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ScienceDirect

Procedia Engineering 62 (2013) 91 – 102

Procedia Engineering

www.elsevier.com/locate/procedia

The 9th Asia-Oceania Symposium on Fire Science and Technology

Experimentally simulating wind driven firebrand showers in wildland-urban interface (WUI) fires: Overview of the NIST firebrand generator (NIST dragon) technology

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Abstract

Evidence suggests that wind driven firebrand showers are a major cause of structural ignition in Wildland-Urban Interface (WUI) fires. While firebrands have been researched for over four decades, prior studies have focused mainly on how far firebrands fly and are of limited use to design firebrand resistant structures. The NIST Firebrand Generator (NIST Dragon) is an experimental device that 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 assessing 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 NIST Dragon's LAIR (Lofting and Ignition Research) facility. The Dragon's LAIR is the only experimental facility capable of simulating continuous wind driven firebrand showers at bench scale. In addition, a detailed description of a new experimental apparatus is presented here for the first time. This device is known as the NIST full scale continuous feed Firebrand Generator (the NIST continuous feed Dragon).When installed inside BRI's FRWTF, the full scale continuous feed Dragon, an improvement of the NIST Dragon, is the first and only experimental apparatus capable of generating, continuous wind driven, controlled firebrand showers that may be directed onto full scale building elements. This paper closes with a discussion of future research needs and opportunities for collaboration.

Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology

Keywords: Firebrands; Wildland-urban interface (WUI) fires; Ignition

1. Introduction

Wildland-Urban Interface (WUI) fires have caused significant destruction to communities in Australia, Greece, Portugal, Spain, and the USA. There have been three significant WUI fires in California over the past six years. The 2003 Cedar Fire in California resulted in $2B in insured losses and destroyed more than three thousand homes. The 2007 Southern California Fire displaced more than 300,000 people, destroyed over one thousand structures, and resulted in $1B paid by insurers in 2007 alone [1]. WUI fires continue to burn in the USA; most recently in Texas in 2011 and Colorado in 2012. In 2009, fires in Victoria, Australia caused the death of more than 150 people, destroying more than two thousand structures.

From a pragmatic point of view, the WUI fire problem can be seen as a structure ignition problem [2]. Ignition resistant structures under WUI fire exposure was listed as one of the major recommendations in the USA GAO 2005 report, Technology Assessment: Protecting Structures and Improving Communications During Wildland Fires [3], and was the

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Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology
doi:10.1016/j.proeng.2013.08.047

subject of a Homeland Security Presidential Directive [4]. In spite of these facts, little effort has been spent on understanding the processes of structure ignition in these fires.

As both vegetation and structures burn in WUI fires, pieces of burning material, known as firebrands, are generated, become lofted, and get carried by the wind. This results in showers of wind driven firebrands. Post-fire studies indicate that firebrand showers have been a significant role in the spread of disastrous WUI fires [4-9]. Interestingly, 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 focused on understanding how far firebrands fly, known as spotting distance [10-21]. Few studies have examined firebrand generation [22-24] and the ultimate ignition of materials by firebrands [25-28]. For these reasons, the prior firebrand studies are of limited helpful in designing firebrand resistant structures.

Scientifically based 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. The reason that prior firebrand investigations have not been able to quantify the vulnerabilities of structures to ignition from firebrand showers is that it is difficult to develop a measurement method to replicate wind driven firebrand bombardment on structures that occur in actual WUI. Entirely new experimental approaches are required to address this problem. To address this problem, a new firebrand research area targeted on quantifying structure vulnerabilities to wind driven firebrand showers has been developed by NIST. This type of firebrand research has never possible prior to the development of the Firebrand Generator.

2. NIST firebrand generator (NIST Dragon)

A unique experimental apparatus, known as the NIST Firebrand Generator (NIST Dragon), has been constructed to generate controlled, repeatable firebrand showers commensurate to those measured from burning conifers and a real WUI fire (see Fig. 1). The purpose of the NIST Dragon is to simulate wind-driven firebrand showers observed in long-range spotting; therefore, glowing firebrands were the initial emphasis. Yet, due to careful design of the NIST Dragon, it is also possible to generate flaming firebrand showers. Another 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 and actual WUI fires, 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 has quantified firebrand distributions from a real WUI fire (Angora Fire) for the first time [29].

Since wind plays a critical role in the spread of WUI fires, 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). BRI's FRWTF, constructed in the late 1990s, is one of the first wind tunnel facilities in the world designed specifically with fire experiments in mind. Japan has been plagued by large urban fires, not WUI fires, for many years. Throughout history, due to its geographical location, Japan has been subjected to many earthquakes; after these earthquakes occur, many fires are ignited. As in WUI fires, firebrands are produced as structures burn. In the presence of high winds, these firebrands are dispersed and transported. This, in turn, produces spot fires that result in severe urban fires. The ability to study urban fire spread was one reason why BRI constructed the FRWTF.

