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On the ignition of fuel beds by firebrands[‡,§]

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SUMMARY

An experimental apparatus has been built to investigate the ignition of fuel beds as a result of impact with burning firebrands. The apparatus allowed the ignition and deposition of both single and multiple firebrands onto the target fuel bed. The moisture content of the fuel beds used was varied, and the fuels considered were pine needle beds, shredded paper beds and crevices constructed of cedar shingles. Firebrands were simulated by machining wood (*Pinus ponderosa*) into small disks of uniform geometry and the size of the disks was varied. Firebrand simulation was necessary because it is difficult to capture and characterize firebrands from an actual burning object. The firebrand ignition apparatus was installed into the fire emulator/detector evaluator to investigate the influence of an air flow on the ignition propensity of fuel beds. The results of this study are presented and compared with relevant studies in the literature. Published in 2005 by John Wiley & Sons, Ltd.

KEY WORDS: firebrands; urban–wildland fires; ignition; fuel beds

INTRODUCTION

Urban–wildland fires have plagued the United States for centuries. Recent urban–wildland fires include the 2002 Hayman Fire, the 2000 Los Alamos Fire and the 1991 Oakland Hills Fire [1]. The devastation caused by these fires is massive: the Hayman Fire in Colorado burned 137 000 acres and destroyed over 600 structures. As a consequence, fires in the urban–wildland interface can have a devastating effect on human life, property loss and local economies.

Urban–wildland fires result in the deployment of firefighting resources (federal, state and local) in an unpredictable, sporadic fashion designed to minimize losses. A more thorough understanding of the fire-spread dynamics in the urban–wildland interface would allow more accurate predictive capabilities that could be used in firefighting resource management, and rational code and ordinance requirements for land use in fire-prone areas.

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Firebrands are produced as trees and other objects burn in urban–wildland fires. These firebrands are entrained in the atmosphere and may be carried by winds over long distances. Hot firebrands ultimately come to rest and may ignite fuel beds far removed from the fire, resulting in fire spread. This process is commonly referred to as spotting. Understanding how these hot firebrands can ignite surrounding fuel beds is an important consideration in mitigating fire spread in communities.

Three prominent mechanisms have been suggested as to how firebrands ignite structures [2]. It is believed that pine needles in the gutters of homes are susceptible to ignition by firebrand showers. Firebrands may be blown into the attics of homes and ignite materials stored there (e.g. paper, clothing). Finally, the trapping of firebrands in small crevices within structures (e.g. shingle overlap) is thought to be another contributor to fire spread due to firebrand attack.

Unfortunately, ignition due to spotting is one of the most difficult aspects to understand in these fires [3]. Consequently, the ignition of fuels due to firebrand impact has been investigated and some laboratory studies are available in the open literature [3]. Babrauskas [3] provides an excellent, detailed review of such studies. Many of these studies have focused on the experimental methodology specified in the ASTM E108 [4] roof test. Investigations most relevant to the present study are discussed here.

Waterman and Takata [5] investigated firebrand impact on a variety of ignitable materials. The largest firebrands used by Waterman and Takata [5] for ignition studies were 38 mm × 38 mm × 20 mm in size (mass of 3 g). Various smaller-sized firebrands were used for the ignition studies as well. The wind speed and the nature of the applied wind were altered in these tests. A radiant flux was applied in conjunction with firebrand impact to ascertain material ignitability. Ignition probabilities were reported for the various materials considered. Ignitions were observed from 38 mm firebrand impact (unassisted—no radiant flux) for most of the building materials tested. Firebrands smaller than 38 mm were unable to ignite the building materials considered.

Dowling [6] performed experiments to investigate the ignition of wood bridge members due to firebrand impact. In these laboratory experiments, Dowling [6] burned wood cribs, and the resultant firebrands were collected and deposited into a 10 mm gap between the wood bridge members (deck plank and gravel beam). The mass of the firebrands (7–35 g) generated was varied by altering the initial mass of the wood crib. The greater the wood crib mass, the greater the mass of the resultant firebrands. It was observed that 7 g of firebrands were able to produce smoldering ignition of the wood members within the 10 mm gap. The state of the firebrands on deposition into 10 mm gaps, i.e. glowing or flaming, was not specified.

