

ON THE USE OF A FIREBRAND GENERATOR TO INVESTIGATE THE IGNITION OF STRUCTURES IN WILDLAND-URBAN INTERFACE (WUI) FIRES

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ABSTRACT

An experimental apparatus has been constructed to generate a controlled and repeatable size and mass distribution of glowing firebrands. The present study reports on a series of experiments conducted in order to characterize the performance of this firebrand generator. Firebrand generator characterization and subsequent structural ignition experiments were performed at the Fire Research Wind Tunnel Facility (FRWTF) at the Building Research Institute (BRI) in Tsukuba, Japan. The firebrand generator was fed with mulch generated from Korean Pine trees. To produce repeatable initial conditions for each experiment, the Korean Pine mulch was sorted using a series of filters prior to being loaded into the firebrand generator. The size and mass distribution of firebrands produced from the generator was tuned to be representative of firebrands produced from burning trees. After the size and mass distribution of firebrands was characterized, the device was then used to direct firebrand fluxes towards a structure installed inside the FRWTF. A gable vent was installed on the front face of the structure and three different steel screens were installed behind the gable vent to ascertain the ability of the screen to block firebrands from penetrating into the structure. The mechanism of firebrand penetration through screens was observed for the first time. The firebrands were not quenched by the presence of the screen and would continue to burn until they were able to fit through the screen opening. Results of the study are presented and discussed.

INTRODUCTION

The Wildland-Urban Interface (WUI) is defined where structures meet or intermingle with undeveloped wildland. Fires in the WUI pose a significant threat to communities throughout the USA. From 1984, WUI fires have consumed an average of 850 homes per year¹. Presently, it is estimated that some 3.2 million homes in California alone are located in the WUI¹. The destruction from a single WUI fire event can be tremendous. In 2003, for example, WUI fires in the vicinity of San Diego, California displaced nearly 100,000 people and destroyed over 3000 homes, leading to over \$2B in insured losses¹.

For structures to burn in WUI fires, they must be ignited. Research conducted in tandem with post-fire analysis by the US Forest Service and the California Department of Forestry suggests that spotting is the major source of structural ignition in WUI fires². Spot fires are defined as new fires that propagate away from the main fire line due to lofted firebrands. These firebrands are produced as vegetation and structures burn in WUI fires. Understanding how these hot firebrands can ignite surrounding structures is an important consideration in mitigating fire spread in communities³. Japan has been plagued by structural ignition from firebrands as well. The initial fire outbreak

mechanism is different in Japan than the USA. Japan is a country subjected to many earthquakes due to its geographical location. After these earthquakes have occurred, many fires are produced. At the same time, traditional ceramic roofing tiles are displaced as a result of the earthquakes exposing the bare wood roof under pining. Firebrands are produced as structures burn and with the presence of high winds these firebrands are dispersed throughout the atmosphere and produce spot fires which result in severe urban fires that are difficult to extinguish.

Due to the sheer complexity involved, it is useful to delineate the firebrand problem into three main areas: the generation from vegetation and structures, subsequent transport through the atmosphere, and the ultimate ignition of fuels after firebrand impingement. Of these processes, firebrand transport has been investigated most extensively⁴⁻¹². These models have generally assumed firebrand sizes to perform transport calculations, since little quantitative data exists with regard to firebrand size or firebrand mass produced from vegetation and structures. Unfortunately, a very limited number of studies have been performed investigating firebrand generation from vegetation and structures¹³⁻¹⁴ and the ultimate ignition of materials due to firebrand attack¹⁵⁻²⁰. The general lack of knowledge of the type of firebrands that are produced as well as the type of materials that may be ignited has greatly hampered further understanding of this problem.

A pragmatic approach to mitigate firebrand ignition of structures in WUI fires is to design homes that are more resistant to firebrand ignition. Consequently, building codes and standards are needed to guide construction of new structures in areas known to be prone to WUI fires in order to reduce structural ignition in the event of a firebrand attack¹. To the authors' knowledge, no experimental methods are presently available to generate a controlled flux of firebrands on a realistic scale and direct this firebrand flux onto structural elements to ascertain their resistance to ignition as a part of a full scale structural system.

