NIST Technical Note 1659

Comparison Testing Protocol for Firebrand Penetration through Building Vents: Summary of BRI/NIST Full Scale and NIST Reduced Scale Results

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National Institute of Standards and Technology • U.S. Department of Commerce

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ABSTRACT

An ASTM task group on vents, organized within Subcommittee E05.14.06, External Fire Exposures, has developed a reduced scale test method (not presently a standard) aimed at evaluating the ability of vents to resist firebrand intrusion into attic and crawl space areas. In the ASTM test method, firebrands are produced by igniting wood pieces and the firebrands are subsequently deposited on top of the vent installed in the test chamber. The vent is placed horizontally in the apparatus and air is pulled through the vent using a fan placed downstream. The mechanism of firebrands residing on top of vents and being pulled down onto vents is not representative of the actual situation. In reality, the firebrands are actually blown onto the vents themselves. Therefore, a comparison testing protocol was undertaken, with the formal support of the ASTM E05.14.06 task group, between the methods developed by ASTM to full scale experiments using the NIST Firebrand Generator (NIST Dragon) coupled to the Fire Research Wind Tunnel Facility (FRWTF) at the Building Research Institute (BRI) in Tsukuba, Japan. The BRI/NIST full scale experiments attempt to simulate a wind driven firebrand attack that is seen in actual fires. NIST has also developed a reduced scale test method aimed at investigating firebrand penetration through building vents that consists of a reduced scale Firebrand Generator (Baby Dragon) coupled to a bench scale wind tunnel. The newly developed NIST reduced scale test, called the NIST Dragon's LAIR (Lofting and Ignition Research), also simulates a wind driven firebrand attack. This comparison testing protocol will determine if the reduced scale methods (ASTM and NIST reduced scale test method) are able to capture the salient physics of firebrand penetration through building vents observed using the full scale test method. Dr. Stephen Quarles (ASTM Subcommittee E05.14.06 chairman), was responsible for supervising and reporting the results of the ASTM reduced scale test method to the ASTM task group on vents. Therefore, only the experiments conducted by NIST (at BRI and NIST facilities) in support of this comparison testing protocol are presented and discussed in this report.

1.0 INTRODUCTION

Fires in the Wildland-Urban Interface (WUI) pose a significant threat to communities throughout the USA. The Southern California WUI fires in 2007 displaced nearly 300,000 people, destroyed over 1000 structures, and resulted in $1B paid by insurers in 2007 alone [1]. The recent 2008 Southern California fires underscore the difficulty of the problem of structure ignition in WUI fires.

For structures to burn in WUI fires, they must be ignited. There is a lack of quantitative information on the processes and conditions of structure ignition in WUI fires. Anecdotal evidence as well as post-fire damage assessment studies suggests that spotting is a major source of structural ignition in WUI fires [2-3]. Spot fires are defined as new fires that propagate away from the main fire line due to lofted firebrands. Understanding how these hot firebrands may ignite surrounding structures is an important consideration in mitigating fire spread in communities.

A pragmatic approach to mitigate firebrand ignition of structures in the USA is to design new homes and retrofit homes to be 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 attack. For these standards to be relevant, a thorough scientific methodology must be developed to understand the types of materials (*e.g.* roofing and siding materials) that can be ignited by firebrands as well as vulnerable points on a structure where firebrands may easily enter (*e.g.* building vents).

Unfortunately, it is not trivial to develop experimental methods to replicate firebrand bombardment of structures seen in actual WUI fires. Furthermore, past firebrand studies [4-15] have been focused on how far firebrands travel and do not address the vulnerabilities of structures from ignition to firebrand showers. Completely new experimental methods are required to understand structure vulnerability to wind driven firebrand showers.

To this end, a unique experimental apparatus, known as the NIST Firebrand Generator (NIST Dragon), has been constructed to generate a controlled and repeatable size and mass distribution of glowing firebrands. Since wind plays a critical role in the spread of WUI fires in the USA and urban fires in Japan, NIST established collaboration with the Building Research Institute (BRI) in Japan in 2006. 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). Although a dearth of information exists regarding actual firebrand exposures in real WUI fires, the full scale experiments conducted recently by NIST at BRI's FRWTF attempt to simulate wind driven firebrand bombardment. In simulating firebrand showers to 10 m/s, these large scale experiments have provided insight into structure vulnerabilities under firebrand attack [16-18].

An ASTM task group on vents, organized within Subcommittee E05.14.06, External Fire Exposures, has developed a reduced scale test method (not presently a standard) aimed at evaluating the ability of vents to resist firebrand intrusion into attic and crawl space areas. In this test method, firebrands are produced by igniting wood pieces and the firebrands are subsequently deposited on top of the vent installed in the test chamber. The vent is placed horizontally in the apparatus and air is pulled through the vent using a fan placed downstream. The mechanism of firebrands residing on top of vents and being pulled down onto vents is not representative of the actual situation. Firebrands are actually blown onto the vents themselves.

A comparison testing protocol was undertaken, with the formal support [19] of the ASTM E05.14.06 task group, between the method developed by ASTM to the full scale experiments using the NIST Firebrand Generator at BRI's FRWTF as these full scale tests developed by BRI/NIST attempt to simulate a wind driven firebrand attack that is seen in actual WUI fires. The newly developed NIST reduced scale test also simulates a wind driven firebrand attack. This comparison testing protocol will determine if the reduced scale methods (ASTM and NIST reduced scale test method) are able to capture the salient physics of firebrand penetration through building vents observed using the full scale test method. Dr. Stephen Quarles (ASTM Subcommittee E05.14.06 chairman), was responsible for supervising and reporting the results of the ASTM reduced scale test method to the ASTM task group on vents. Therefore, only the experiments conducted by NIST (at BRI and NIST facilities) in support of this comparison testing protocol are presented and discussed in this report.