Ellis [7] considered the ignition of pine needles due to eucalyptus firebrand impact. The size of the firebrands considered was 50 mm × 15 mm × 5 mm (mass of 0.7–1.8 g). Both glowing and flaming firebrands were deposited on the pine needles and the moisture content of the pine needles was varied. The air flow across the pine needles was adjusted. Ignition probabilities were reported for the pine needles used. Ellis [7] reported that for flaming eucalyptus firebrands impacting pine needles (with no air flow), all the pine needle targets ignited (flaming ignition) when the moisture content was less than 9%. When glowing eucalyptus firebrands were deposited onto pine needles, flaming ignitions were not observed when no air flow was applied. The probability of flaming ignition (from glowing firebrand impact) increased to 50% when the moisture content of the needles was reduced to less than 3% and an air flow of 1 m/s was applied.

A major advance in urban–wildland fire research would be the development of a model to predict the ignitability of materials due to firebrand impact [3]. Some theories have been published [8], but the lack of a detailed theory on the ability of firebrands to ignite remote objects limits the utility of detailed computational fluid dynamic models that could be used to predict fire spread by firebrands [3]. Detailed experimental ignition studies of fuel beds typically found in the urban–wildland interface due to firebrand impact are required to validate such models.

Consequently, the goal of this study is to investigate firebrand ignition of fuel beds found in the urban–wildland interface. To this end, this paper describes an apparatus that has been constructed to investigate the ignition propensity of the materials due to the impingement of firebrands. The apparatus allowed the ignition and deposition of *single* and *multiple* firebrands onto a target fuel bed. The ability to deposit multiple firebrands onto a target fuel bed is important, as most homes and other structures are bombarded by firebrand showers in urban–wildland interface fires. The moisture content of the fuel beds used was varied and the fuels considered were pine needle beds, shredded paper beds and crevices constructed of cedar shingles. Shredded paper beds were used as a surrogate for typical cellulosic fuels that are found in attic spaces. Pine needle beds were intended to simulate gutters filled with pine needles. Crevices were constructed to simulate the trapping of firebrands under shingles on roofs of homes and other structures. The apparatus was designed to be implemented into the fire emulator/detector evaluator (FE/DE). The FE/DE was used here as a wind tunnel to investigate the influence of an air flow on the ignitability of fuel beds. Finally, the experimental results presented here were compared with relevant studies available in the literature.

EXPERIMENTAL DESCRIPTION

Figure 1 is a schematic of the experimental apparatus used for firebrand impact studies. The firebrand ignition apparatus consists of four butane burners and a firebrand mounting probe. The butane flowrate is controlled by a metering valve coupled to a solenoid valve. The firebrand or, in the case of multiple firebrand impact, firebrands are held in position and the air pressure is activated, which moves the actuator and clamps the firebrand(s) into position.

The motion of butane burners is displayed in Figure 1. The butane torches are mounted on a sliding bracket that is coupled to a linear actuator. After the firebrands are mounted, the spark is activated and the fuel solenoid is opened. The butane burners are ignited and, through the use of another linear actuator, the entire assembly is moved into position under the firebrand(s). The retraction of the burner on ignition and the free-burn time of the firebrands are computer controlled, which ensures repeatability. Each butane burner was designed to be switched on or off, depending on the number of firebrands needed for the particular experiment.

As mentioned, the experimental apparatus was designed to release and deposit multiple firebrands simultaneously. It was important to space each firebrand carefully when performing multiple firebrand ignition studies. The reason for this is that it was desired to simulate the flux of multiple firebrands onto a fuel bed. If the firebrands were aligned too closely, they would not burn in the space between each firebrand. As a result, under such conditions, it was not possible to produce glowing firebrands. Therefore, a series of brass spacers was used to hold the firebrands in place. Up to four firebrands were loaded into the firebrand ignition apparatus. All firebrands were ignited with the grain oriented vertically.

