Structure Vulnerability to Firebrands from Fences and Mulch

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Abstract—Fences and mulch contribute to the spread of wildland-urban interface fires, acting both as ignition targets and as sources that may ignite nearby objects through direct flame contact and firebrand generation.

This paper presents the findings from outdoor experiments that investigated the spread of fire through firebrand spotting from fences and mulch beds near a structure in a wind field. A fence section, mulch bed, or combination was arranged perpendicular to a small structure, with a large fan directing wind toward the structure. After ignition, data were collected on firebrand spotting time, time for the spot fire to reach the wall, and flame spread rate over the fence and mulch bed.

Fence type, wind speed, and type of mulch were found to affect firebrand spotting. For fence and mulch combinations, spotting usually occurred within 7 minutes. Time to spotting generally decreased with increasing wind speed. Two parallel fence panels burned significantly more intensely, and spotted more quickly, than a single fence panel. In the absence of mulch, spotting from fences often occurred more slowly or not at all. The combination of a fence and a mulch bed decreased the time to spotting over either the mulch bed or the fence alone.

Keywords: fence, firebrand, mulch, structure vulnerability, wildland-urban interface (WUI) fire

INTRODUCTION

Wildland-urban interface (WUI) fires threaten an estimated 70,000 communities, 46 million homes, and 120 million people within the United States (ICC and NARCD Councils 2013). In recent years, the United States has been losing on the order of 3,000 homes per year, and the costs are rising, with $14 billion spent in 2009 alone on fire suppression and damages.

Firebrands generated by a wildfire are carried by the wind and may ignite fires in a community far downstream of the fire front. After the fire has reached the community, firebrands generated from burning combustible objects near a structure contribute to the firebrand assault. Postfire investigations have demonstrated that firebrands are a major contributor to structure losses in WUI fires.

Fences and mulch are common contributors to the spread of WUI fires within WUI communities. They act both as ignition targets and as sources that may themselves ignite nearby objects through direct flame contact and firebrand generation. The linear nature of fences gives them the capability of spreading fire over long distances. In a study of the 2011 Tanglewood Complex Fire near Amarillo, Texas performed by the National Institute of Standards and Technology (NIST) (Maranghides and McNamara 2016), 2.4 km of fences within a community of 25 homes were found to be damaged or destroyed. Combustible fences also contributed to fire spread in the 2012 Waldo Canyon Fire in Colorado (Maranghides et al. 2015). Firefighters were documented removing fences as part of their defensive strategy to contain this fire, reducing resources allocated to suppression.

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The goal of this work is to improve our understanding of the mechanisms by which fences and other combustible landscaping elements can transport fire to a home, including exposure to wind-driven firebrands. The results will be used to improve codes and standards, which in turn will provide guidance to homeowners and firefighters.

EXPERIMENTAL DESIGN

Setup

To investigate the spread of fire through firebrand spotting, a series of field experiments are being performed on fences, mulch beds, woodpiles, and other combustible landscaping elements arranged in front of a structure in a wind field.

Figure 1 shows a schematic of the experimental setup for fences and mulch beds. A wind machine, consisting of an airboat fan mounted on a trailer, was aimed toward a small structure. A flow straightener directed the wind downward slightly so the wind field would reach the ground and the base of any combustible object being tested. A fence section, with or without a mulch bed beneath, was arranged perpendicular to the wall of the structure. The fence section was 2.44 m long and 1.83 m high for privacy fences or 1.22 m high for lattice fences, attached to 0.09 m × 0.09 m pine (*Pinus* spp.) posts at each end. The fence or mulch bed was placed in contact with the wall of the structure or separated from it by some fixed distance.

To study the ability of firebrands to threaten a house, a target pan of hardwood mulch that was 0.46 m wide was arranged at the base of the structure wall. This mulch bed served as a surrogate for any combustible material next to a house. Because of its rough texture, any firebrands landing on this surface tended to stay in place.

Before being arranged in steel pans, the mulch was dried to a moisture content between 6 and 7 percent, as measured by a moisture analyzer. The mulch beds were prepared by filling the pans with an even layer of mulch and compressing it lightly by foot. The mulch beds were 0.05 m thick except for cases in which the mulch beds were reduced to half thickness (0.025 m).