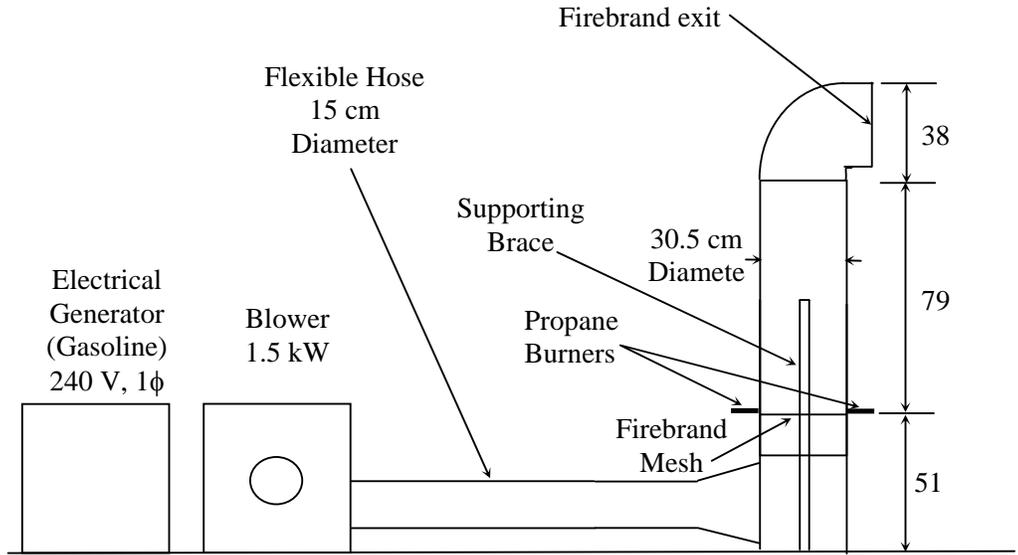
To this end, an experimental apparatus has been constructed to generate a controlled and repeatable size and mass distribution of glowing firebrands. The present study reports on a series of experiments conducted in order to characterize the performance of this firebrand generator. Firebrand generator characterization experiments were performed at the FRWTF at the Building Research Institute (BRI) in Tsukuba, Japan. The effort described is part of an international collaboration established between the National Institute of Standards and Technology (NIST) in the USA and the Building Research Institute (BRI) in Japan to quantify firebrand production from vegetation and investigate firebrand ignition of structures. The firebrand generator was fed with mulch generated from Korean Pine trees. The size and mass distribution of firebrands produced from the generator was selected to be representative of firebrands produced from burning vegetation. After the size and mass distribution of firebrands was characterized, the device was then used to direct firebrand fluxes towards a structure installed inside the FRWTF. A gable vent was installed on the front face of the structure and three different steel screens were installed behind a gable vent to ascertain the ability of the screen to block firebrands from penetrating into the structure. Behind the screen, shredded paper of fixed moisture content was placed in pans to observe if the firebrands that penetrated the vent and subsequent screen were able to produce an ignition event.

EXPERIMENTAL DESCRIPTION

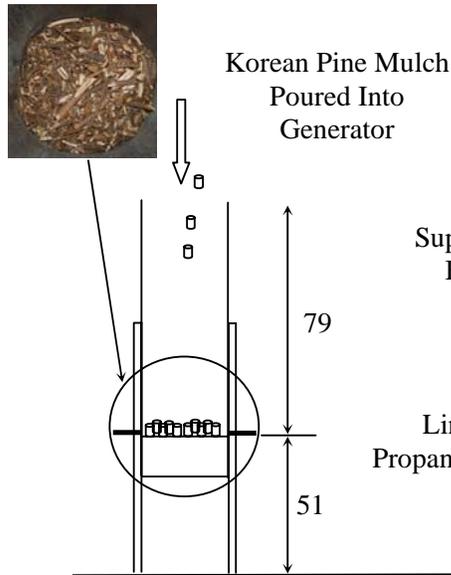
Figure 1 is a drawing of the experimental apparatus. The present apparatus is a scaled up version of a smaller first generation, proof-of-concept device²¹. The bottom left panel displays the procedure detailing the methodology for loading the Korean Pine tree mulch into the apparatus. The mulch pieces 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. A total of 2.1 kg of mulch was used as the initial mass for each of the experiments. The average moisture content of the mulch pieces used at ignition was 10 % (dry basis).

**Firebrand Generator Assembled
Side View**



**Firebrand Generator Disassembled
To Load Firebrands
Front View**



**Firebrand Generator Assembled
Front View**

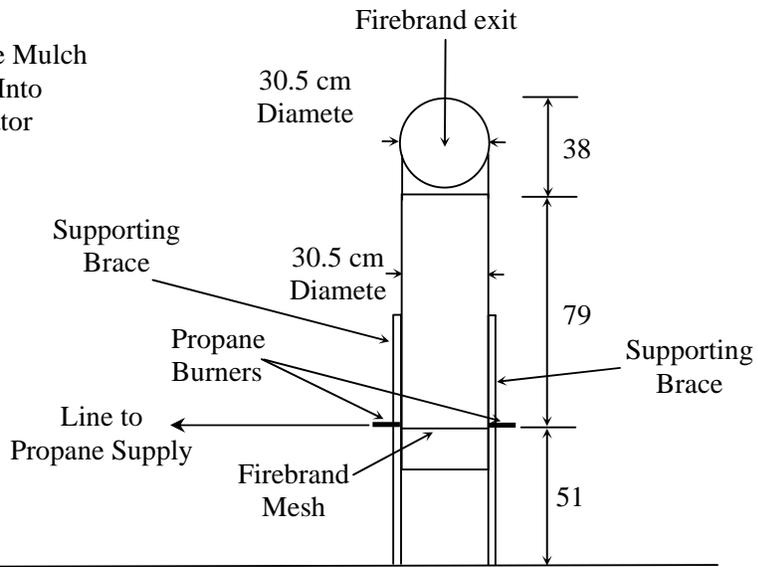


Figure 1 Schematic of the firebrand generator. Both front and side views are shown.