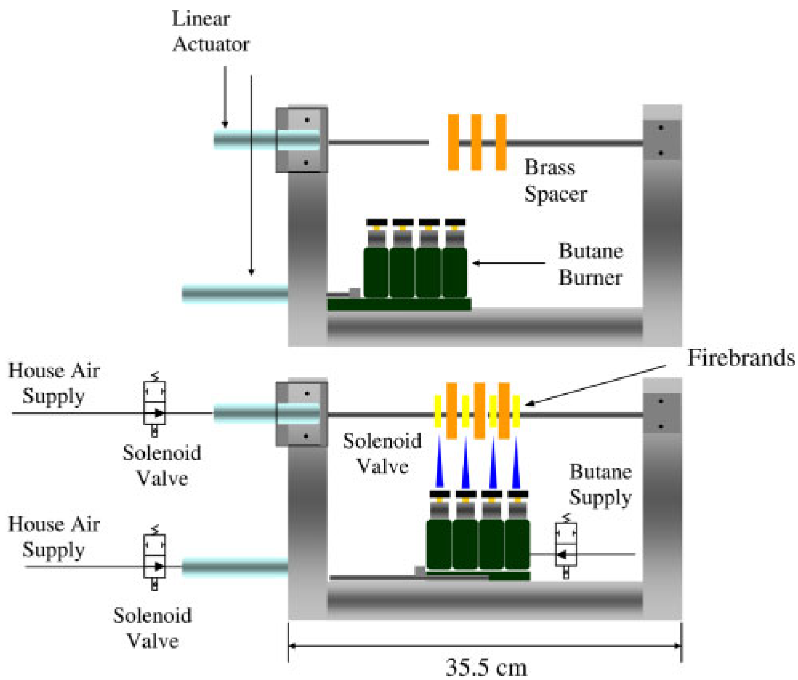


Figure 1. Schematic of the firebrand ignition and release apparatus, which demonstrates the loading process for four firebrands.

The firebrand ignition apparatus was installed in the duct of the FE/DE. The FE/DE is described elsewhere [9,10] and was used here as an air flow source for the experiments. The FE/DE allowed air flow rates up to 3 m/s, and these velocities were verified through laser Doppler velocimetry measurements.

Firebrands were simulated by machining wood into sections of uniform geometry. Firebrand simulation was necessary because it is difficult to capture firebrands from burning objects [5]. An important consideration in simulating firebrands is in the size and shape [3, 11–13], because it is these properties that determine the lofting characteristics and burn time of the firebrands.

For the present study, firebrands were simulated as disks of two different sizes. The first size produced was 25 mm in diameter with a thickness of 8 mm. The second size used was 50 mm in diameter and 6 mm thick. Disks are believed to be a representative shape that can easily be generated in urban–wildland fires [12–14]. In addition, disks of this size range are capable of being lofted over long distances [12–14].

Ponderosa pine (*Pinus ponderosa*) was selected as the wood type for these experiments because it is abundant in the western United States, and it is here that urban–wildand fires are most prevalent [15]. Prior to machining the disks, the ponderosa pine planks were stored in a conditioning room at 21°C and 50% relative humidity. After the disks were machined, they were stored in the conditioning room prior to the experiments.

