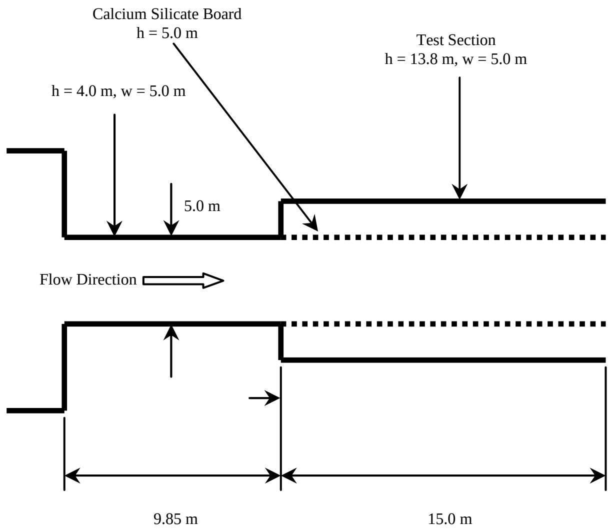

Figure 2 Schematic of FRWTF.

Figure 3 Photograph of a burning Douglas-Fir tree (5.2 m) used for firebrand collection.

III. ROOFING VULNERABILITIES

An experimental campaign was conducted to investigate the vulnerabilities of ceramic tile roofing assembles to ignition under a controlled firebrand attack using the NIST Firebrand Generator. Although current standards exist (*e.g.* ASTM E108 [23]) 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 firebrands landing under ceramic tiles/gaps as a function of time is not taken into account. A summary of these findings follows; further details regarding these experiments are provided elsewhere [18].

When new, ceramic tile roofing assemblies are constructed by placing a base layer of oriented strand board (OSB), then tar paper (TP) is installed on top of the OSB for moisture protection, and finally ceramic tiles (CT) are applied. Aged or weathered ceramic tile roofing assemblies were simulated by not installing tar paper. For simulated aged ceramic tile roof assemblies, without the installation of bird stops, the firebrands were observed to be blown under the ceramic tiles (see Figure 4). Bird stops, as the name suggests, are intended to mitigate the construction of nests by birds under the ceramic tiles. Eventually, several firebrands would collect and would produce smoldering ignition (SI) within the OSB base layer. With continued application of the airflow, holes were formed within the OSB and eventually the SI would transition to flaming ignition (FI). Simulated aged ceramic tile roof assemblies, with bird stops installed, were also constructed for testing. Even though bird stops were installed, many firebrands were able to penetrate the gaps that exist between the ceramic tiles and the bird stops. These firebrands were observed to produce SI within the OSB base layer; holes were observed in some cases within the OSB base layer. The SI ignition never transitioned to FI when bird stops were applied.

Figure 4 Images of experiments conducted using OSB/CT without bird stops installed. Intense SI was observed within the OSB base layer and eventually 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 use of tar paper was then used to simulate a newly constructed ceramic tile roof assembly. With the application of tar paper, experiments were conducted first without bird stops installed. Once again, firebrands were blown under the ceramic tiles. The firebrands were able to burn several holes within the tar paper and produced SI within the OSB base layer. The SI was not intense enough to result in the production of holes within the OSB base layer. Tests were then conducted that considered the application of tar paper with bird stops installed. These conditions resulted in no ignition in the tar paper and thus no ignition within the OSB layer.

The influence of dried pine needles and leaves accumulating under the ceramic tiles was subsequently considered. Even when bird stops were installed, as ceramic tile roof assemblies were exposed to the elements over time, the deposition of dead needles and leaves under the tiles would be expected. The result, summarized above, namely that the combination of the bird stop installation coupled with the tar paper application provided a barrier to ignition, does not hold true if dead needles and leaves were placed under the tiles. If needles and leaves are deposited under the tiles, ceramic tile roofing assemblies are ignitable under all conditions considered in this study.

All of the experiments summarized above considered perfectly aligned roofing tiles. As ceramic tile roof assemblies age, the tile alignment does not remain so closely spaced. In fact, large gaps develop within the tiles themselves leading to openings where firebrands may enter and accumulate. To quantify this vulnerability, a final series of experiments were conducted where the ceramic tiles were not fit together perfectly. Due to the presence of gaps within the tiles, ignition under the tiles within the OSB base layer was observed: (1) whether or not bird stops were installed, (2) whether or not tar paper was installed. This result is somewhat obvious and suggests that when gaps exist within the alignment of the ceramic tiles, ignition of the assembly is rather easy. The application of dead needles and leaves was not even considered with gaps present in the ceramic tiles as this would only compound the vulnerabilities to ignition. These results are the first ever experiments to ascertain the vulnerabilities of ceramic tile roofing assemblies.