Parametric studies have been conducted using the NIST Dragon installed in BRI's FRWTF to expose roofing assemblies, building vents, siding treatments, walls fitted with eaves, and glazing assemblies to wind-driven firebrand showers [30-35]. In addition, the dangers of firebrand accumulation in front of structures have been quantified for the first time. Some key results of how NIST research has helped stakeholders to date are delineated below.

The 2007 California Building Code of Regulations, Title 24, Part 2, Chapter 7A desired to mitigate firebrand penetration through building vents by recommending that a metal mesh of 6 mm be placed behind building vents [36]. Yet, this mesh size was not based on any scientific testing since no test methods were available at that time. It was possible to study the penetration of firebrands into building vents for the first time using the NIST Dragon at BRI's FRWTF. These results showed that firebrands were not quenched by the presence of the mesh and would continue to burn on the mesh until they were small enough to pass through the mesh opening. For the 6 mm mesh, a majority of the firebrands simply flew through the mesh, resulting in more rapid ignition of flammable materials behind the mesh than that observed for the smaller mesh sizes of 3 mm and 1.5 mm.

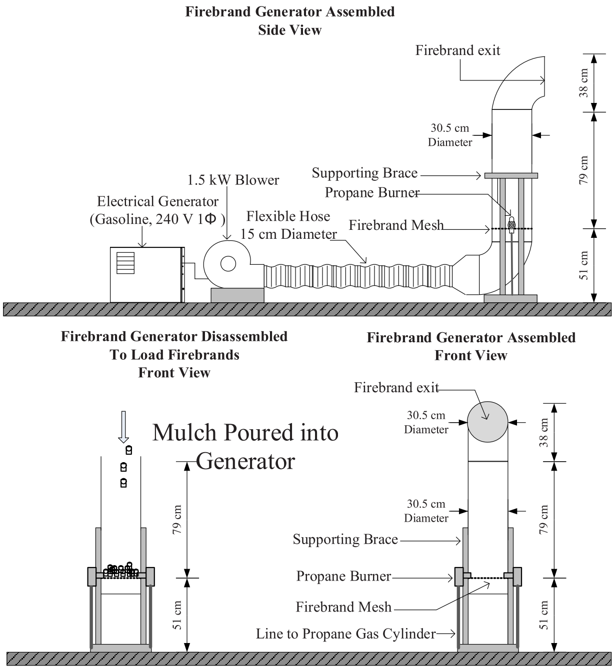

Fig. 1. Schematic of NIST Firebrand Generator (NIST Dragon).

During the 2010 triennial code change cycle in California, no standard test methods were available to evaluate and compare firebrand-resistant vent technologies. Therefore, NIST worked with CALFIRE as part of a task force in order to reduce mesh size used to cover building vent openings to lessen the potential hazard of firebrand entry into structures. These changes were formally adopted into the 2010 California Code of Regulations, Title 24, Part 2, Chapter 7A, and were effective January 2011 [37].

Post-fire studies have observed building ignition mechanism where small firebrands penetrate under non-combustible tile roof covering (Spanish tile roofing). While standards exist 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. Experiments conducted using the NIST Dragon have provided experimental confirmation of this ignition mechanism (see Fig. 2).

Fig. 2. Images of experiments conducted using oriented strand board/ceramic tile (OSB/CT) without bird stops installed [32]. 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.

Firebrand accumulation in front of structures has also been demonstrated using full-scale experiments. If ignitable materials are located in front of structures, it is very easy for firebrands to accumulate and ignite materials. The subsequent ignition of such materials may in fact produce additional firebrands that would lead to even more ignitions near structures. The accumulation of firebrands in front of structures presents a severe threat to homes in the WUI (see Fig. 3).

It is worth noting the NIST Dragon technology has now been reproduced by other research laboratories. Specifically, the Insurance Institute for Business and Home Safety (IBHS) has used the NIST Dragon concept to generate firebrand showers in their full scale wind tunnel facility [38].

Fig. 3. In the image on left side, firebrands have caused smoldering ignition in the mulch bed [35]. In the image on the right side, smoldering ignition has transitioned to flaming ignition and the wall assembly has ignited. The dimensions of the wall assembly were 244 cm by 244 cm.