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 (see figure 1). These power requirements were not available at the FRWTF, necessitating the use of a portable power source. Furthermore, the firebrand generator was designed to be fully portable in order to test ignition of any structure or structural element.

The experiments were conducted in the following manner. After the Korean Pine tree mulch was loaded, the top section of the firebrand generator was coupled to the main body of the apparatus (see figure 1). With the exception of the flexible hose, all components of the apparatus were constructed from galvanized steel sections (0.8 mm in thickness). 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. The Korean Pine mulch was ignited for a total time of 45 seconds. After 45 seconds of ignition, the fan speed of the blower was increased (2.0 m/s flow inside the duct measured upstream of the wood pieces). The burners were subsequently switched off at 90 seconds after ignition. This sequence of events was selected in order to generate a continuous flux of glowing firebrands for approximately six minutes duration.

The principle behind the operation of the apparatus was rather simple, after ignition, the mulch would begin to burn and the density decreased until which point the low air flow passing through the support mesh was able to loft and exit the device as firebrands at low velocity. The timing and fan blower speed timing is not random; if a higher fan speed of the blower was selected, the firebrands produced would be forced out of the exit earlier, resulting in flaming firebrands, which was not desired in this phase of characterization.

The firebrand generator was installed inside the test section of the FRWTF at BRI. A drawing of the facility is shown in Figure 2 and displays the location of the firebrand generator with respect to the structure used for ignition testing. 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 21 point 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. A total of 157 rectangular pans (water-filled) were used to collect firebrands. Each pan was 49.5 cm long by 29.5 cm wide. The arrangement and width of the pans was not random; rather it was based on scoping experiments to determine the locations where the firebrands would most likely land. After the experiments were completed, the pans were collected and the firebrands were filtered from the water using a series of fine mesh filters. The firebrands were subsequently dried in an oven held at 104 °C for eight hours. The firebrand sizes were then measured using precision calipers (1/100 mm resolution). Following size determination, the firebrands were then weighed using a precision balance (0.001 g resolution). For each experiment conducted, more than 200 firebrands were dried and measured.

After the generator was characterized, the structure used for vent penetration experiments was installed inside the FRWTF (see Figure 2). Prior to conducting the experiments, computer simulations were performed using the NIST Fire Dynamics Simulator (FDS) to help guide the location of the structure with respect to the firebrand generator. Figure 3 is a detailed drawing of the front face of the structure, showing the location of the gable vent. The overall dimensions of the structure were 3.06 m in height, 3.04 m wide, and 3.05 m in depth. A common type of gable vent, 30.5 cm wide by 45.7 cm long, was used. Experiments were conducted using the same vent but modifying the screen placed behind the vent.

Three different screen sizes were used, 1.5 mm, 3 mm, and 6 mm. The justification for these sizes is provided below.