IV. BUILDING VENT VULNERABILITES

The Firebrand Generator has been used to study the penetration of firebrands into building vents [16]. The WUI California Building Standards intended to mitigate firebrand penetration through building vents by recommending a mesh size of 6 mm motivated that study (this mesh size was not based on scientific testing) [24]. Recently, an investigation aimed at extensively quantifying firebrand penetration through building vents using full scale tests at BRI was completed. In these experiments, six different mesh sizes were considered as well as four different types of ignitable material placed inside the structure, behind the mesh. Mesh size was varied to determine if mesh alone can retard firebrand penetration into building vents. A summary of these findings follows as a detailed discussion is provided elsewhere [19].

The overall dimensions of the target structure, placed 7.5 m downstream of the NIST Dragon, were 3.06 m in height, 3.04 m in width, and 3.05 m in depth. The structure was constructed of calcium silicate (non-combustible) board. A generic building vent design, consisting of only a frame fitted with a metal mesh, was used. The vent opening was fitted with six different types of metal mesh: 4 x 4 mesh x 0.65 mm wire diameter, 8 x 8 mesh x 0.43 mm wire diameter, 10 x 10 mesh x 0.51 mm wire diameter, 14 x 14 mesh x 0.23 mm wire diameter, 16 x 16 mesh x 0.23 mm wire diameter, and 20 x 20 mesh x 0.23 mm wire diameter. These mesh sizes corresponded to opening sizes of: 5.72 mm (4 x 4), 2.74 mm (8 x 8), 2.0 mm (10 x 10), 1.55 mm (14 x 14), 1.35 mm (16 x 16), and 1.04 mm (20 x 20). Mesh was defined, per the manufacturer, as the number of openings per 25.4 mm (1”).

Behind the mesh, four different materials were placed to ascertain whether the firebrands that were able to penetrate the building mesh assembly could ignite these materials. The materials were shredded paper, cotton, crevices constructed with oriented strand board (OSB) and wood (to form 90° angle). For the crevice tests, experiments were conducted with the crevice filled with or without shredded paper. The purpose of using the crevice was to determine if firebrands that penetrated the mesh were able to ignite building materials. Paper in the crevice was intended to simulate fine fuel debris.

For the full scale tests, the wind tunnel speed was fixed at 7 m/s (± 10 %). The velocity behind the mesh varied from 7 m/s (4 x 4 mesh; 5.72 mm opening) to 5 m/s (20 x 20 mesh; 1.04 mm opening). The uncertainty in these measurements is ± 10 %.

Three repeat experiments were conducted for each of the four ignitable materials considered and the results are tabulated in Table 1. The acronyms in the table are as follows: NI – no ignition; SI – smoldering ignition; FI – flaming ignition.

Mesh	Paper	Cotton	Crevice	Crevice with paper
4 x 4 (5.72 mm)	SI to FI	SI	SI	SI to FI (paper) SI (OSB)
8 x 8 (2.74 mm)	SI to FI	SI	SI	SI to FI (paper) SI (OSB)
10 x 10 (2.0 mm)	SI to FI	SI	NI	SI to FI (paper) (SI OSB)
14 x 14 (1.55 mm)	SI	SI	NI	SI (paper) SI (OSB)
16 x 16 (1.35 mm)	SI	SI	NI	NI
20 x 20 (1.04 mm)	NI (twice) SI (once)	SI (twice) NI (once)	NI	NI

Table 1 Summary of Ignition Results.

When shredded paper was used, a repeatable SI was observed for all mesh sizes up to 16 x 16 (1.35 mm). As for the smallest mesh size tested (20 x 20) (1.04 mm), SI was observed in only one experiment out of three. For cotton, the ignition behavior was similar for all mesh sizes. The firebrands would deposit into the cotton bed and simply burn holes into the cotton.