Three different materials were used as test fuel beds for the ignition studies: (1) pine needles, (2) shredded paper and (3) cedar wood. The impact of burning firebrands on pine needle beds

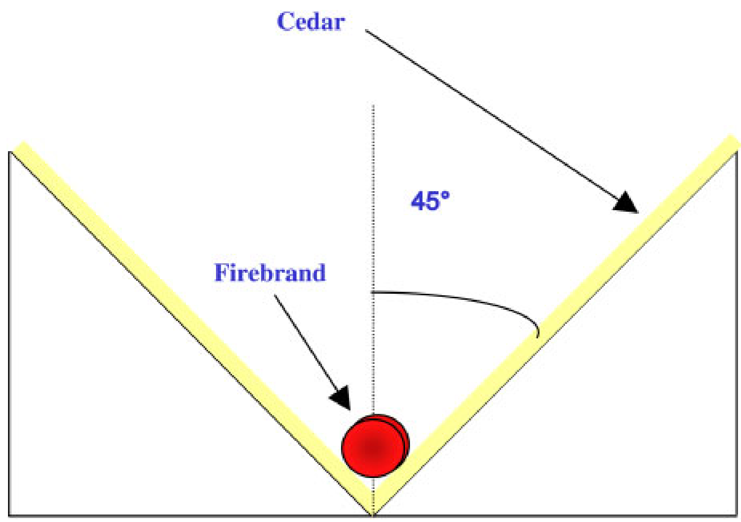


Figure 2. Schematic of the crevice used for ignition experiments. Cedar shingles were used.

was designed to simulate the showering of firebrands into gutters. Shredded paper beds were used to simulate firebrand impact upon materials within attic spaces. Crevices were simulated by using cedar shingles installed in a V-shaped duct (see Figure 2). The pine needles and shredded paper were contained in aluminium foil pans of 23 cm length × 23 cm width × 5.1 cm depth. The initial mass was fixed for the fuel beds to ensure repeatability. The moisture content of these materials was varied from 0 to 11%, and was determined by oven drying the samples. It was found that 3 h of oven drying at 104°C was sufficient to remove all the moisture in the pine needle beds, shredded paper beds and cedar shingles used to construct crevices.

The firebrand ignition process and release onto the target fuel beds was captured using a CCD camera coupled to a zoom lens. The zoom lens is used to obtain the required spatial resolution to resolve the fuel bed ignition due to firebrand impact. In addition, high-resolution digital still photography (2084 × 1024 pixel resolution) was used to capture the ignition of the target fuel bed due to firebrand impact.

In the firebrand transport process, firebrands are formed, ignited and land on fuel beds. To be a threat to the environment, the firebrands must land on fuel beds and still be burning. Therefore, it is important to determine the burning history of simulated firebrands as a function of disk size and air flow. Firebrands were ignited for a fixed duration and were allowed to free burn. The firebrands were then released onto a load cell, and the burning history of the firebrands was obtained from gravimetric measurements. Figure 3 displays results obtained for *Pinus ponderosa* disks. Each data point is the average of five measurements and the error bars display the standard deviation.

Three conditions are shown in the figure: (1) no air flow, (2) an air flow of 0.5 m/s and (3) an air flow of 1.0 m/s. No air flow conditions were used presently to investigate the influence of an air flow on firebrand burning only. Under air flow conditions, the firebrands were ignited under low flow conditions and the air flow was ramped up as soon as the ignition process was over. The ignition time for 25 and 50 mm firebrands was 30 and 45 s, respectively. Under no air flow