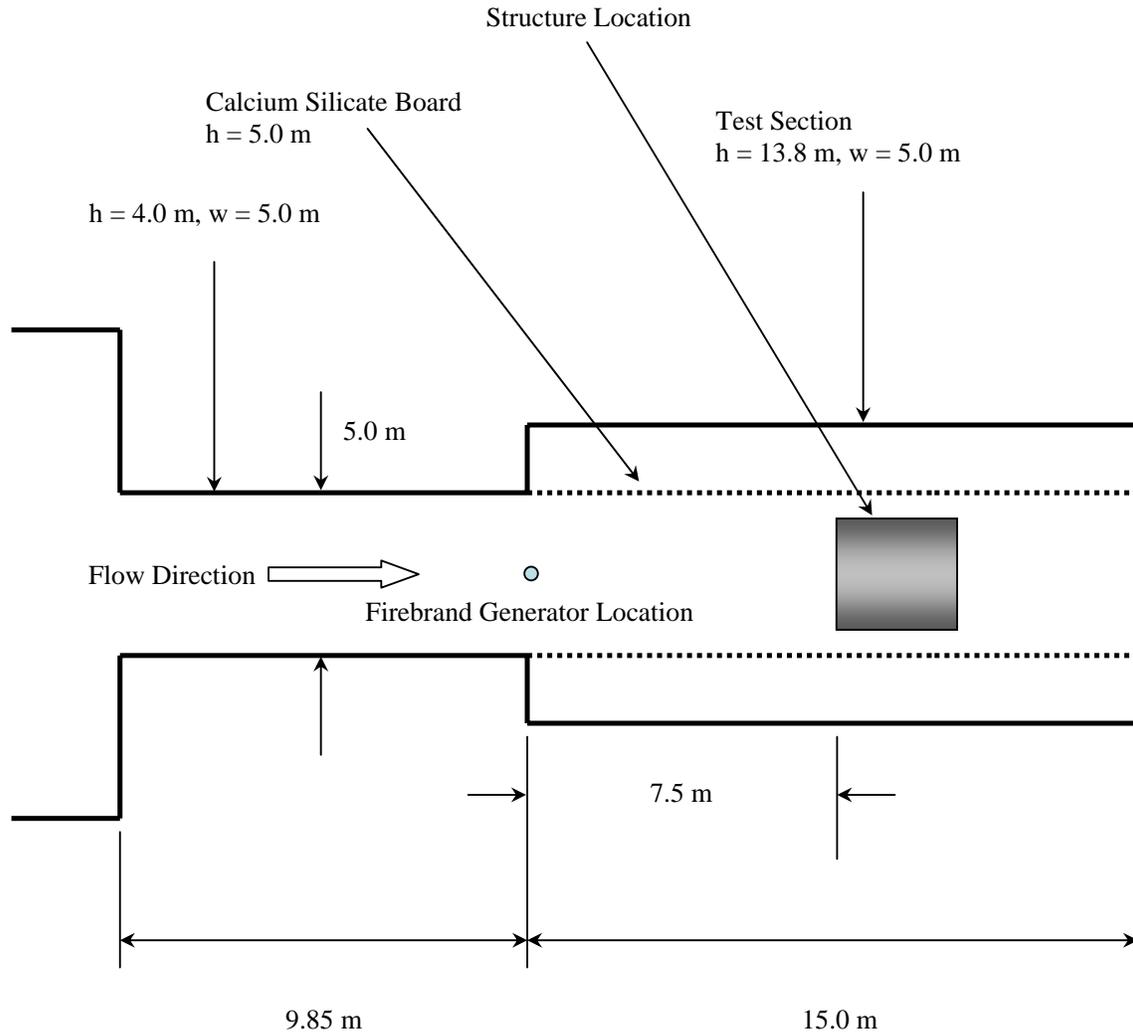


Figure 2 Drawing of the FRWTF (Top View). The location of the firebrand generator is shown.

Two pans, 49.5 cm long by 29.5 cm wide, filled with shredded paper (5 % moisture content dry basis) were placed under the vent opening (behind the screen) to ascertain ignition inside the structure. Firebrands that were able to penetrate the vent and subsequent screen landed in the paper filled pans. Shredded paper was used as a surrogate for cellulosic fuels typically found in attic spaces. The moisture content of 5 % was selected based on work of Manzello *et al.*¹⁸; firebrands ignite paper at 5 % moisture content.

RESULTS AND DISCUSSION

Experiments were first conducted to determine the size and mass distribution of the firebrands produced from the firebrand generator. The impetus for these experiments was to be able to produce firebrands that are characteristic of those produced by burning trees. Manzello *et al.*^{14,22} have performed a series of experiments to characterize firebrand production from burning trees. 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 the mass distribution of firebrands produced from two different tree species under similar

moisture levels and crown size ranges were similar for mass classes up to 0.4 g. A noticeable difference was observed in the larger mass classes. It was also observed that more than 85 % of the firebrands produced from trees were in mass classes up to 0.4 g.

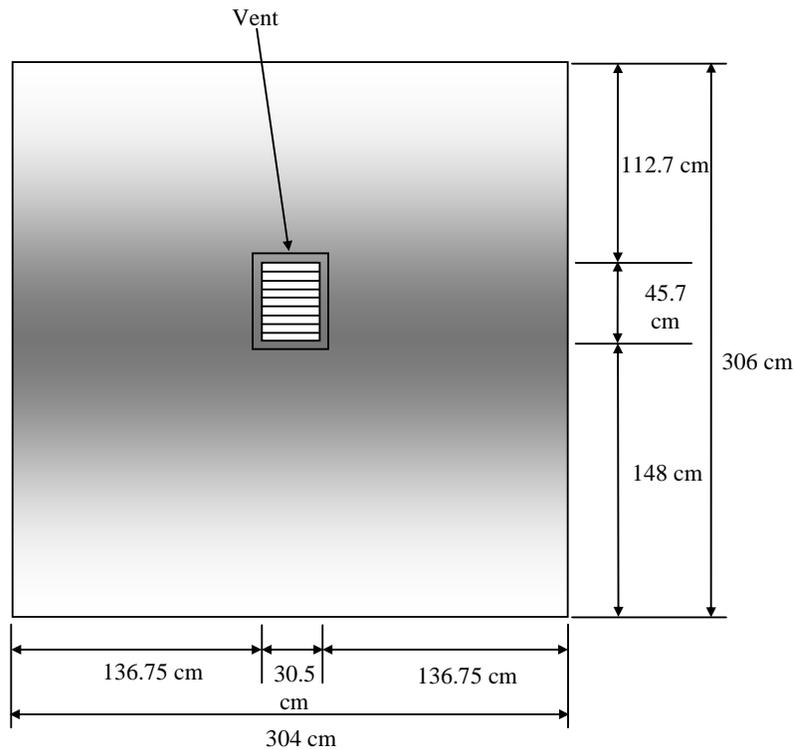


Figure 3 Schematic of the front face of the structure. The location of the gable vent is shown.