2.0 EXPERIMENTAL DESCRIPTION

2.1 Full Scale Tests at BRI

Figure 1 is a drawing of the NIST Firebrand Generator. A photograph of the device is shown in Figure 2. A brief description of the device is provided here for completeness and follows prior descriptions very closely [16-18]. This version derives from the first-generation, proof-of-concept device [20]. The bottom panel displays the procedure for loading the Norway Spruce (*picea abies Karst)* tree mulch into the apparatus. Norway Spruce (*picea abies Karst)* was chosen since it belongs to the *Pinaceae* family, which includes such species as Ponderosa Pine (*Pinus Ponderosa)* and Douglas-Fir *(Pseudotsuga menziesii)*; common conifer species dominant in the USA. The mulch was produced from 6 m Norway Spruce trees. Norwegian

Spruce is found in more than 20 states in the USA. These trees were used as a source for mulch for the Firebrand Generator since they were quite easy to locate in Japan.

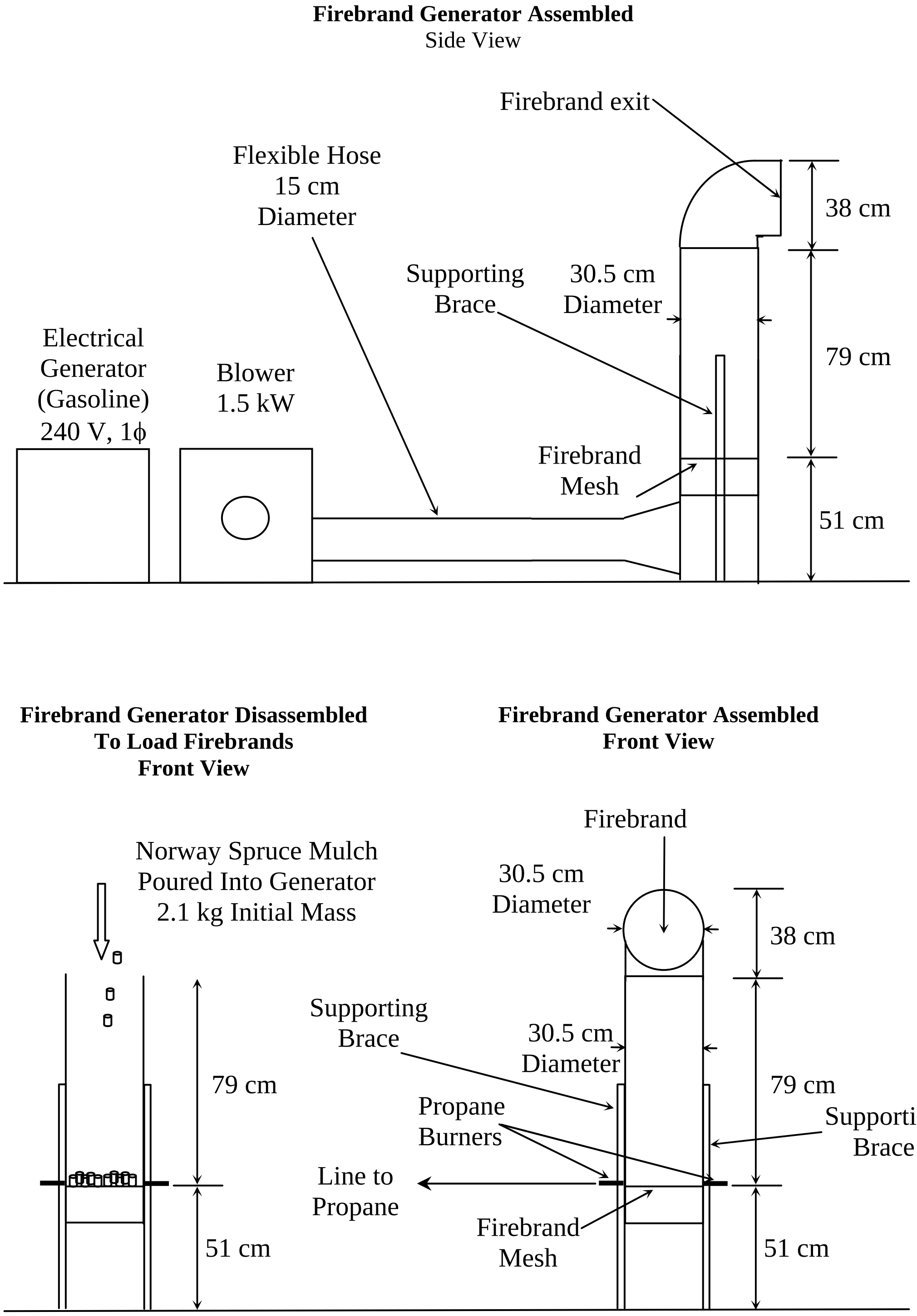


Figure 1 Side and front view drawings of NIST Firebrand Generator (Dragon) used for Full Scale Tests.

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). 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 mulch loading was fixed at 2.1 kg. The Firebrand Generator was driven by a 1.5 kW blower.

After the Norway Spruce tree mulch was loaded, the top section of the Firebrand Generator was coupled to the main body of the apparatus. With the exception of the flexible hose, all components of the apparatus were constructed from either galvanized steel or stainless steel (0.8 mm in thickness). The blower was then started 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 device. 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 Norway Spruce mulch was exposed to the igniter for a total of 45 s. After 45 s, the fan speed of the blower was increased (2.0 m/s flow inside the duct measured upstream of the wood pieces). This sequence of events was selected to generate a continuous flow of glowing firebrands for approximately four minutes duration.

Figure 2 Picture (side view) of NIST Firebrand Generator (Dragon) used for Full Scale Tests. One of the burners used for ignition is shown.

The Firebrand Generator was installed inside the test section of the FRWTF at BRI. Figure 3 displays a layout of the facility. The facility used a 4.0 m diameter fan to produce the wind field and was capable of producing a flow of 10 m/s. The wind flow velocity distribution was measured using a hot wire anemometer array. To track the evolution of the size and mass distribution of firebrands produced, a series of rectangular pans (water-filled) were placed downstream of the Firebrand Generator. 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 firebrands were filtered from the water using a series of fine mesh filters.

The firebrands were subsequently dried in an oven 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, more than 100 firebrands were collected, dried, and measured.