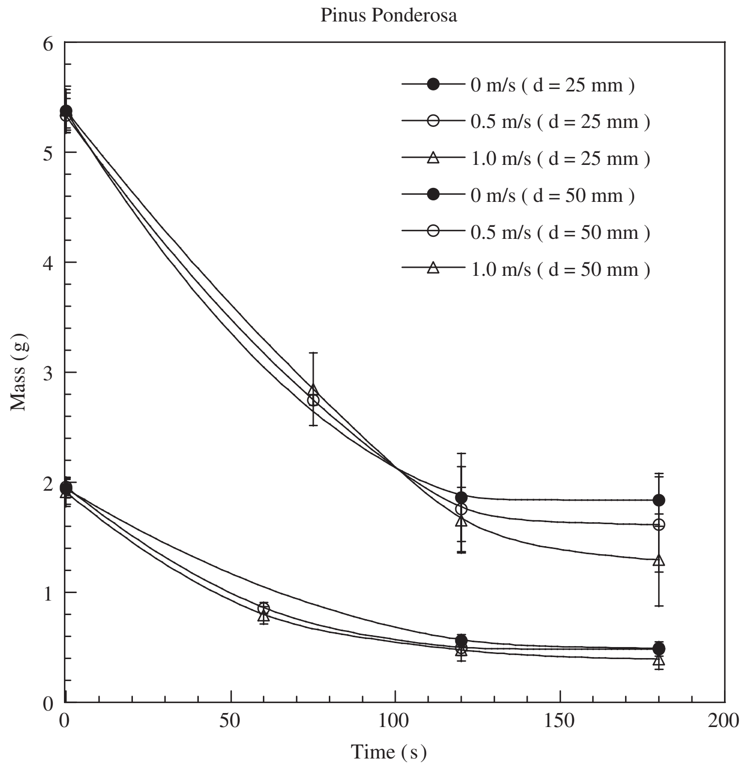


Figure 3. Variation in firebrand mass loss as a function of air flow velocity (note: a 50 mm firebrand corresponds to higher initial mass).

conditions, the firebrand remained in a flaming state. When an air flow was introduced, the air flow blew off the envelope flame from the leading edge of the firebrand and gradually blew the flame off the back side of the firebrand. After the flame was blown off, a glowing firebrand resulted.

The firebrands were released onto the target fuel beds in both a flaming state and a glowing state. A glowing firebrand was obtained when the attached flame was blown off completely. 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 [5, 11]. However, it is possible for firebrands to remain in a flaming state under an air flow, and therefore it is reasonable to assume that some firebrands may still be flaming upon impact [3]. As a result, the ignition propensity of the pine needle beds, shredded paper beds and cedar crevices was assessed based on *both* glowing and flaming firebrand impact.

When the burning firebrands were deposited onto fuel beds, experiments were performed only under conditions of an air flow (0.5 and 1.0 m/s), because it is not expected that the flow conditions would be quiescent as firebrands impact fuel beds during urban–wildland fires. It is important to note that the ambient temperature inside the duct of the FE/DE was monitored and fixed at 21°C for all experiments reported here. Ambient temperature conditions are known to influence ignition outcomes for fuel beds [16].

DISCUSSION

Single firebrand ignition results

Experiments were performed for single firebrand impact (both flaming and glowing) to investigate whether it was possible to ignite fuel beds under such conditions. Plate 1 displays characteristic images of glowing firebrands that were released onto the fuel beds. The ignition results obtained for single glowing firebrand impact into pine needle beds are displayed in Table I. Each result was based on identical, five repeat experiments. The mass of a single glowing firebrand at the time of release into the fuel bed was 0.5 and 1.5 g for the 25 and 50 mm firebrands, respectively. The acronym NI denotes no ignition.

For the firebrand sizes tested and the experimental combination tested, it was not possible to ignite pine needle beds from single glowing firebrand impact. After the firebrand impacted the pine needle bed, one or two needles would smolder and the smolder front would not propagate further in the bed. The results of single glowing firebrand impact with a dried pine needle bed are shown in Plate 2.

Table I displays results obtained for single glowing firebrand impact into shredded paper beds. The acronym SI denotes smoldering ignition. Smoldering ignition was possible for single glowing firebrand impact. Presently, smoldering ignition was defined when the smoldering front propagated outwards from the deposited firebrand into the bed. This is shown pictorially in Plate 3. When the shredded paper beds were dried, smoldering ignition was observed in all cases. As the moisture content of the shredded paper bed was increased, ignition was not possible for the 25 mm firebrands under the conditions of an air flow of 0.5 m/s. As the air flow was increased, it was possible to ignite shredded paper at 11% moisture using the 25 mm firebrands.

Table I. Firebrand ignition data for firebrand impact on pine needle beds, shredded paper beds and cedar crevices.