The wind field was monitored by a set of bidirectional probes just upwind of the end of the fence. The ambient wind speed and direction were measured by

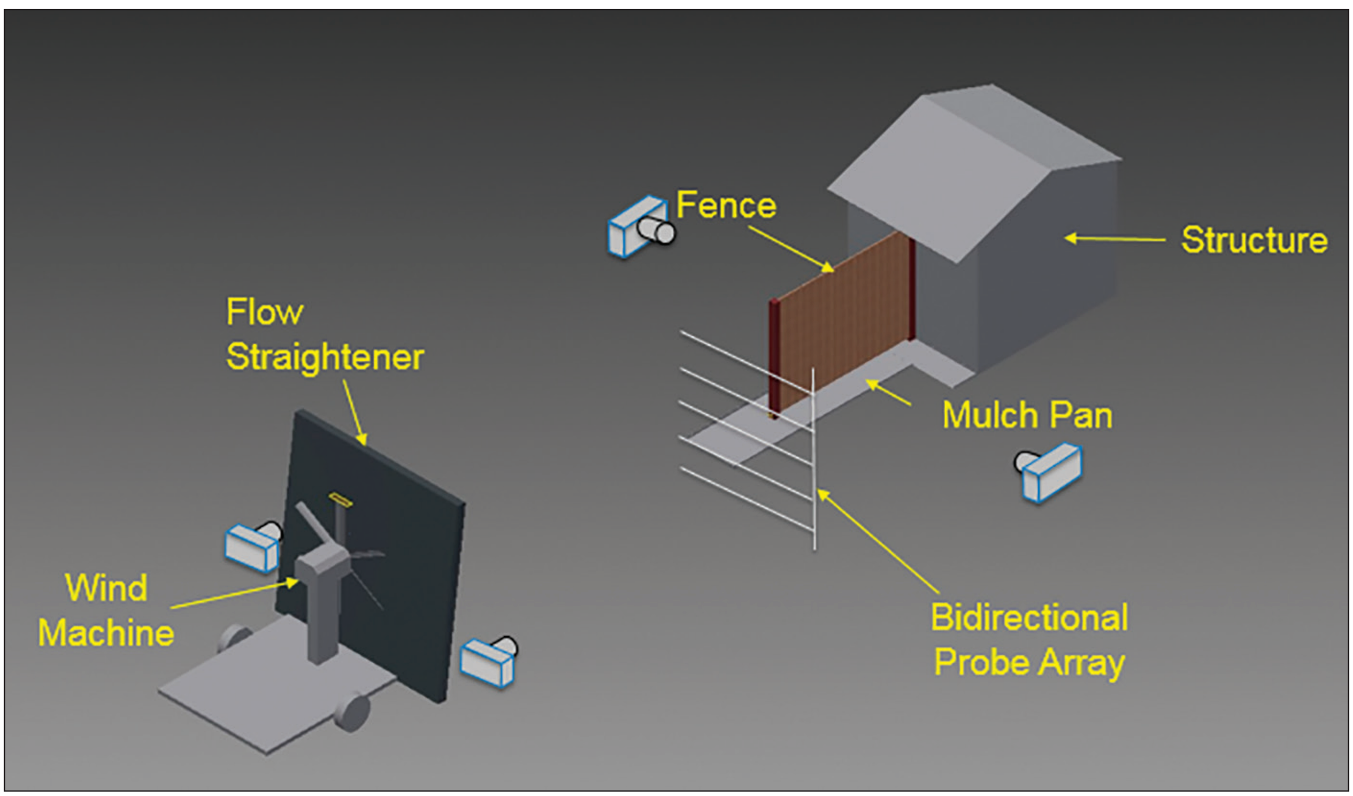

Figure 1—Experimental setup.

an anemometer mounted on a shed away from the experimental setup, and the ambient temperature was measured with a thermocouple near the test setup. Four video cameras monitored the experiment from right and left sides and from each side of the fan.

The ambient wind speed was required to be less than one-third the nominal wind speed in order to carry out the experiment. Under these conditions, the impact of the ambient winds on the wind field generated by the fan was minimal.

Procedure

A propane burner was used to ignite the fence or mulch bed at the base of the fence farthest from the structure. After 90 seconds, when the fire was judged to be self-sustaining, the fan was turned on, a timing clock was started, and the winds were brought to the speed required by the experiment. The experiment ended when a fire in the mulch bed at the base of the structure reached the wall and after fire had also reached the end of the fence or fence mulch bed. Flames at the wall from spot fires were extinguished if the fire had not yet spread over the entire length of the fence with mulch bed. At the end of the test, the clock was reset and all fires were extinguished with a water hose.

Uncertainties

The measurements of wind speed, distances, and times discussed in this paper each have uncertainties associated with them. Uncertainties generally consist of several components, which are grouped into two categories according to the method used to estimate their value. Type A uncertainties are evaluated by statistical methods, and type B uncertainties are evaluated by other means, often based on scientific judgment using all available relevant information (Taylor and Kuyatt 1994). Type B uncertainties are evaluated by estimating lower and upper limits a_- and a_+, such that the probability that the value lies in the interval a_- to a_+ is essentially 100 percent. If the value is equally probable to lie anywhere within the interval, the best estimate is $(a_+ + a_-)/2$, with standard deviation $u_j = a/\sqrt{3}$, where $a = (a_+ - a_-)/2$. Once all components have been estimated by either type A or type B analysis, they are combined using the square root of the sum of the squares (RSS) method to yield the combined standard uncertainty (estimated standard deviation), u_c. Finally, expanded uncertainties are given by $\pm ku_c$, where $k = 2$ is the coverage factor for a confidence level of 95 percent.