Figure 4 is a detailed drawing of the front face of the target structure showing the location of the vent opening. The overall dimensions of the structure 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 since the purpose of the experiments was to assess the proposed test methods and not specific proprietary vent technology. The vent opening was fitted with six different types of metal mesh: 4 x 4 mesh x 0.65 mm (0.025”) wire diameter (galvanized after welded), 8 x 8 mesh x 0.43 mm (0.017”) wire diameter (woven SS 304), 10 x 10 mesh x 0.51 mm (0.020”) wire diameter (woven SS 304), 14 x 14 mesh x 0.23 mm (0.009”) wire diameter (woven SS 304), 16 x 16 mesh x 0.23 mm (0.009”) wire diameter (woven SS304), and 20 x 20 mesh x 0.23 mm (0.009”) wire diameter (woven SS 304). 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). These opening sizes were obtained from the manufacturer and subsequently verified using measurements at NIST. This range of mesh types was based upon the recommendations of the ASTM E05.14.06 task group. Mesh was defined, per the manufacturer, as the number of openings per 25.4 mm (1”).

Prior to conducting the experiments, computer simulations were conducted using the NIST Fire Dynamics Simulator (FDS) to visualize the flow around the structure in the FRWTF. As a result, the placement of the mesh assembly, on the front face of the structure, was intentionally selected to provide for an intense exposure of firebrand showers from the NIST Firebrand Generator. It also allowed for comparison to prior BRI/NIST work that considered a gable vent fitted with a mesh assembly [16].

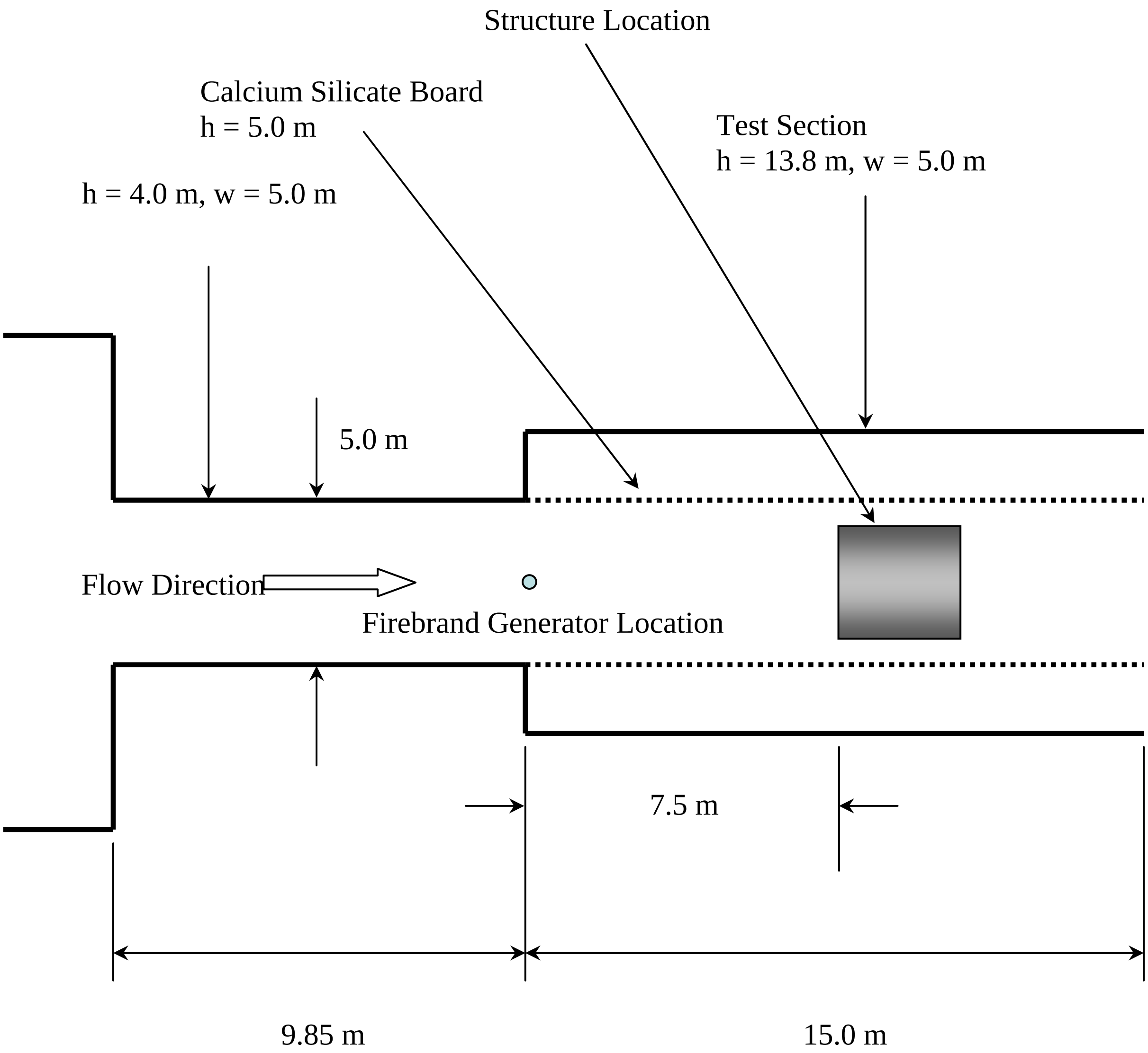


Figure 3 Drawing of the FRWTF (Top View). The location of the Firebrand Generator is shown as well as the structure used for testing. The structure was intentionally constructed of calcium silicate board (non-combustible).