3. Bench scale experiments – NIST Dragon's LAIR (lofting and ignition research) facility

Full-scale experiments are required to observe the vulnerabilities of structures to firebrand showers, but bench scale test methods afford the capability to evaluate firebrand resistant building elements and may serve as the basis for new standard testing methodologies. To this end, Manzello et al. [33, 34] developed the NIST Dragon's LAIR (Lofting and Ignition Research) facility to simulate wind driven firebrand showers at reduced-scale. This facility consists of a bench scale Firebrand Generator (known as the NIST Baby Dragon) coupled to a bench-scale wind tunnel.

While the NIST Dragon's LAIR facility and the full-scale NIST Dragon coupled to BRI's FRWTF have been used to expose building elements to firebrand showers, the duration of exposure using the existing apparatus is limited. To develop test methods needed to evaluate different building materials resistance to firebrand showers requires the capability to generate firebrand showers of varying duration. To determine if it was feasible to develop a continuous feed Firebrand Generator, it was decided to first improve the bench scale device (baby Dragon).Accordingly, the NIST bench scale continuous feed Firebrand Generator (the NIST continuous feed Baby Dragon) was developed. The unique features of the NIST continuous feed Baby Dragon, over the present NIST Baby Dragon, are the ability to produce a constant firebrand shower in order to expose building materials to continual firebrand bombardment. Suzuki and Manzello [39] characterized the performance of this device. The Dragon's LAIR facility has now been upgraded to include the NIST continuous feed Baby Dragon. The interested reader is referred elsewhere for a very detailed description of the new and improved Dragon's LAIR facility [40]; capability is presented briefly below. For ease of understanding, Fig. 4a-b shows a schematic of the new and improved Dragon's LAIR facility. The NIST continuous feed Baby Dragon has been copied by University of Coimbra – Institute for Interdisciplinary Research, Europe's largest institute focused on WUI fires.

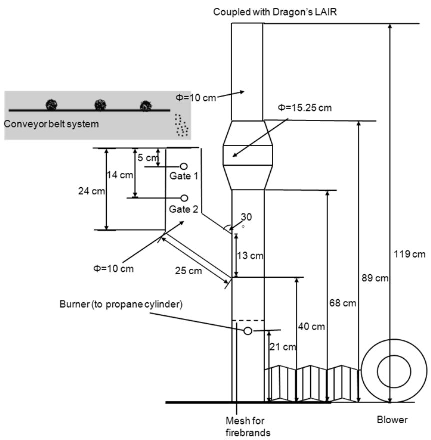

Fig. 4a. Schematic of NIST bench scale continuous feed Firebrand Generator (the NIST continuous feed Baby Dragon) [40].