Accordingly, the input conditions for the firebrand generator were intentionally selected to produce firebrands with mass classes up to 0.4 g. This was accomplished by sorting the Korean Pine tree mulch using a series of filters prior to being loaded into the firebrand generator. Figures 4 displays a picture of typical firebrands produced from the firebrand generator under these conditions. Since many of the firebrands produced are cylindrical, the length and diameter of the generated firebrands was measured. This information was then used to calculate the surface area of the firebrands produced and was plotted as a function of the measured firebrand mass (see Figure 5). Figure 5 also displays the same analysis performed for firebrands collected from Douglas-Fir trees as well as Korean Pine Trees under similar moisture content. From the figure, the firebrand generator was capable of producing the size and mass distribution of firebrands from burning trees up to 0.4 g.



Figure 4 Digital picture of the firebrands produced from the firebrand generator. These images are taken after the firebrands were extracted from the water filled collection pans and dried.

The average total mass of firebrands generated per experiment was 131 g (varied from 110 g to 163 g). The total firebrand mass was an important parameter to characterize since it allows for a comparison of the total mass of firebrands generated from the device as compared to the amount of firebrands generated from a single tree burn. Based upon the results of the tree burning experiments, the firebrand generator, under the present operating conditions, was capable of producing about 2.5 times the total mass of firebrands produced from a single 4.5 m crown height Douglas-Fir tree. For completeness, figure 6 displays the measured size distribution of the cylindrical firebrands produced from the generator.

Once the firebrand size and mass distribution was characterized and similar to that produced from burning trees up to 0.4 g, the vent penetration experiments were conducted. In order to ensure repeatability of the firebrand size and mass distributions generated, the sorted Korean Pine tree mulch was metered out and weighed using a precision balance for each subsequent experiment.

Figure 7 displays a digital picture of a typical experiment conducted with a 3 mm screen mesh in place. A wind flow of 9 m/s was selected to direct firebrands towards the structure. The reason for this flow selection was twofold: the firebrands were observed to be lofted from the generator and carried to the structure, and it was desired to replicate a firebrand shower in these experiments as firebrand showers in WUI fires are observed under windy conditions (*e.g.* Santa Ana winds).

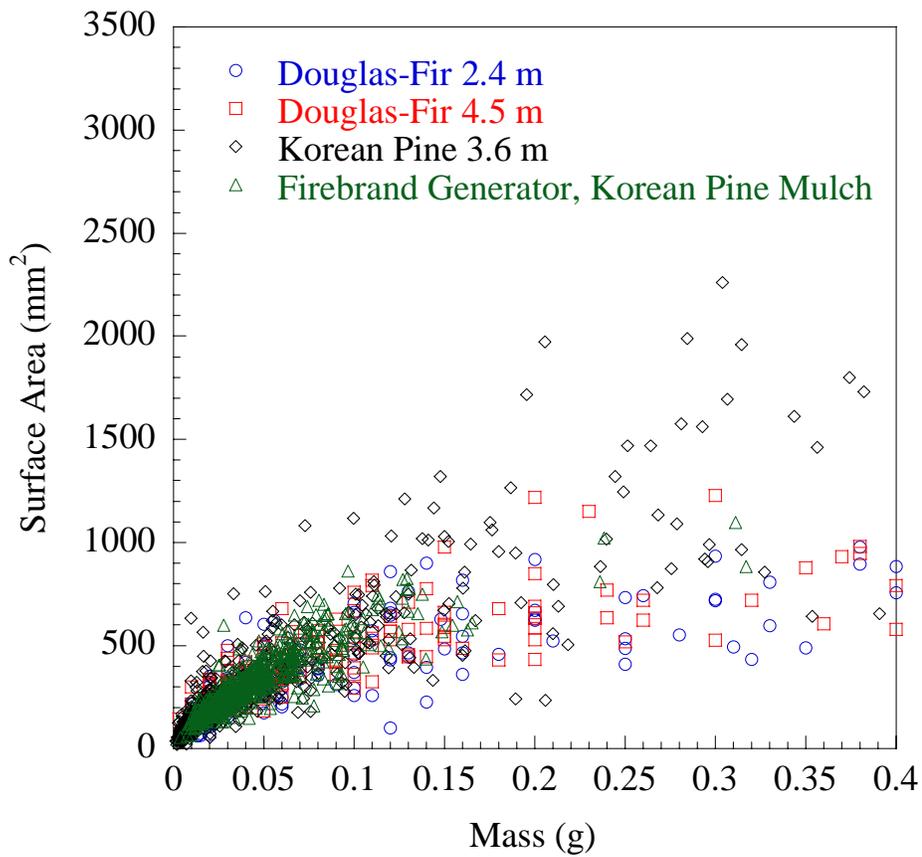


Figure 5 Comparison of firebrands produced from burning trees to those produced from the firebrand generator.