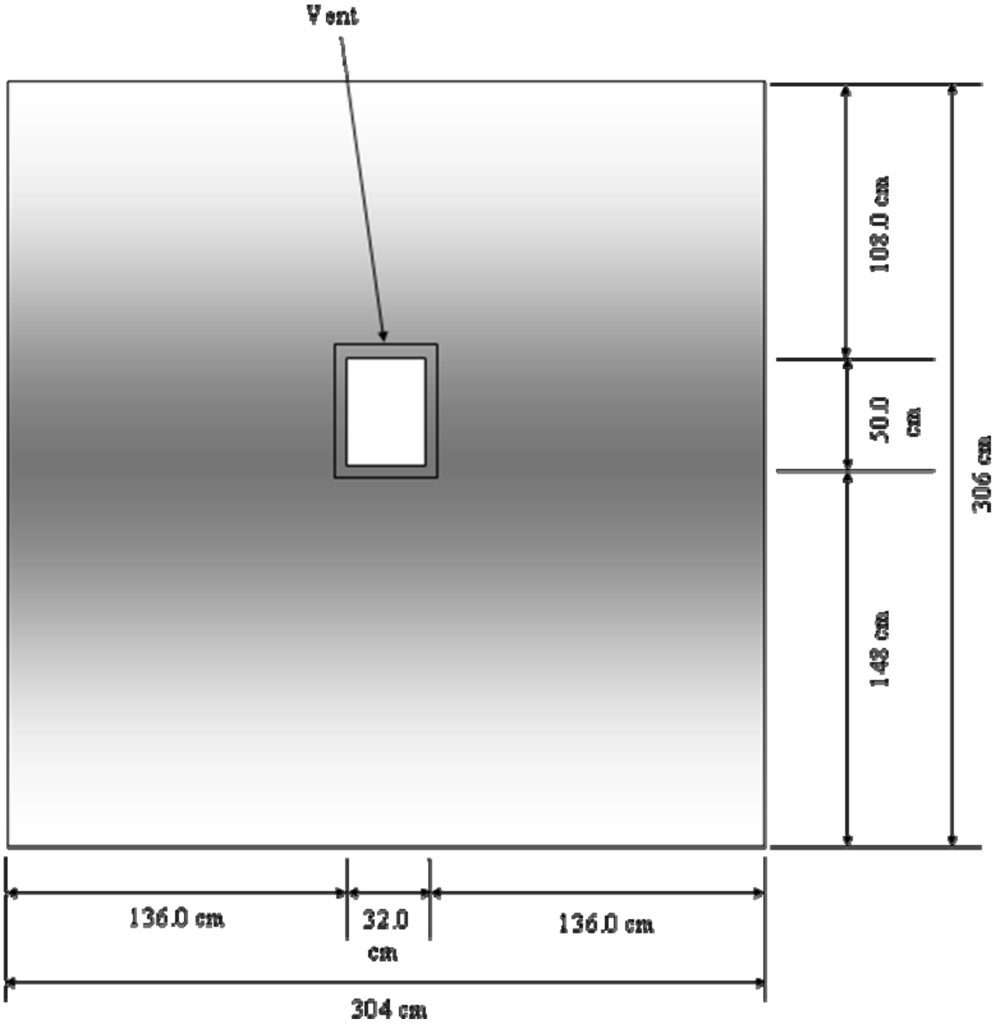


Figure 4 Schematic of structure used. The vent opening is shown where the mesh was placed.

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). The wood cross-section was 3.7 cm x 8.7 cm. 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, such as sawdust. To simplify comparisons, all materials were oven dried in these experiments and care was taken to ensure consistency with the testing materials used for NIST full scale tests, NIST reduced scale tests, and ASTM tests. For the shredded paper tests, the paper loading used was based on area: 0.11 g/cm^2. For the crevice tests, the paper loading used was a mass per unit length value: 0.5 g/cm since determining the area was difficult for the crevice.

All of these materials used for ignition testing were placed 19 cm below the mesh assembly inside the structure. The back side of the structure was fitted with an opening 92 cm high and 172 cm wide. This opening allowed for access into the structure to change out the ignitable materials and to investigate the influence of a back opening on the measured velocity behind the mesh inside the structure. The size of this back opening was varied from fully open to half open, and then fully closed. The velocity was then measured for each mesh size used as a function of the back opening. For all mesh sizes tested, there was no difference in the velocity measured behind the mesh as the opening was changed from fully open to half open. When the back opening was fully closed, the velocity behind the mesh was observed to decrease slightly as compared to the fully open case; depending on mesh size the velocity reduction was on the order of 15 %. In a real structure, an attic space would not be fitted with only one vent and sealed, so all experiments reported here were conducted with the back fully open. Experiments were also conducted with the back fully closed and the same ignition behaviors were observed as those when it was fully open.

Inside the structure, behind the mesh, a screen was placed to direct firebrands that penetrated the mesh towards the ignitable materials. Without a guide, the firebrands that penetrated the mesh would simply land in various places inside the structure. The purpose of these experiments was to create a worst case scenario; directing the firebrands that penetrated the mesh to the ignitable materials was desired.

2.2 Reduced Scale Tests at NIST – Dragon's LAIR Facility

Figure 5 is a schematic of the NIST Dragon's LAIR (Lofting and Ignition Research) facility. The Dragon's LAIR consisted of a reduced scale Firebrand Generator (Baby Dragon) coupled to a reduced scale wind tunnel (see Figure 5). With the exception of the flexible hose, all components of the Baby Dragon were constructed from either galvanized steel or stainless steel (0.8 mm in thickness).

To produce firebrands, the Baby Dragon was fed with wood pieces. For all reduced scale 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. The total initial mass was fixed at 150 g for all tests. The reason for using wood pieces for the reduced scale tests, as opposed to mulch, was: (1) the use of wood pieces would be easier for other testing laboratories to obtain and (2) due the small amount of wood required it was quite easy to produce it for the reduced scale tests. For the full scale tests (described above), mulch was far easier to use due to the sheer amount of material needed per test. Finally, the size of the wood pieces used in the Baby Dragon was based on a series of characterization experiments that consisted of using mulch and then determining the most appropriate sized wood pieces necessary to generate similar firebrand showers.

After the wood pieces were loaded, the window of the wind tunnel was closed, the desired wind tunnel flow was set, and the blower was then started to provide a low flow for ignition. One propane burner was ignited and simultaneously inserted into the side of the generator. The 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. The wood pieces were ignited for a total time of 40 s. This sequence of events was selected in order to generate a continuous flow of glowing firebrands for approximately four minutes duration and resulted in little or no smoke production.

The test section of the wind tunnel was 50 cm x 50 cm x 200 cm. The flow was provided by an axial fan 91 cm in diameter. To track the evolution of the size and mass distribution of firebrands produced, a series of water pans was placed downstream of the Baby Dragon. 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 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).

The same mesh sizes described for the full scale tests (see section 2.1 above) were used. Each mesh was mounted in a metal mounting bracket with the same effective area as the full scale tests (1600 cm^2). The mesh was placed 100 cm downstream of the test section. Behind the mesh, the same ignitable materials used in the full scale tests were placed; namely shredded paper, cotton, crevices constructed with oriented strand board (OSB), and wood (to form 90 degree angle; with and without shredded paper).