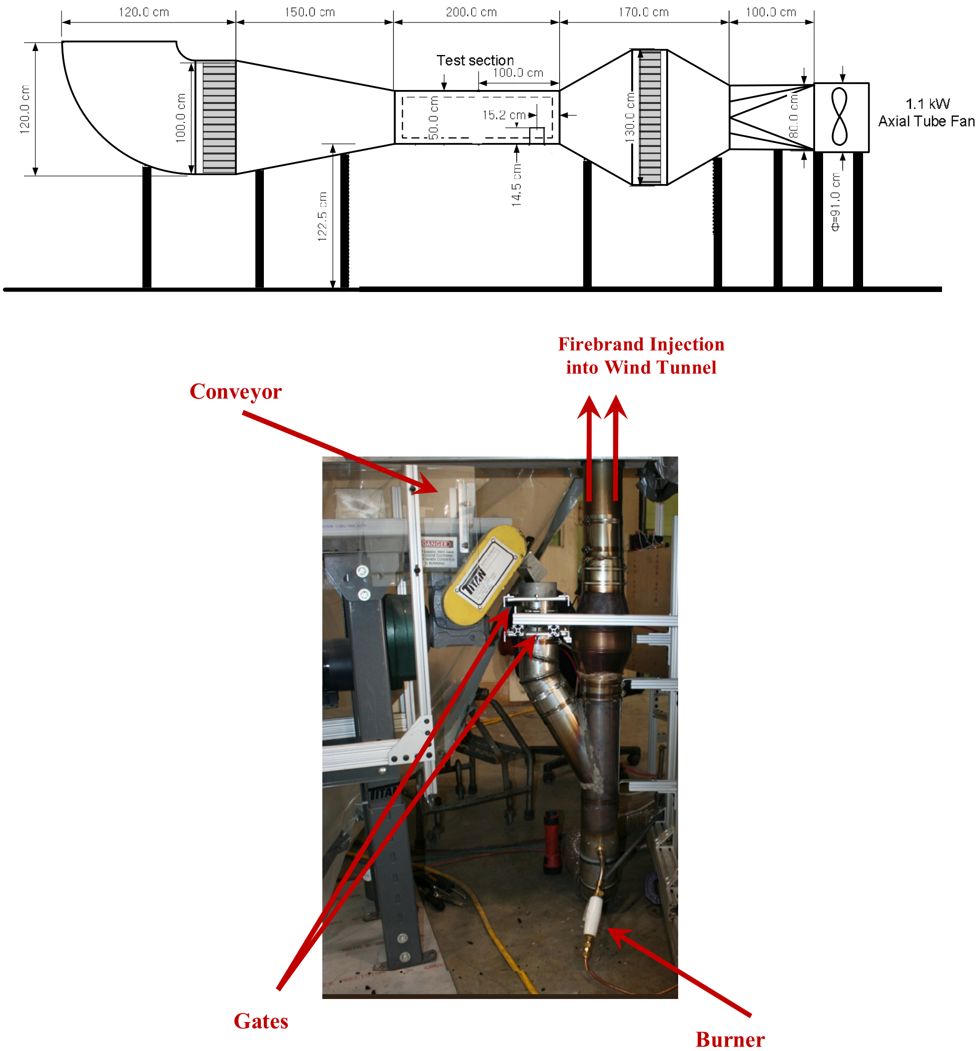

Fig. 4b. New and Improved Dragon's LAIR Facility. The apparatus in Fig. 2a has been coupled to a bench scale wind tunnel to construct the Dragon's LAIR facility [40].

The efficacy of the Dragon's LAIR facility to determine ignition regime maps of building materials exposed to continuous wind driven firebrand showers has been determined. To do this, cedar crevices were constructed for ignition testing. Two pieces of cedar were aligned at an angle of 60 degrees. This angle was selected since consistent ignition behavior has been observed for other building materials ignited by firebrands using this configuration (see [40]). The dimensions of each cedar piece used were 114 mm wide by 448 mm long. These dimensions were selected since the length covered nearly the entire wind tunnel length and the low width allowed for less flow obstruction. Since the cedar used in these experiments is used for siding, each piece was tapered. Specifically, the largest edge thickness was 11 mm and tapered down to 3 mm. Due to the arrangement of the crevice, the thick edge of each cedar piece was offset and this allowed for a nominal thickness of 7 mm at the center of the crevice where ignition (described below) was observed. The cedar pieces were held in place using a custom mounting bracket. The location of the cedar crevice was placed about 760 mm from the exit of the mouth of the NIST continuous feed Baby Dragon. This location was selected simply due to the fact that the firebrands were observed to land within the crevice using the wind speed selected in these experiments (6 m/s). The moisture content of the cedar pieces was varied using an oven. Specifically, experiments were conducted using cedar held at 11% moisture content (dry basis) as well as oven dried). Cedar was selected since it is a common material used for both siding and roofing assemblies.

The experiments were conducted in the following manner. The cedar crevice was placed inside the test section and the door of the test section was then closed. The blower of the NIST reduced scale continuous feed Baby Dragon was set at 4.4 m/s (to generate glowing firebrands) and one propane burner was ignited and inserted into the side of the device. The propane burner was kept on during the entire experiment. The conveyer was then switched on and wood pieces were fed into the stainless-steel pipe first, and then the gate near the conveyer was opened. The gate near the conveyer was then closed, and the other gate was then opened to allow the wood pieces to fall into the Dragon for ignition. Feeding continued for various durations; 5 min, 10 min, until ignition was observed. The experiments were recorded using a digital video recorder (30 frames per second) for subsequent analysis (described below).

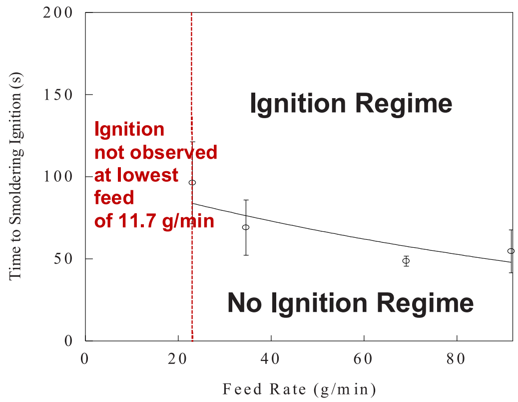

Fig. 5. Ignition regime maps (smoldering ignition) as a function of feed rate for fixed wind tunnel speed (6 m/s) when using dried cedar crevices [40].