The bare wood crevice experiments resulted in SI in the OSB layer for the 4 x 4 (5.72 mm) and 8 x 8 (2.74 mm) mesh sizes. As the mesh size was reduced to 10 x 10 (2.0 mm), the firebrands were not able ignite the bare wood crevices. When the crevices were filled with shredded paper, SI followed by FI occurred in the paper for mesh sizes up 10 x 10 (2.0 mm). The OSB layer was then observed to ignite by SI and subsequently produced a self sustaining SI that continued to burn holes into the OSB. For the smallest mesh sizes tested (16 x 16 and 20 x 20), NI was observed in the paper and consequently NI in the crevice. A photograph of a typical experiment is shown in Figure 5.

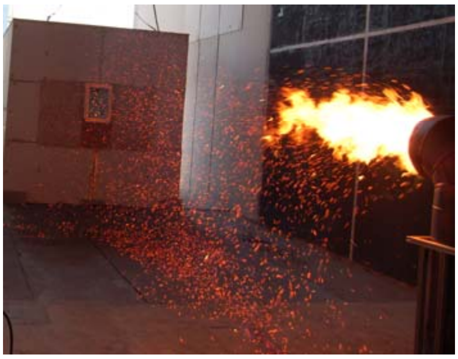

Figure 5 Typical experiment using NIST Firebrand Generator at BRI’s FRWTF. The mesh installed in this experiment was 20 x 20 (1.04 mm), the wind tunnel speed was 7 m/s, and the Firebrand Generator was located 7.5 m from the structure.

These experiments found that firebrands were not quenched by the presence of the mesh and would continue to burn until they were able to fit through the mesh opening, even down to 1.04 mm opening. While mesh size reduction did mitigate ignition of bare wood crevices, the presence of fine fuels would be expected in attic spaces. Firebrand resistant vent technologies are needed.

V. REDUCED SCALE EXPERIMENTS

While full scale tests are necessary to highlight vulnerabilities of structures to firebrand showers, reduced scale test methods afford the capability to test new firebrand resistant technologies and may serve as basis for new standard testing methodologies.

As a result, a new reduced scale experimental facility developed has been developed at NIST. The newly developed facility is known as the NIST Dragon’s LAIR (Lofting and Ignition Research). The NIST Dragon’s LAIR has been developed to simulate a wind driven firebrand attack at reduced scale. The facility consists of a reduced scale Firebrand Generator (Baby Dragon) coupled to a bench scale wind tunnel (test section dimensions of 50 cm in width by 50 cm in height by 200 cm in length). Figure 6 is a schematic of the NIST Dragon’s LAIR (Lofting and Ignition Research) facility. Figure 7 is a photograph demonstrating the testing of a generic building vent assembly using the Dragon's LAIR facility. Details regarding the operation of the facility are provided in [19]. It is important to point out that the Dragon's LAIR was able to reproduce the results obtained from the full scale mesh experiments conducted at BRI (described in section IV)

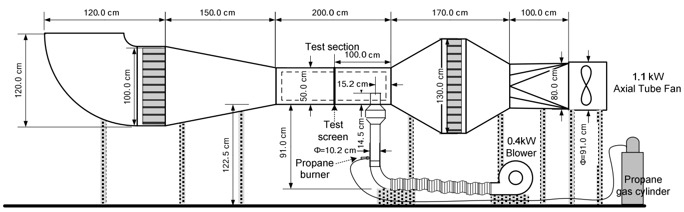

Figure 6 Schematic of Dragon's LAIR Facility. The Baby Dragon (coupled to 0.4 kW blower) as well as the firebrand seeding locating into the wind tunnel are shown.

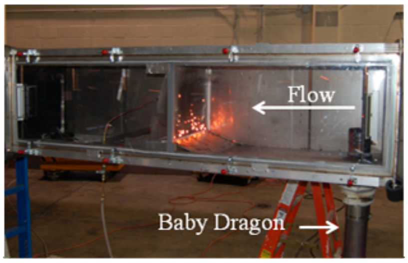

Figure 7 Picture of typical experiment using the Dragon's LAIR. A 14 x 14 (1.55 mm) mesh was being used when this photograph was taken.