Behind the mesh, a screen was placed to direct firebrands that penetrated the mesh towards the ignitable materials. Without a guide, the firebrands that penetrated the mesh would continue to flow downstream of the test section. The purpose of these experiments was to create a worst case scenario thus directing the firebrands that penetrated the mesh to the ignitable materials was desired.

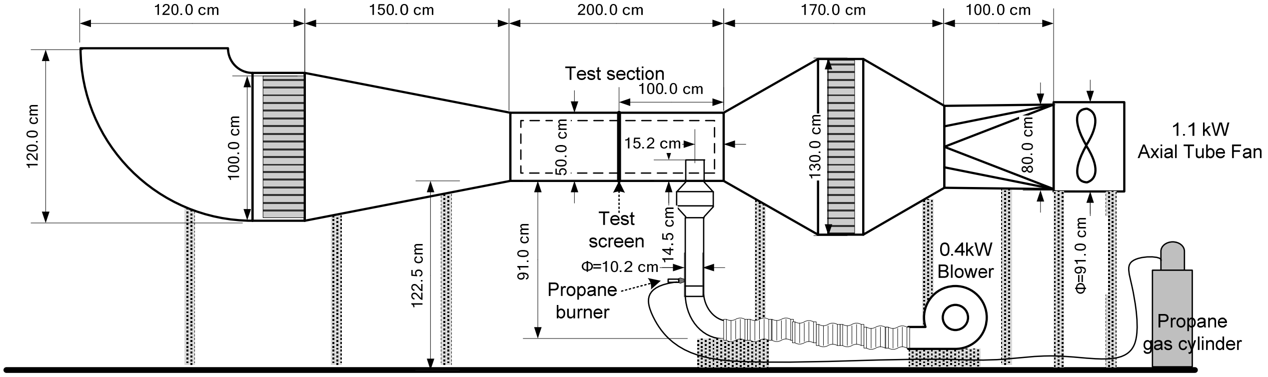


Figure 5 Schematic of Dragon's LAIR Facility. The Baby Dragon (coupled to 0.4 kW blower) as well as the firebrand seeding locating into the wind tunnel are shown.

3.0 RESULTS

3.1 Full Scale Tests at BRI

The Firebrand Generator was designed to be able to produce firebrands characteristic to those produced from burning trees. Manzello *et. al.* [21-22] conducted a series of experiments quantifying firebrand production from burning trees. 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].

In this study, the input conditions for the Firebrand Generator were intentionally selected to produce firebrands with masses as large as 0.2 g. This was accomplished by sorting the Norway Spruce tree mulch using a series of filters prior to being loaded into the Firebrand Generator (as described above). A similar filtering procedure was used previously when other conifer species were used as the mulch source [16-17]. The size and mass distribution of firebrands produced using the Firebrand Generator is displayed in Figure 6. The total mass of firebrands produced was also determined based on repeat experiments. With mulch loadings of 2.1 kg, an average of 196 g (varied from 192 g to 200 g) of glowing firebrands were produced. Therefore, the total number of firebrands directed at the structure for each experiment was quite repeatable.

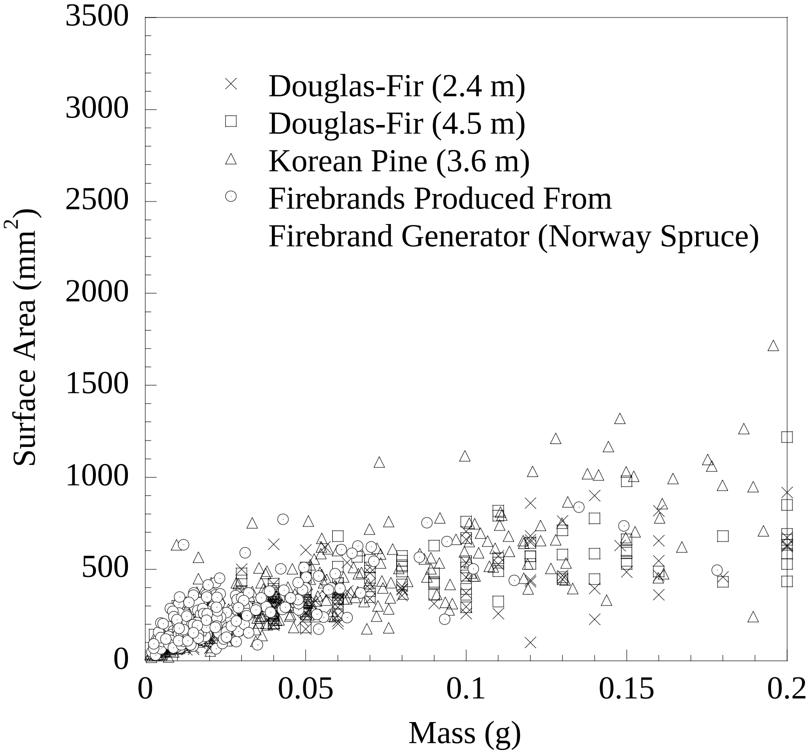


Figure 6 Firebrands produced from burning trees compared to those produced using the Firebrand Generator. The uncertainty in determining the surface area is ± 10 %.

For the full scale tests, the wind tunnel speed was fixed at 7 m/s (± 10 %). For each mesh tested, the velocity was measured behind the mesh (at the centerline) using a hot wire anemometer. 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 %.

Figure 7 displays a picture of a typical experiment. In this particular experiment, the mesh used was 20 x 20 (1.04 mm).

An important factor to consider for the full scale tests was that while the Firebrand Generator produced a large number of firebrands as a function of time, all of these firebrands do not actually arrive at the mesh location due to flow recirculation produced by the presence of the structure. To quantify the distribution of firebrands arriving at the mesh area as a function of time, experiments were conducted using the 20 x 20 (1.04 mm) mesh since this mesh size initially trapped all firebrands on it prior to their eventual mass loss from burning and ultimate penetration through the mesh. This allowed for the ability to simply count (using custom computer algorithms) the time varying number of firebrands arriving at the given mesh area. This data is shown in Figure 8.

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.