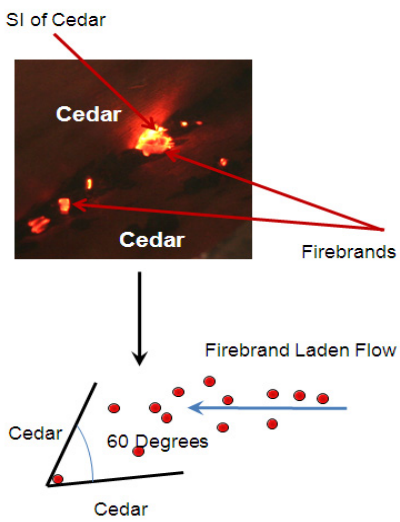

Fig. 6. Picture of smoldering ignition of the cedar crevice [40]. In this image, the cedar was oven dried, the wind tunnel speed was 6 m/s, and the firebrand generation rate was 0.03 g/s (based on a feed of 23.1 g/min).

Five different loadings of wood pieces were used for the ignition studies; 5, 10 15, 30, and 40 pieces. The mean mass for each loading was: 2.4 g for 5 pieces (feed rate of 11.7 g/min), 4.8 g for 10 pieces (feed rate of 23.1 g/min), 7.2 g for 15 pieces (feed rate of 34.6 g/min), 14.4 g for 30 pieces (feed rate of 69.1 g/min), and 19.1 g for 40 pieces (feed rate of 91.7 g/min), respectively. The uncertainty in the mass was 10 %.The number flux, at the exit of the device, was measured as a function of the feed rate. Mass flux data were calculated by multiplying the number flux and the average mass of each firebrand at different feed rates. To measure the firebrand mass, a series of water pans were placed downstream of the NIST Reduced Scale Continuous Feed Baby Dragon after firebrand production reached steady conditions. Water pans were used to quench combustion of the firebrands. If the water pans were not used, the firebrands would continue to burn and by the time collection was completed only ash would remain. These analyses were critical to determine the mass generation rate of firebrands for each feed rate.

Ignition regime maps were determined as a function of feed rate (related to firebrand generation rate) for fixed wind tunnel speed (6 m/s) and two different cedar crevice moisture contents. Results are shown in Fig.5. Ignition delay times were measured from the time the first firebrand was deposited inside the crevice to the observation of smoldering ignition (smoldering ignition, defined as intense glowing combustion within the cedar - see Fig. 6). Three repeat experiments were performed for each feed rate. Each data point represents the average of three experiments (average ± standard deviation). As can be seen, for a given moisture content and wind speed, the ignition delay time was observed to decrease as the feed rate was increased. This work has set the stage to be able to evaluate and compare the resistance to ignition from firebrand showers for the first time.

4. New full scale continuous firebrand generator

Since it was possible to successfully develop the bench scale continuous Firebrand Generator, efforts were undertaken to scale this device up and construct a full scale continuous feed Firebrand Generator. By coupling this device to the Building Research Institute's (BRI) Fire Research Wind Tunnel Facility (FRWTF), the goal is to expose full scale building elements to continuous, wind driven firebrand showers. To this end, the efficacy of this new experimental device to generate continuous wind driven firebrand showers is presented.

Figure 7 is a picture of new full scale continuous Firebrand Generator. This version of the device is modified from the NIST Dragon [30-35] and consisted of two parts: the main body and continuous feeding component. The feeding part was connected to the main body and was equipped with two gates to prevent fire spread (described in more detail below).Each gate was opened and closed alternatively. A blower was connected to the main body and the purpose of the blower is also described below. All components of the Firebrand generator were constructed of stainless steel. A major challenge when constructing this device was designing a completely contained feeding system shielded from the wind tunnel flow. When the bench scale continuous feed baby Dragon was developed and coupled the bench scale wind tunnel to from the Dragon's LAIR, a conveyer was used to feed wood pieces continually into the continuous feed baby Dragon. While this was a simple and elegant feeding strategy, this would not work for the full scale device since the entire apparatus must be exposed to the wind tunnel flow. For the bench scale device, the feeding system is completely external to the wind tunnel (see Fig. 4b).

Figure 8 shows how this challenge was overcome. The feeding system consisted of a pneumatic cylinder coupled to a cylindrical container where wood pieces were stored. The pneumatic cylinder was contained inside a metal sleeve. Inside the metal sleeve, the sliding rod of the pneumatic cylinder was connected to a plate that allowed the volume of wood contained within the sleeve to be varied. This volume was set precisely to allow a specific mass of firebrands to fall into this volume. When the air pressure was applied, the sliding rod of the pneumatic cylinder moved 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 Fig. 9). Care was taken to select the pneumatic cylinder (15 cm bore with 15 cm stroke; maximum pressure of 1.7 MPa and maximum load of 31 kN); smaller sized pneumatic cylinders were observed to be unable to force the wood pieces to the first gate and would jam. The gate system was required to contain the fire from spreading from the Dragon to the feeding system and each was gate was driven by pneumatic cylinders as well. For all tests, Douglas-fir wood pieces machined with dimensions of 7.9 mm (H) by 7.9 mm (W) by 12.7 mm (L) were used to produce firebrands (see Fig. 10).These same size wood pieces were used to feed the bench scale continuous Firebrand Generator in past studies and have been shown to be commensurate with sizes measured from full-scale burning trees, as well as distributions obtained from actual WUI fires [23, 29].