VI. SUMMARY

A brief summary of key results to date using the NIST Dragon were provided. For the first time, it is possible to quantify vulnerabilities that structures may have to firebrand showers. Future work using the NIST Dragon will quantify the vulnerabilities of siding treatments and glazing assemblies to firebrand attack. The reduced scale NIST Dragon's LAIR facility is a powerful tool with the capability to test new firebrand resistant technologies and serve as the basis for new standard testing methodologies. Reduced scale experiments will allow may different types of firebrand resistant technologies to be tested and the performance of these technologies can then be verified using full scale testing.

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REFERENCES

[1] Mitchell JW, Patashnik O (2007) 'Firebrand Protection as the Key Design Element for Structural Survival During Catastrophic Wildfire Fires.' *In Proceedings of the 10th International Conference on Fire and Materials Conference*, San Francisco, CA.

[2] Blanchi R, Leonard JE, Leicester RH (2006) 'Lessons Learnt from Post-Fire Surveys at the Urban Interface in Australia.' *In Proceedings of the Fifth International Conference on Forest Fire Research*, Figueria da Foz, Portugal.

[3] Maranghides A, Mell WE, *NIST TN 1635*, April (2009).

[4] Albini F (1983) Combustion Science and Technology 32, 277-288.

[5] Muraszew A, Fedele JF (1976) 'Statistical Model for Spot Fire Spread.' The Aerospace Corporation Report No. ATR-77758801 (Los Angeles, CA).

[6] Tarifa CS, del Notario PP, Moreno, FG (1965) *Proceedings of the Combustion Institute* 10, 1021-1037.

[7] Albini F (1983) Combustion Science and Technology 32, 277-288.

[8] Muraszew A, Fedele JF (1976) 'Statistical Model for Spot Fire Spread.' The Aerospace Corporation Report No. ATR-77758801 (Los Angeles, CA).

[9] Tarifa CS, del Notario PP, Moreno, FG (1965) *Proceedings of the Combustion Institute* 10, 1021-1037.

[10] Tse SD, Fernandez-Pello AC (1998) *Fire Safety Journal* 30, 333-356.

[11] Woycheese JP (2000) Ph.D. Thesis, University of California, Berkeley.

[12] Knight IK (2001) *Fire Technology* 37, 87-100.

[13] Anthenien R, Tse, SD, Fernandez-Pello AC (2006) *Fire Safety Journal* 41, 349-363.

[14] Himoto K, Tanaka, T (2005) Transport of Disk Shaped Firebrands in a Turbulent Boundary Layer. In D.T. Gottuk and B.Y. Lattimer (Eds.) *Fire Safety Science - Proceedings of the Eigth International Symposium* vol. 8, 433-444.

[15] Sardoy N, Consalvi JL, Kaiss A, Fernandez-Pello AC Porterie B (2008) *Combustion and Flame* 154, 478-488.

[16] Manzello SL, Shields JR, Yang JC, Hayashi Y, Nii D (2007) 'On the Use of a Firebrand Generator to Investigate the Ignition of Structures in WUI Fires,' *In Proceedings of the 11th International Conference on Fire Science and Engineering (INTERLFAM)*, Interscience Communications, London, pp. 861-872.

[17] Manzello SL, Shields JR, Hayashi Y, Nii D (2008) Investigating the Vulnerabilities of Structures to Ignition From a Firebrand Attack. In B Karlsson (Ed.) *Fire Safety Science - Proceedings of the Ninth International Symposium* vol. 9, 143-154.

[18] Manzello SL, Hayashi Y, Yoneki Y, Yamamoto Y (2010) *Fire Safety Journal* 45, 35-43.

[19] Manzello SL, Park SH, Shields JR, Suzuki S, Hayashi Y, *NIST TN* 1659, January 2010.

[20] Manzello SL, Shields JR, Cleary TG, Maranghides A, Mell WE, Yang, JC, Hayashi Y, Nii D, Kurita T (2008) *Fire Safety Journal* 43, 258-268.

[21] Manzello SL, Maranghides A, Mell WE (2007) *International Journal of Wildland Fire* 16, 458-462.

[22] Manzello SL, Maranghides A, Shields JR, Mell WE, Hayashi Y, Nii D (2009) *Fire and Materials Journal* 33, 21-31.

[23] Standard Test Methods for Fire Tests of Roof Coverings, ASTM E108, American Society for Testing and Materials, West Conshohocken, PA.

[24] California Code of Regulations, Title 24, Part 9, California Fire Code, Article 8604 B 2.1, Materials and Construction Methods for Exterior Wildfire Exposure, Attic Ventilation.