When shredded paper was used, a repeatable SI was observed for all mesh sizes up to 16 x 16 (1.35 mm). As the mesh size was reduced, the number of locations in the fuel bed where ignition was observed was reduced greatly. For example, for the 16 x 16 (1.35 mm) mesh, SI was observed only in one location in each of the repeat experiments. As for the smallest mesh size tested (20 x 20) (1.04 mm), SI was observed in only one experiment out of three. Subsequent repeats resulted in NI for this mesh size but the paper showed evidence of burns from firebrands. For several of the larger mesh sizes, the SI transitioned to FI. The shredded paper results are in agreement with prior BRI/NIST work using gable vents fitted with 6.0 mm, 3.0 mm, and 1.5 mm mesh [16].

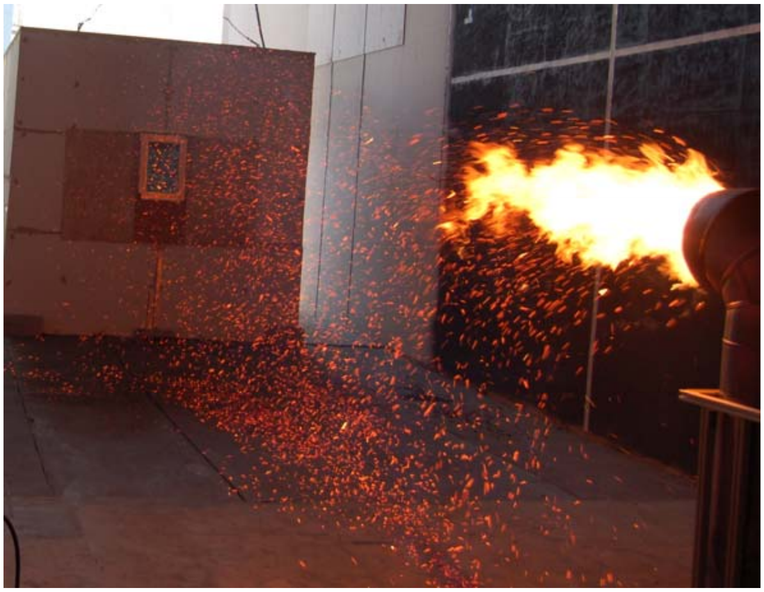


Figure 7 Typical experiment using NIST Firebrand Generator at BRI's FRWTF. The mesh installed in this experiment was 20 x 20 (1.04 mm), the wind tunnel speed was 7 m/s, and the Firebrand Generator was located 7.5 m from the structure.

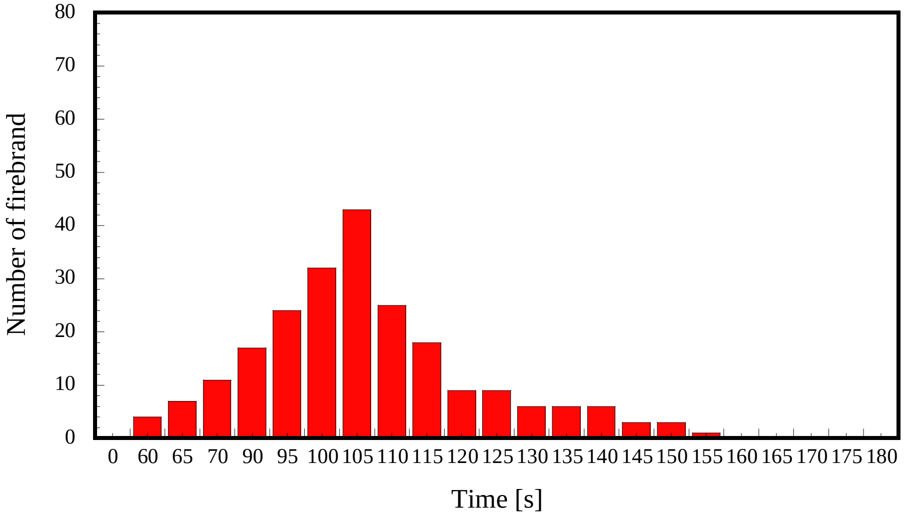


Figure 8 Number of firebrands arriving on the mesh as a function of time for the full scale experiments. The mesh area was 1600 cm^2. At each time, the number of firebrands plotted in the figure was based on the average of three repeat experiments. The relative variation in the average number of firebrands measured was similar for all times (less than 20 %).

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. In several cases, the firebrands burned holes directly through the cotton samples. While a reduction in mesh size resulted in fewer holes in the cotton, ignition was never fully suppressed. A transition to FI was never observed. Figure 9 displays images obtained from cotton tests for the 4 by 4 (5.72 mm) mesh. The shredded paper and cotton tests demonstrate that mesh size reduction was not effective in reducing ignition from firebrand showers for these full scale experiments.

Figure 9 Images obtained for cotton tests using 4 by 4 (5.72 mm) mesh. The image on the right demonstrates complete burn through of 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. These results can be explained by a comparison to the shredded paper experiments (described above). The available area for the firebrands to contact the shredded paper bed was greatly reduced for the paper filled crevice experiments as compared to pans of shredded paper. Therefore, it is not surprising that as the target area available for firebrands to land was reduced, ignition was no longer observed for smaller mesh sizes for crevices filled with shredded paper. The results of an experiment conducted using 10 x 10 (2.0 mm) mesh are shown in Figure 10.

Experiments were also conducted where the temperature was measured at the location of the fuel bed to investigate whether there was any pre-heating during the experiments. The source of any potential pre-heat was the heat generated by the Firebrand Generator. The temperature rise measured at the fuel bed was on the order of 3 °C.

Table 1 Summary of full scale tests at BRI.

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)	Two tests: NI; One test SI	Two tests: SI One Test NI	NI	NI

NI - no ignition; SI – smoldering ignition; FI – flaming ignition.

Figure 10 Images obtained (top view) for crevice filled with paper tests using 10 x 10 (2.0 mm) mesh.

3.2 Reduced Scale Tests at NIST – Dragon's LAIR Facility

Similar to the full scale experiments, the size and mass distribution of firebrands produced using the Baby Dragon was determined (see Figure 11). These sizes/masses were within the range of firebrands produced using the NIST Firebrand Generator (see Figure 6). The total mass of firebrands produced using the Baby Dragon was also determined based on repeat experiments. With an initial loading of 150 g, an average of 12.2 g (varied from 11 g to 13.6 g) of glowing firebrands were produced. Therefore, the total number of firebrands directed at the mesh was repeatable for each experiment.