An operational parameter that was varied was the blower speed. When the blower was 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 was supplied for combustion and this resulted in a great deal of smoke being generated in addition to firebrands. Above 3.0 m/s, smoke production was mitigated but then many firebrands produced were in a state of flaming combustion as opposed to glowing combustion. It has been suggested that firebrands fall at or near their terminal settling velocity. As such, when firebrands contact ignitable fuel beds, they are most likely in a state of glowing combustion, not open flaming [13]. 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 glowing firebrands were desired. It was observed that velocity needed to generate glowing firebrands was slightly lower for the full scale device as compared to the bench scale device (in Fig 4a). For the bench scale device, the velocity measured at the exit was 4.4 m/s. These differences are due to the fact that larger pressure drop existed for the full scale device and the fire size was also larger, so firebrands may be lofted in a glowing state under lower velocities.

As in prior experiments using the NIST Dragon, the new experimental device was installed inside BRI's FRWTF. The facility was equipped with a 4.0 m diameter fan to produce the wind field. The cross section of the FRWTF is 5.0 m wide by 4.0 m high. The experimental device was installed inside the test section of the FRWTF to allow firebrands to be carried over a distance of 15.0 m downstream of the device.

The experiments were conducted in the following manner. The wind tunnel speed was set to the desired level (*e.g.* 6 m/s). Wood pieces were first loaded into the cylinder storage container and the air compressor needed to provide compressed air for the pneumatic cylinder and gate system was switched on (air compressor pressure was set to 0.7 MPa).The blower was set at 3.0 m/sand two propane burners were ignited and inserted into the side of the device. The propane burners were kept on continuously during the experiment. The pneumatic piston was then activated and the sliding rod was positioned to allow wood pieces to enter the volume in the metal sleeve. The sliding rod was moved to push the wood pieces (200g) to the first gate. The gate was opened, closed, and the second gate was then opened, and the wood fell into the Dragon. The feeding was varied to determine the optimal conditions. It was observed that 200g, fed into the Dragon every 15 sec provided an adequate firebrand generation rate to ignite building materials. For completeness, 200 g corresponded to approximately 400 wood pieces deposited every 15 sec.

Fig. 7. Full scale continuous feed Firebrand Generator installed in BRI's FRWTF. The device is not producing firebrands at the time of this photograph.

The number flux (number of firebrand generated/m^2s), at the exit of the device, was measured at a feeding rate 200g every 15 sec (800g/min). Time zero was set as the time when the propane burners were inserted into the generator. To determine the number flux, the number of firebrands was counted at every frame of the video recording, summed up every second, and then summed up again at every ten seconds. Based on the analysis, the number flux reached a steady value of 342. 0/m^2s at a time of 300 sec after feeding began. The first firebrands began to be generated after ~ 100 sec after feeding was commenced.

Mass flux data (mass of firebrands generated/m^2s) were calculated by multiplying the number flux and the average mass of each firebrand at a feeding rate of 200g every 15 sec. To measure the firebrand mass, a series of water pans were placed downstream of the NIST full scale continuous feed Firebrand Generator. Water pans were required in order to quench combustion of the firebrands. If the water pans were not used, the firebrands would continue to burn and by the time collection was completed; only ash remained. After the experiment was finished, the pans were collected and the firebrands were filtered from the water using a series of fine mesh filters. Firebrands were dried in an oven, at 104 °C, for 16 hours. As in previous work, the mass versus drying time was monitored to determine the duration need to completely dry the firebrands. The mass and dimension of each firebrand was measured using precision calipers (1/100 mm resolution) and a precision balance (0.001 g resolution).The mean mass and standard deviation of each firebrand was obtained and was observed to be 0.05 ± 0.016 g. Therefore, the mass flux of generated firebrands was calculated to be 17. 1 g/m^2s.