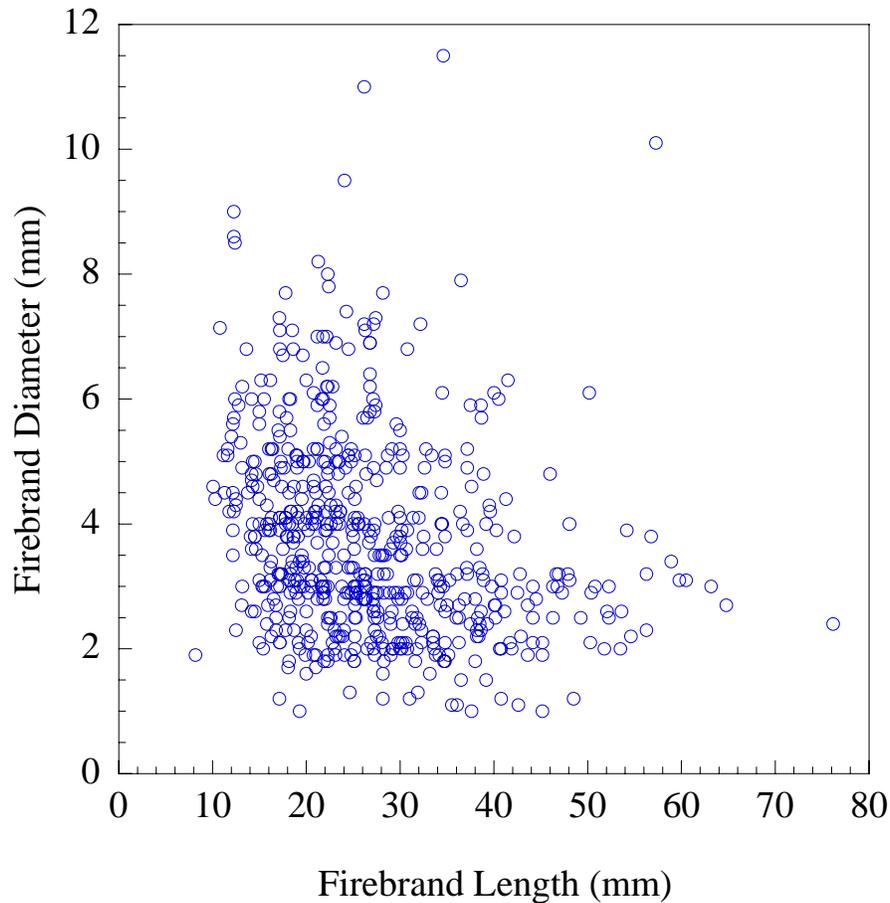


Figure 6 Size distribution of firebrands produced from the firebrand generator.

Three different steel screen sizes were tested in these experiments. The first screen size used was 6 mm (1/4"). This size was selected since it has been recommended in the recently adopted WUI California Building Standards intended to mitigate firebrand penetration through building vents²³. However, smaller screen sizes of 3 mm and 1.5 mm are commercially available. Consequently, it was desired to test these smaller sizes as well. Only non-combustible steel screens were used in this study. Prior to conducting the experiments, it was hypothesized that combustible screens (*e.g.* plastic) would be of no use to preventing firebrand penetration into a structure. For each screen size, three similar experiments were performed.

Two standard video cameras were located inside the structure; one camera directly behind the vent/screen assembly and another camera focused on the shredded paper bed below the vent/screen assembly. Figure 8 displays still images taken from video graphic records obtained from the camera focused behind the vent/screen assembly for a 3 mm screen.

The mechanism of firebrand penetration through screens was observed for the first time. Firebrands were blown through the vent and were pressed against the steel screen. The firebrands were not quenched by the presence of the screen and would continue to burn until they were able to fit through the screen opening. For all screen sizes tested, the firebrands were observed to penetrate the screen and produce a self-sustaining smoldering ignition inside the paper beds installed inside the structure. Figure 9 displays a digital photograph taken 10 minutes after the experiment was completed demonstrating the self-sustaining smoldering propagation inside the paper bed for a 6 mm screen. It is important to point out that for the 6

mm screens tested; a majority of the firebrands simply flow through the screen, resulting in an ignition of the paper behind the screen considerably more quickly as compared to the smaller screen sizes of 3 mm and 1.5 mm.

The flow field was characterized using a 21 point anemometer array outside the structure in front of the building vent. In addition to this, the flow field was measured at six points, 1 cm behind the vent/screen assembly. It was desired to characterize the flow field through the vent/screen assembly as future work will attempt to provide similar flow conditions using a bench scale wind generator and investigate the salient dynamics of firebrand penetration through vents at reduced scale.