In the reduced scale tests, all firebrands generated landed on the mesh. To quantify the distribution of firebrands arriving at the mesh area as a function of time, experiments were conducted using the 20 x 20 (1.04 mm) mesh since this mesh size initially trapped all firebrands on it prior to their eventual burn down and penetration through the mesh. This allowed for the ability to simply count the time varying number of firebrands arriving at the target mesh. This data is shown in Figure 12.

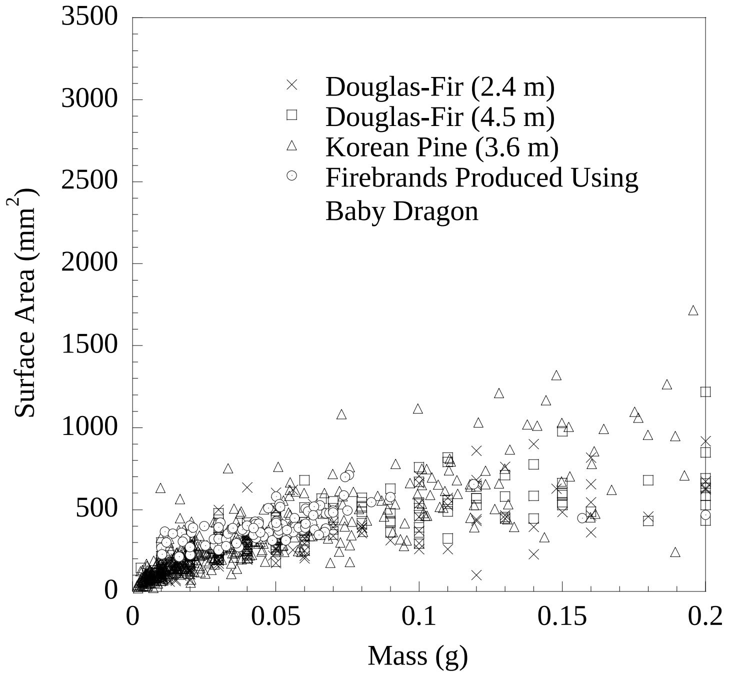


Figure 11 Firebrands produced from burning trees compared to those produced using the Baby Dragon. The uncertainty in determining the surface area is ± 10 %.

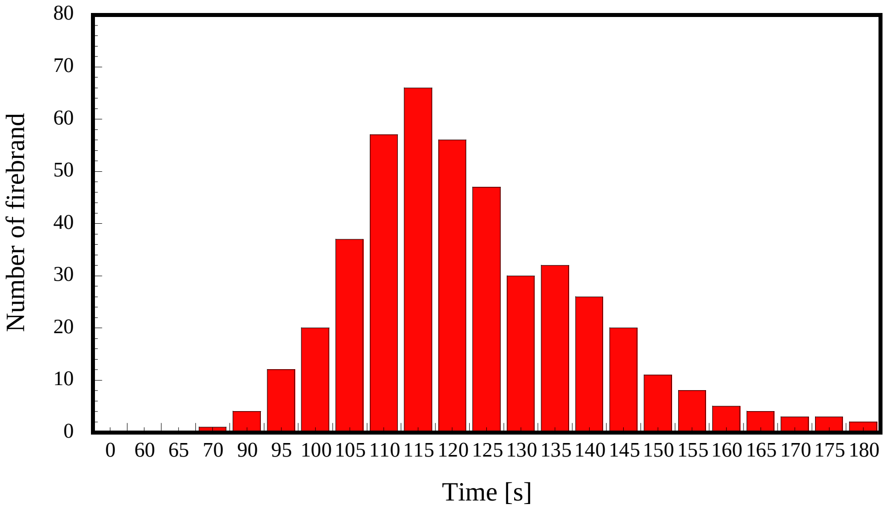


Figure 12 Number of firebrands arriving on the mesh as a function of time for the reduced scale experiments. The mesh area is 1600 cm^2. The number of firebrands plotted in the figure, at each time, was based on the average of three repeat experiments. The relative variation in the average number of firebrands measured was similar for all times (less than 10 %).

To provide a meaningful comparison for the ignition studies, the velocity was matched behind the mesh for the reduced scale experiments to those velocities measured behind the mesh for the full scale tests. Figure 13 displays a picture of a typical experiment using the Dragon's LAIR. In this particular image, the mesh used was 14 x 14 (1.55 mm). Three repeat experiments were conducted for each of the four ignitable materials and the results are tabulated in Table 2.

When shredded paper was used, a repeatable SI was observed for all mesh sizes up to 16 x 16 (1.35 mm). As the mesh size was reduced, the number of locations where ignition was observed in the shredded paper beds was reduced greatly. For example, for the 16 x 16 (1.35 mm) mesh, SI was observed only in one location in each of the repeat experiments. These results were identical to the full scale tests. As for the smallest mesh size tested (20 x 20; 1.04 mm), NI was observed in all experiments. The paper showed evidence of burns from firebrands but these did not produce self sustaining SI. In the full scale tests, the shredded paper was observed to produce a SI in only one of the experiments for the 20 x 20 (1.04 mm) mesh. For several of the larger mesh sizes, the SI transitioned to FI.

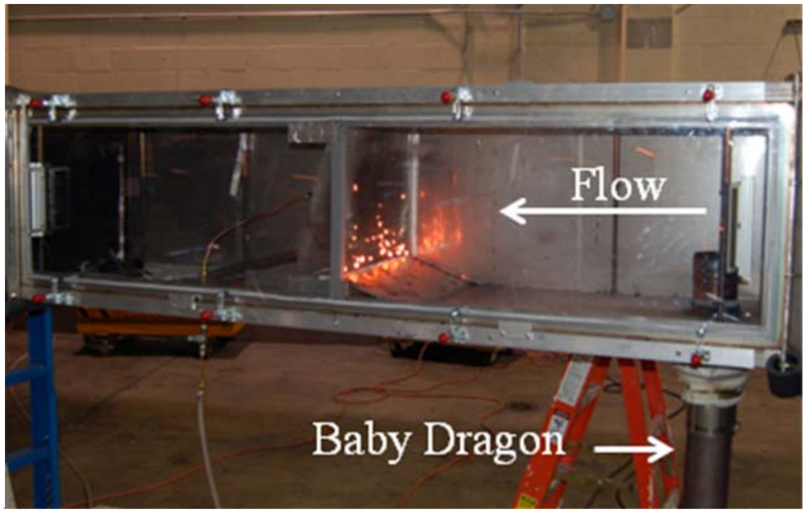


Figure 13 Picture of typical experiment using the Dragon's LAIR. A 14 x 14 (1.55 mm) mesh was being used when this photograph was taken.