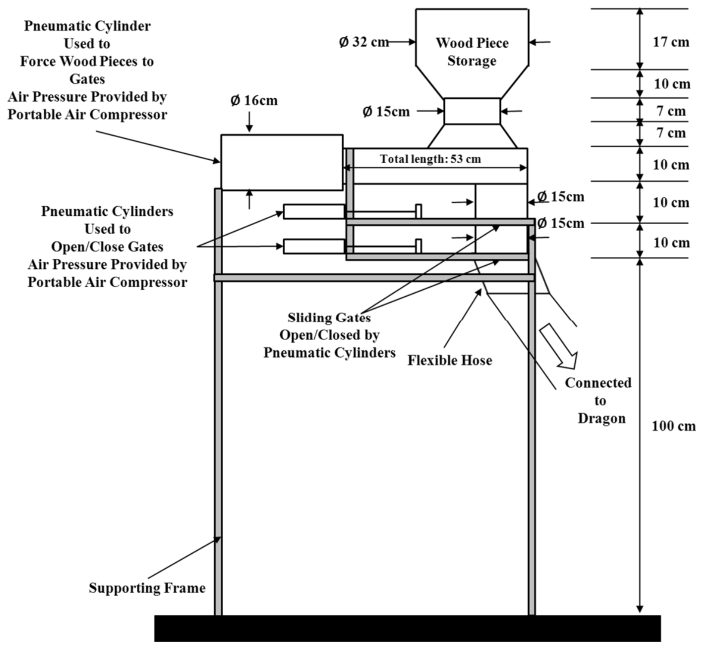

Fig. 8. Detailed schematic of the feeding system for full scale continuous feed Firebrand Generator.

Naturally, it is critical to compare the total firebrand mass generated from this new full scale continuous device to that of the bench scale device [39, 40]. For the bench scale device, at feed rate of 34.6 g/min (most steady firebrand generation rate was observed at that feed rate), it was observed that 0.05 g/s of firebrands were generated. For the full scale device in this paper, the feeding rate used was 800 g/min, and based on the number/mass flux data analyses; this corresponds to a firebrand generation rate of 1.25 g/s. As the feed rate is nearly 23 times larger for the full scale device, the generation rate of firebrands has scaled up rather well. For completeness, the non-continuous Dragon (Fig. 1) generated 200g of firebrands over a period of 4 minutes; after that firebrand production ceased so the advantages of the full scale continuous device presented in this paper is apparent.

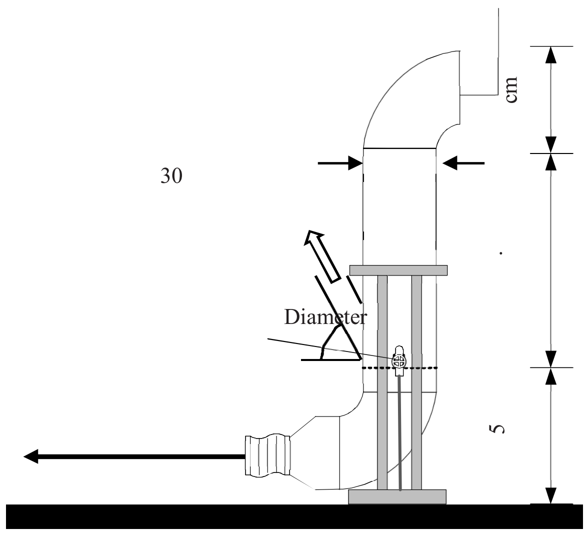

Fig. 9. Side view of the main body (or Dragon) of the full scale continuous Firebrand Generator. The location where the feeding system provided wood pieces into the device is shown.

A great deal of effort has been made to link the firebrand sizes using this device with those from actual burning vegetation, and actual WUI fires. Specifically, firebrand sizes produced using this device is commensurate with the characteristics of firebrand exposure at a single location during a severe WUI fire in California that destroyed 254 homes [29]. This is incredibly important since empirical characterization of firebrand exposure is extremely limited, especially with respect to firebrand size distributions during actual WUI fire conditions. Consistently small sizes of windblown firebrands, similar to those generated using this device, were observed by data collection adjacent to a home that survived severe interface fire exposure. This is in stark contrast with the size of firebrands referenced in existing test standards (*e.g.* ASTM E108 [41]) and wildfire protection building construction recommendations. The interested reader is referred to the recent paper of Foote et al. [29].

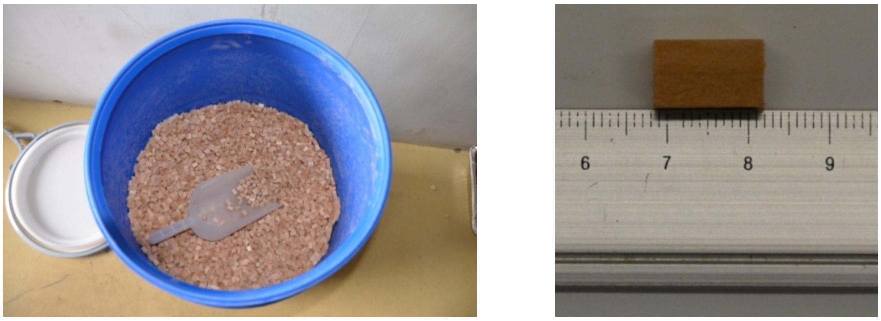

Fig. 10. Picture of wood pieces (bulk – image on left) needed to feed the full scale continuous Firebrand Generator. Detailed image (on right) of a single wood piece along with a metric ruler.