Number of firebrands deposited	State of firebrand at impact	Air flow (m/s)	Firebrand size (mm)	Pine needles		Shredded paper		Cedar crevice	
				Dry	11%	Dry	11%	Dry	11%
1	Glowing	0.5	25	NI	NI	SI	NI	NI	NI
1	Glowing	0.5	50	NI	NI	SI	SI	NI	NI
1	Glowing	1	25	NI	NI	SI	SI	NI	NI
1	Glowing	1	50	NI	NI	SI	SI	NI	NI
1	Flaming	0.5	25	FI	FI	FI	FI	NI	NI
1	Flaming	0.5	50	FI	FI	FI	FI	FI	NI
1	Flaming	1	25	FI	FI	FI	FI	NI	NI
1	Flaming	1	50	FI	FI	FI	FI	FI	NI
4	Glowing	0.5	25	NI	NI	NT	NT	NI	NI
4	Glowing	0.5	50	NI	NI	NT	NT	NI	NI
4	Glowing	1	25	NI	NI	NT	NT	NI	NI
4	Glowing	1	50	SI to FI	SI to FI	NT	NT	NI	NI
3	Flaming	0.5	25	NT	NT	NT	NT	FI	FI
3	Flaming	0.5	50	NT	NT	NT	NT	FI	FI
3	Flaming	1	25	NT	NT	NT	NT	FI	FI
3	Flaming	1	50	NT	NT	NT	NT	FI	FI

Ignition events were not observed when single glowing firebrands were deposited onto cedar crevices (see Table I). Consequently, it was observed that single glowing firebrands posed an ignition danger only to shredded paper beds.

Table I shows ignition results for single flaming firebrand impact onto pine needle beds, shredded paper beds and cedar crevices. To produce flaming firebrands, the firebrands were ignited and then allowed to free burn for 30 s prior to release into the samples. The mass of a single flaming firebrand at release into the fuel bed was 1 and 2.9 g for the 25 and 50 mm firebrands, respectively. The acronym FI denotes flaming ignition. Under all conditions considered, it was possible to produce flaming ignition from single firebrand impact when the firebrands were released in a flaming state onto pine needle beds and shredded paper beds. These results suggest that if the firebrands are in flaming mode, only a single firebrand is required to begin an ignition event for these materials. The ignition process due to a single flaming firebrand impacting a pine needle bed is shown in Plate 4.

For cedar crevices, it was possible to produce ignition *only* when single 50 mm flaming firebrands were deposited onto dried cedar. This implies that under the conditions presented in this study, single flaming firebrands are a threat for crevices constructed from dried wood.

Multiple firebrand ignition results

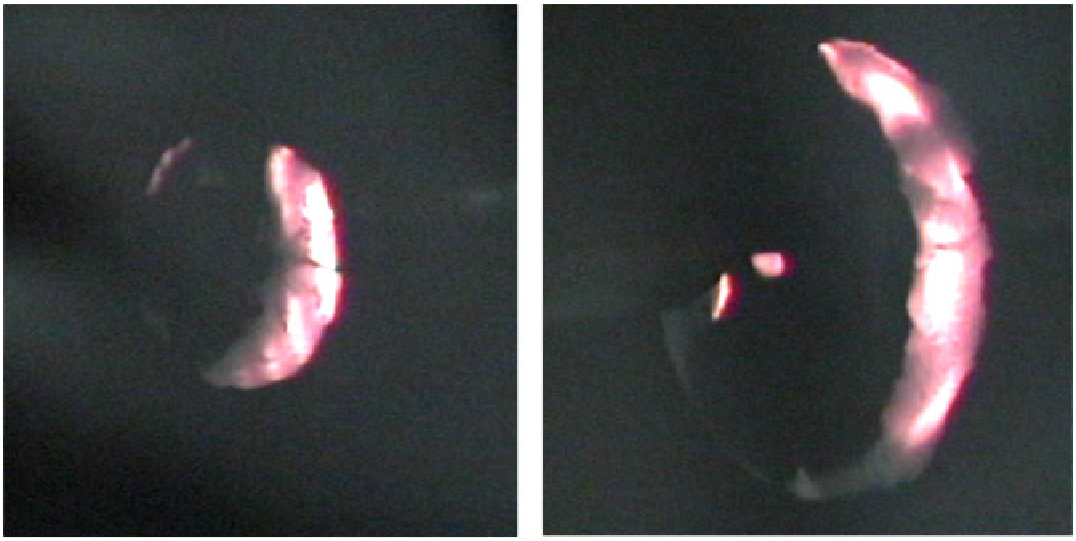
It was apparent from the single firebrand ignition studies that it was possible to ignite shredded paper beds from single glowing firebrand impact. This result suggests that it may not require a large flux of firebrands to ignite a home, provided the firebrands are able to penetrate attic spaces. On the other hand, for single flaming firebrands, it was possible to ignite pine needle beds and shredded paper beds, but cedar crevices were more resistant to ignition. Only 50 mm firebrands that landed on *dried* cedar caused ignition. Therefore, on the basis of these findings, the flux of firebrands is clearly an important parameter that must be considered.