For cotton, the behavior was similar for all mesh sizes. The firebrands were deposited in the cotton bed and burned holes into the cotton. In several cases, the firebrand burned holes completely through the cotton samples. While a reduction in mesh size resulted in fewer holes in the cotton, ignition was never fully suppressed. The only notable difference between the reduced scale tests and full scale tests for cotton was a transition from SI to FI was observed for the largest mesh size tested (4 x 4; 5.72 mm). In the full scale tests, a transition from SI to FI was not observed for the largest mesh size.

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 to provide any ignition of the bare wood crevices. This behavior was the same as that observed in the full scale tests.

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. These results were also the same as the full scale tests (described above). The results of an experiment conducted using 10 x 10 (2.0 mm) mesh are shown in Figure 14.

Finally, experiments were also conducted in which the temperature was measured at the location of the fuel bed to investigate whether there was any pre-heating (by the Firebrand Generator) of the fuel bed during the experiments. The temperature rise measured at the full bed was on the order of 9 °C.

Table 2 Summary of reduced scale tests at NIST.

Mesh	Paper	Cotton	Crevice	Crevice with paper
4 x 4 (5.72 mm)	SI to FI	SI to FI	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	SI	NI	NI

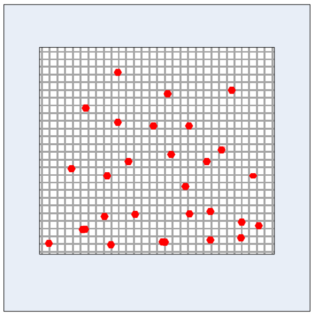
NI - no ignition; SI – smoldering ignition; FI – flaming ignition.

Figure 14 Images obtained (top view) for crevice filled with paper tests using 10 x 10 (2.0 mm) mesh using NIST Dragon’s LAIR.

4.0 DISCUSSION – MESH EFFECTIVENESS

Similar to prior BRI/NIST experiments that used a gable vent fitted with a mesh (6.0 mm, 3.0 mm, and 1.5 mm) [16], 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. In the present work, the same behavior was observed for the smaller mesh sizes used (16 x 16, 1.35 mm; 20 x 20, 1.04 mm). The reduced scale experiments also showed the same behavior, namely firebrands were not quenched by the presence of the mesh but would continue to burn until sufficient mass loss allowed the firebrands to penetrate the mesh. A schematic of this behavior is shown in Figure 15.

(a) Front view



(b) Side view

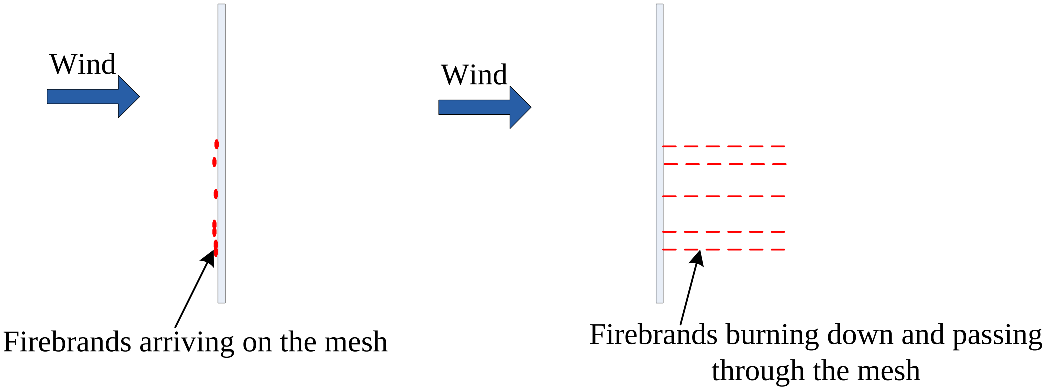


Figure 15 Schematic of firebrand penetration through a mesh. The identical behavior, even for the smallest mesh size of 20 x 20 (1.04 mm), was observed in both full scale and reduced scale experiments.

The full scale experiments using the Firebrand Generator are extremely conservative; the firebrand attack lasted for four minutes. In real WUI fires and urban fires, firebrand attack has been observed for several hours and with winds in excess of 20 m/s [23]. Even under such conservative conditions in the present experiments, ignition was observed behind the 20 x 20 (1.04 mm) mesh for the fine fuels used. While mesh size reduction did mitigate ignition of bare wood crevices, the presence of fine fuels would be expected in attic spaces. When crevices were filled with fine fuels, ignitions were observed down to 14 x 14 (1.55 mm) mesh size, even under the conservative conditions of these experiments.

Due to design of the FRWTF, it was not possible to test using wind speeds higher than 10 m/s. It was also not possible to increase the duration the firebrand attack using the present version of the Firebrand Generator. In real fires, the duration of firebrand attack would most likely be longer than the one simulated presently and increase the potential for a greater number of firebrands to penetrate a given mesh size. Thus, in real fire, it is plausible that a greater number of firebrands would penetrate the mesh (due to increased firebrand attack duration and higher wind speed) and land inside structures as compared to the present experiments, providing favorable conditions for ignition. Therefore, the use of mesh to mitigate ignition is not effective and firebrand resistant vent technologies are needed. The reduced scale Dragon’s LAIR facility has demonstrated that it may be used to assess such technologies to a wind driven firebrand attack.

5.0 SUMMARY

The BRI/NIST full scale and NIST reduced scale 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. The experiments demonstrate that mesh was not effective in reducing ignition for the fine fuels tested and firebrand resistant vent technologies are needed. The results of the experiments conducted by NIST demonstrate that the reduced scale Dragon's LAIR facility was able to reproduce the results obtained from the full scale experiments conducted at BRI. While the Dragon's LAIR facility was used to investigate firebrand penetration through building vents in this study, it is not limited to vents and may be used to expose building materials to a wind driven firebrand attack.

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