5. Conclusions

In this paper, a summary has been provided on an extended research effort to quantify structure vulnerabilities to wind driven firebrand showers. These results have laid the foundation for this important research direction. Nevertheless, it is important to discuss the findings in the context of actual WUI fires and consider paths for future research.

In real WUI fires, firebrand showers have been observed for several hours and with winds in excess of 20 m/s [42]. It was not possible to conduct experiments using higher wind speeds since the FRWTF was not designed to generate a wind field in excess of 10 m/s. Future work will consider:

- longer firebrand exposures
- various firebrand size/mass distributions
- evaluate technologies intended to mitigate firebrand ignition of structures (*e.g.* wetting agents, foams, gels, building protection technologies)
- additional building components (*e.g.* boxed in eaves, fencing, decking)
- couple firebrand generator with radiant panels to study combined radiation/firebrand influence on ignition
- consider all of the above at higher wind speeds

Progress is now being made on all of these fronts. To address longer firebrand exposures, the new, full scale continuous feed Firebrand Generator described in this paper is being used. In fact, experiments were recently completed to determine the vulnerabilities of decking assemblies to wind driven firebrand showers using this newly developed experimental device. A workshop was held recently to provide input to these decking assembly experiments [43].

For the Firebrand Generator to generate different firebrand size/mass distributions, work is also in progress to determine firebrand production (size/mass) from building components and full scale burning structures [22, 44]. Specifically, experiments have been conducted to determine firebrand production from actual building components/full scale burning structures since it is believed that structures themselves may be a significant source of firebrands, in addition to the vegetation. Firebrand size/mass distributions obtained from these experiments is being compared to those from burning vegetation and actual WUI fires.

To be able to consider higher wind speeds, NIST plans to partner with Insurance Institute for Business and Home Safety (IBHS). Specifically, IBHS has used the NIST Dragon concept to generate firebrand showers in their new (opened in 2011) full scale wind tunnel facility that is capable of wind speeds higher than 10 m/s [38]. At present, they have no capability to conduct continuous firebrand showers since they have implemented an array of firebrand generators based on the original

NIST Dragon described in this paper. Now that NIST has developed the new, full scale continuous feed Firebrand Generator, it is expected that NIST will work with IBHS to implement this improved capability in their wind tunnel.

Finally, the bench 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 allow many different types of firebrand resistant technologies to be tested and the performance of these technologies can then be verified using full scale testing.

Large outdoor fires – opportunities for international collaboration

As has been discussed above, WUI fires are an important, emerging research topic in fire safety engineering. In addition to WUI fires, another prominent example of large outdoor fires that present risk to the built environment is urban fires, common in Japan. While there are substantial phenomenological similarities between urban and WUI fires, research in Japan and in the United States has been conducted in each country independently, with little chance of constructive research collaboration. To this end, an international workshop was held within the Fire Research Division at NIST's Engineering Laboratory in June 201 [45]. The workshop was entitled "Urban and Wildland-Urban Interface (WUI) Fires: A Workshop to Explore Future Japan/USA Research Collaborations." The goal of this workshop was to open dialogue to embark on new research collaborations in an effort to begin developing scientifically based building codes and standards that will reduce the devastation caused by urban and WUI fires. Contributed papers from this workshop, guest edited by Manzello of NIST and Himoto of Kyoto University, will appear in a special issue of *Fire Safety Journal* that will be published in 2012. Recently, NIST signed a statement of intent with the Japan Association for Fire Science and Engineering (JAFSE) to hold two more workshops over the next four years focused on developing scientifically based building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires. The next meeting is being held in Tokyo in 2012.

Due to NIST's research in developing the Dragon technology and collaborating with BRI in Japan to use its FRWTF, it is now possible to begin removing the guesswork out of structure vulnerability to ignition from wind-driven firebrand showers. It will take many research organizations to unravel this challenging problem.

Acknowledgements

The authors would like to acknowledge the many contributions from Mr. Edward Hnetkovsky, Mr. John Shields, Mr. Laurean DeLauter, Mr. Tony Chakalis, and Mrs. Doris Rinehart, all of the Engineering Laboratory (EL) at NIST. Dr. Matthew Bundy, NIST National Fire Research Laboratory (NFRL) Associate Director, is acknowledged for making NFRL technicians available to support this work. Dr. Yoshihiko Hayashi of BRI (Japan) is appreciated for allowing us to use the FRWTF to conduct the experiments outlined in this paper.

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