The experiments were repeated, but now multiple firebrands were deposited on pine needle beds and cedar crevices. Since ignition was possible under conditions of single firebrand impact for shredded paper beds (both glowing and flaming), multiple firebrand impact experiments were not performed using this material. In addition, single flaming firebrands were able to ignite pine needle beds and shredded paper; thus multiple flaming firebrand experiments were not conducted for these materials. These cases are denoted by the acronym NT, for not tested (see Table I).

Table I displays ignition results obtained for multiple glowing firebrand impact on pine needle beds. The deposition of four 25 mm glowing firebrands did not produce an ignition event under the conditions tested. For the 50 mm glowing firebrands, smoldering ignition was observed to occur when four firebrands were deposited on pine needle beds under an air flow of 1.0 m/s. Under an air flow of 0.5 m/s, 50 mm glowing firebrands did not produce an ignition. When four 50 mm glowing firebrands were deposited on pine needle beds, smoldering was observed followed by a transition to flaming combustion under an air flow of 1.0 m/s.

The following conclusions were drawn from the pine needle bed experiments. Pine needle bed ignition was only observed for glowing firebrand impact under conditions of multiple firebrand deposition. The sizes of the firebrands, as well as the degree of the air flow, were important parameters in determining ignition.

Ignition results observed for multiple glowing firebrand impact on cedar crevices are shown in Table I. Glowing firebrands were unable to ignite cedar crevices under the conditions tested. The



(a) (b)

Plate 1. Glowing firebrand: (a) $d_0 = 25\,\mathrm{mm}$; (b) $d_0 = 50\,\mathrm{mm}$.

Plate 2. Glowing firebrand, $d_0 = 25\,\mathrm{mm}$, on a pine needle bed at 0% moisture content. No ignition was obtained.

Plate 3. Single glowing firebrand which produced smoldering ignition in a shredded paper bed at 11% moisture content, $d_0 = 25\,\text{mm}$.

Plate 4. Single flaming firebrand which produced flaming ignition in a pine needle bed held at 11% moisture, $d_0 = 25\,\text{mm}$.

flux of flaming firebrands deposited on cedar crevices was varied as well (see Table I). A critical flux of three flaming firebrands was required to achieve ignition for multiple flaming firebrands into moist cedar crevices. As mentioned, when the constructed cedar crevice samples were dried, it was observed that only one 50 mm flaming firebrand was required to produce ignition.

Comparison with prior firebrand ignition studies

It is useful to compare the present pine needle results with those obtained by Ellis [7]. Ellis [7] reported that for flaming eucalyptus firebrands impacting pine needles (with no air flow), all the pine needle targets ignited (flaming ignition) when the pine needle moisture content was $<9\%$. When glowing eucalyptus firebrands were deposited onto pine needles, flaming ignitions were not observed when no air flow was applied. The probability of flaming ignition (from glowing firebrand impact) increased to 50% when the moisture content of the pine needles was reduced to $<3\%$ and an air flow of 1 m/s was applied.