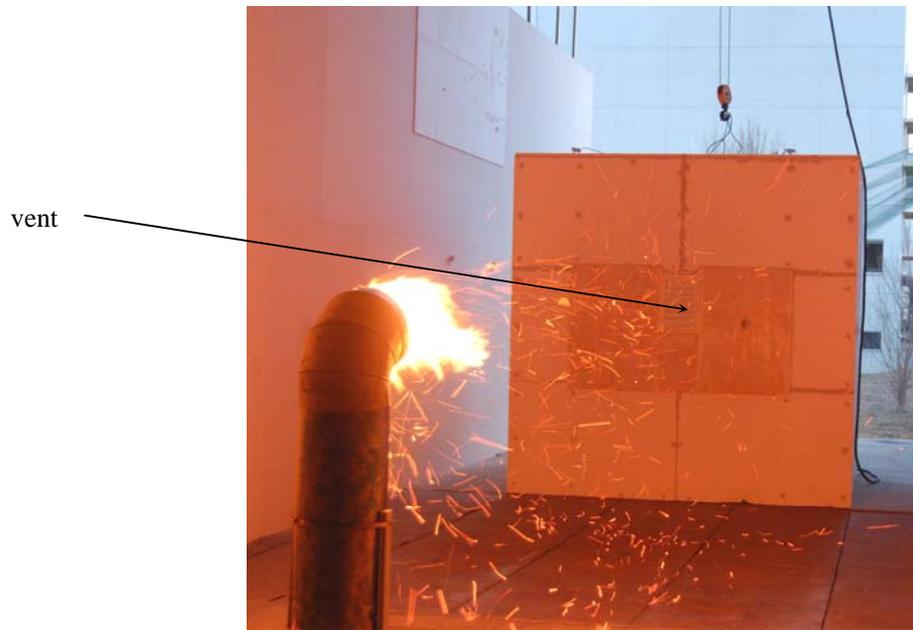


Figure 7 A digital picture of a typical experiment. A 3 mm steel screen is located behind the gable vent in this particular experiment. The arrow shows the vent location.

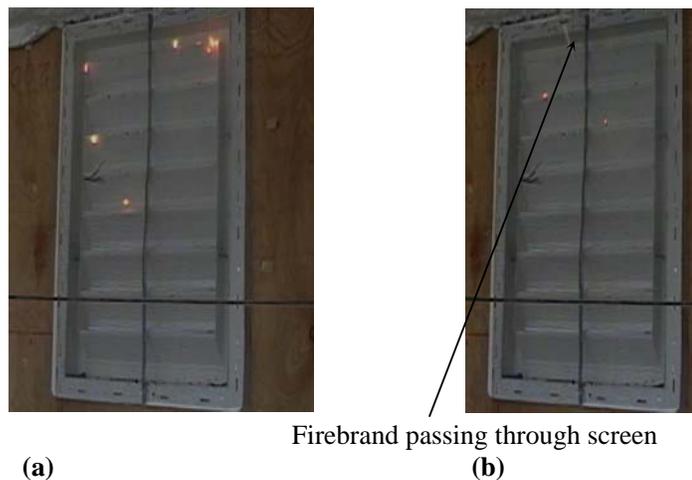


Figure 8 Images of the steel screen (3 mm) located behind the gable vent. Panel (b) shows a firebrand penetrating the screen after burning to a small enough size (see arrow).

The results of these experiments have demonstrated the danger of firebrand storms in WUI fires. In Japan, many buildings have similar vents used for ventilation as in the USA. It is desired to use these results to provide scientific guidance for enhanced WUI building standards in the USA. Additional experimental work will be required to design building vents that can resist the penetration of firebrands. Finally, the utility of the firebrand generator has been demonstrated. It was simple to operate and capable to direct repeatable firebrand fluxes for structural ignition studies.



Figure 9 Picture taken 10 minutes after completion of the experiments. Self-sustaining smoldering ignition is observed in the shredded paper bed at 5 % moisture content (dry basis). This image was taken for a 6 mm screen installed behind the vent. The obscuration in the image was due to smoke production due to smoldering combustion.

CONCLUSIONS

The effort described in this paper is part of an international collaboration established between the National Institute of Standards and Technology (NIST) in the USA and the Building Research Institute (BRI) in Japan to quantify firebrand production from vegetation and investigate firebrand ignition of structures. The firebrand generator was fed with mulch generated from Korean Pine trees. The size and mass distribution of firebrands produced from the generator was selected to be representative of firebrands produced from burning trees. After the size and mass distribution of firebrands was characterized, the device was then used to direct firebrand fluxes towards a structure installed inside the FRWTF. A gable vent was installed on the front face of the structure and three different steel screens were installed behind a gable vent to ascertain the ability of the screen to block firebrands from penetrating into the structure. Behind the screens, shredded paper of fixed moisture content was placed in pans to observe if the firebrands that penetrated the vent and subsequent screen were able to produce an ignition event.

The mechanism of firebrand penetration through screens was observed for the first time. Firebrands were blown through the vent and were pressed against the steel screen. The firebrands were not quenched by the presence of the screen and would continue to burn until they were to fit through the screen opening. For all screen sizes tested, the firebrands were observed to penetrate the screen and produce a self-sustaining smoldering ignition inside the paper beds installed inside the structure. For the 6 mm screens tested a majority of the firebrands simply flew through the screen, resulting in an ignition of the paper behind the screen considerably more quickly as compared to the smaller screen sizes of 3 mm and 1.5 mm. The results of these experiments demonstrate the danger of firebrand storms in WUI fires.

It is desired to use these results to provide scientific guidance for enhanced WUI building standards in the USA. In Japan, firebrands produce fire spread by not only landing on bare wood roofs but also by firebrands penetrating through vent openings; these results can provide valuable information in Japan.

Additional experimental work will be required to design building vents that can resist the penetration of firebrands. Future work will attempt to provide similar flow conditions using a bench scale wind generator and investigate the salient dynamics of firebrand penetration through vents at reduced scale.