Under all conditions considered in the present study, it was possible to produce flaming ignition of pine needle beds from flaming firebrand impact (the minimum firebrand mass for ignition was 1 g). This result agrees qualitatively with the findings of Ellis [7]. No ignitions were observed presently for pine needle beds as a consequence of single glowing firebrand impact over the range of moisture contents studied. Smoldering ignition with a subsequent transition to flaming ignition was observed when four 50 mm glowing firebrands (mass 6.0 g) were deposited on the pine needle beds, with an air flow of 1 m/s (over the range of pine needle moisture content considered). The results obtained for glowing firebrand impact differ from those of Ellis [7]. The main reasons for the differences between the present study and that of Ellis [7] may be due to (1) differences in firebrand geometry and (2) firebrand composition (eucalyptus firebrands versus ponderosa pine firebrands). Woycheese [12,13] has shown that the particular species of wood influences the burning process. This, in turn, may influence the characteristics of the glowing firebrand generated.

Dowling [6] performed experiments to investigate the ignition of wood bridge members due to firebrand impact. It was observed that 7 g of firebrands were able to produce smoldering ignition of the wood members within the 10 mm gap. The size and total number of these firebrands were not reported by Dowling [6].

In the present study, for flaming firebrands, one 50 mm firebrand was needed to ignite dried cedar crevices and produce flaming ignition. For moist crevices, a minimum of three 25 mm flaming firebrands was required to produce flaming ignition of cedar crevices. Four 50 mm glowing firebrands (mass 6.0 g) were unable to produce an ignition event for cedar crevices. Dowling [6] did not mention explicitly whether the firebrands used in his investigation were glowing or flaming, so a direct comparison to his results is difficult. If it is assumed that his firebrands were indeed glowing, the present findings suggest that 6.0 g of glowing firebrands are insufficient to ignite cedar crevices, which agrees qualitatively with the results of Dowling [6].

CONCLUSIONS

This paper has described an apparatus that was constructed to investigate the ignition propensity of materials due to the impingement of firebrands. The apparatus allowed the ignition and deposition of *single* and *multiple* firebrands onto a target fuel bed. The ability to deposit multiple firebrands onto a target fuel bed is important, as most homes and other structures are bombarded by firebrand showers in urban–wildland interface fires. The moisture content of the fuel beds used was varied, and the test fuel beds considered were pine needle beds, shredded paper beds and crevices constructed of cedar shingles. Shredded paper beds were used as a surrogate for typical cellulosic fuels that are found in attic spaces. Pine needle beds were intended to simulate gutters filled with pine needles. Crevices were constructed to simulate the trapping of firebrands under shingles on roofs of homes and other structures. The apparatus was designed to be implemented into the FE/DE. The FE/DE was used here as a wind tunnel to investigate the influence of an air flow on the ignitability of fuel beds.

It was apparent from the single firebrand ignition studies that it was possible to ignite shredded paper beds from single glowing firebrand impact. This result suggests that it may not require a large flux of firebrands to ignite a home, provided the firebrands are able to penetrate attic spaces. Multiple glowing firebrands were unable to ignite cedar crevices.

On the other hand, for single flaming firebrands, it was possible to ignite pine needle beds and shredded paper beds, but cedar crevices were more resistant to ignition. Only 50 mm firebrands that landed on *dried* cedar caused ignition. The critical flux of three flaming firebrands was required to achieve ignition for moist cedar crevices.

On the basis of these findings, the flux of firebrands, the size of firebrands, and the degree of air flow are important parameters to determine the ignition propensity of a fuel bed. It is desired that these results, in conjunction with other literature studies, will be used to validate firebrand ignition models.

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