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Mr. Syuuji Nanno and Mr. Kazutaka Nakamura (BRI Guest Researchers, under the supervision of Dr. Ichiro Hagiwara of BRI) completed some of the analysis for the firebrand mass and size distributions; their able help in this regard is appreciated. Dr. William 'Ruddy' Mell is acknowledged for assisting in FDS simulations. Mr. Alexander Maranghides, NIST Large Fire Laboratory Manager, is acknowledged for providing access to the LFL to test the operation of the firebrand generator. Dr. William Grosshandler, Fire Research Division Chief, is acknowledged for supporting this research at NIST. The work conducted by BFRL-NIST staff at BRI was possible through a Memorandum of Understanding (MOU) in place between BFRL-NIST and BRI.

REFERENCES

1. Government Accountability Office (2005) 'Technology Assessment: Protecting Structures and Improving Communications During Wildland Fires.' GAO-05-380 (Washington, DC).
2. NIST Session (William Mell, BFRL-NIST Moderator) *Structure Ignition in WUI Fires*, at 2nd Fire Behavior and Conference, March 26-30 Destin, FL, 2007. Presentations-Jack Cohen, US Forest Service; David Sapsis, California Department of Forestry; Samuel L. Manzello, BFRL-NIST.
3. Babrauskas V (2003) 'Ignition Handbook.' (Fire Science Publishers: Issaquah, WA)
4. Albin F (1979) 'Spot Fire Distances From Burning Trees – A Predictive Model.' USDA Forest Service General Technical Report INT-56. (Missoula, MT).
5. Albin F (1983) Transport of Firebrands by Line Thermals. *Combustion and Flame* **32**, 277-288.
6. Muraszew A, Fedele JF (1976) 'Statistical Model for Spot Fire Spread.' The Aerospace Corporation Report No. ATR-77758801 (Los Angeles, CA).
7. Tarifa CS, del Notario PP, Moreno, FG (1965) On the Flight Paths and Lifetimes of Burning Particles of Wood. *Proceedings of the Combustion Institute* **10**, 1021- 1037.
8. Tarifa CS, del Notario PP, Moreno FG (1967) 'Transport and Combustion of Fire Brands.' Instituto Nacional de Tecnica Aeroespacial "Esteban Terradas", Final Report of Grants FG-SP 114 and FG-SP-146, Vol. 2. (Madrid, Spain).
9. Tse SD, Fernandez-Pello AC (1998) On the Flight Paths of Metal Particles and Embers Generated by Power Lines in High Winds and Their Potential to Initiate Wildfires. *Fire Safety Journal* **30**, 333-356.
10. Woycheese JP (2000) 'Brand Lofting and Propagation for Large-Scale Fires.' Ph.D. Thesis, University of California, Berkeley.
11. Woycheese JP (2001) Wooden Disk Combustion for Spot Fire Spread. In '9th Fire Science and Engineering Conference Proceedings (INTERFLAM)' (Ed. S. Grayson) pp. 101-112. (Interscience Communications: London).
12. Knight IK (2001) The Design and Construction of a Vertical Wind Tunnel for the Study of Untethered Firebrands in Flight. *Fire Technology* **37**, 87-100.

13. Waterman TE (1969) 'Experimental Study of Firebrand Generation.' IIT Research Institute, Project J6130. (Chicago, IL).
14. Manzello SL, Maranghides A, Mell WE (2007) Firebrand Generation from Burning Vegetation. *International Journal of Wildland Fire*, in press.
15. Waterman TE, Takata AN (1969) 'Laboratory Study of Ignition of Host Materials by Firebrands.' Project J6142 – OCD Work Unit 2539A, IIT Research Institute, (Chicago, IL).
16. Dowling VP (1994) Ignition of Timber Bridges in Bushfires. *Fire Safety J.* 22:145-168.
17. Ellis PF (2000) 'The Aerodynamic and Combustion Characteristics of Eucalypt Bark – A FireBrand Study.' Ph.D. Dissertation, Australian National University, Canberra.
18. Manzello SL, Cleary TG, Shields JR, Yang JC (2006) On the Ignition of Fuel Beds by Firebrands. *Fire and Materials* **30**, 77-87.
19. Manzello SL, Cleary TG, Shields JR, Yang JC (2006) Ignition of Mulch and Grasses by Firebrands in Wildland-Urban Interface (WUI) Fires. *International Journal of Wildland Fire* **15**, 427-431.
20. Manzello SL, Cleary TG, Shields JR, Maranghides A, Mell WE, Yang JC (2007) Experimental Investigation of Firebrands: Generation and Ignition of Fuel Beds. *Fire Safety Journal* in press.
21. Manzello SL, Cleary TG, Shields JR, Yang JC, Maranghides A, Mell WE, Hayashi, Nii D (2007) On the Development and Characterization of a Firebrand Generator. *Fire Safety Journal* in review.
22. Manzello SL, Shields JR, Maranghides A, Mell WE, Hayashi Y, Nii D (2007) On the Size and Mass Distribution of Firebrands Produced From Burning Korean Pine Trees. *Fire and Materials* in review.
23. 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.