Table 1 shows the components of uncertainty for the measurements given in this paper. The extensive data collection on wind speed enables the evaluation of type A uncertainties; most other uncertainties on this list are type B, either estimated through scientific judgment or obtained from the literature.

Wind speed uncertainties involve the bidirectional probe design and the measurement statistics from the wind field. A paper by McCaffrey and Heskestad (1976) states that velocities are estimated within ±10 percent provided the approach flow direction is within approximately 50° of the probe axis. Since the variability of the fan was greatest at the lowest setting, which was close to the idle speed, statistical analysis was carried out for each wind speed level separately. Repeatability was calculated as the standard deviation of the average wind speed for each experiment (the average from five probes in the central wind field) from the average wind speed overall. The random component reflects the fluctuations in measured wind speed due to turbulence, and was calculated by the root-mean-square of the standard deviations of wind speed over all experiments at each wind speed level.

The time to spotting required identification of two events in videos taken by the camera positioned to the right or left side of the experiment. The first event was the time at which the fan was turned on. The engagement of the fan engine could be determined very accurately, although it should be noted that the wind speed was adjusted for up to 20 seconds afterwards before reaching a steady state value. The second event was the ignition within the target mulch bed of the first spot fire that eventually reached the wall of the structure. After identification in one of the videos, this spot fire was tracked backwards in time to the point at which the first sign of smoke could be detected in the mulch, which could be defined within an estimated ± 5 seconds. These sources of uncertainty are likely dwarfed, however, by the repeatability of time to spotting for multiple tests under the same conditions and the random nature of firebrand generation and ignition processes, neither of which is available for this study.

Table 1—Uncertainty in experimental data.

Measurement	Component standard uncertainty, ± u_j	Combined standard uncertainty, ± u_c	Total expanded uncertainty, ± $2u_c$
Wind speed			
Calibration	±10%		
Repeatability*			
6 m sec-1	±11%		
10 m sec-1	±6%		
14 m sec-1	±8%	6 m sec-1: ±24%	6 m sec-1: ±48%
Random*		10 m sec-1: ±15%	10 m sec-1: ±31%
6 m sec-1	±19%	14 m sec-1: ±15%	14 m sec-1: ±30%
10 m sec-1	±10%		
14 m sec-1	±8%		
Time to spotting			
Fan on	±1 sec		
Smoke detected	±3 sec	> ±3 sec	> ±6 sec
Repeatability*	Unknown		
Random*	Unknown		
Separation distance			
Placement	±0.002 m	±0.004 m	±0.008 m
Adjustment	±0.003 m		
Mulch thickness			
Variability	±0.005 m	±0.005 m	±0.010 m
Target mulch bed width			
Variability	±0.01 m	±0.01 m	±0.02 m

* Type A uncertainty (evaluated by statistical means). All other uncertainties are type B (evaluated by other than statistical means).

The separation distance between the fence or mulch bed and the wall of the structure was established by using a tape measure to adjust the location of the fence with mulch bed to the desired position. Sources of uncertainty include the placement of the tape measure and the ability to adjust the position of the fence with mulch bed accurately.

The mulch bed thickness varied over its surface due to the nature of the mulch as overlapping particles whose individual thicknesses are an appreciable fraction of the thickness of the mulch layer. The mulch bed thickness depended on the evenness of the spreading over the mulch bed and the uniformity of the compaction.

The target mulch bed at the base of the shed was not confined by a lip on the outside edge facing the fence, allowing firebrands to land on the target mulch without needing to clear a height. The width of the target mulch bed thus varied over its length.

Variations of dimensional values were estimated using scientific judgment.

Experimental Combinations

During 2016 and 2017, 111 experiments were carried out in the configuration just described. Figure 2 shows the distribution of experiments that have been performed on a variety of combinations of fences and mulch, at four separation distances from 0 m to 1.8 m, and at three wind speeds of 6 m second^{-1}, 10 m second^{-1}, and 14 m second^{-1}. The fences include privacy fences constructed of western redcedar (*Thuja plicata*) and vinyl and lattice fences constructed of redwood (*Sequoia* spp.) and pine. The mulches include shredded hardwood mulch at two thicknesses, pine bark mulch, and pine straw mulch.

RESULTS

Burning Characteristics for a Privacy Fence with Mulch Bed

Figure 3 shows an image from a typical experiment with a western redcedar fence sitting in a bed of shredded hardwood mulch. In this experiment, the wind speed was 10 m second^{-1} and the separation distance between the end of the fence and the small structure was 1.8 m. This image shows the conditions at about 4.5 minutes after the fan was turned on following ignition of the fence and mulch. At this point firebrands had ignited spot fires in the mulch bed at the base of the structure at several locations. A few spot fires can be seen at the front edge of the mulch bed, in addition to one close to the wall. The fence itself was burning along its entire length, although discoloration and other signs of deterioration show that the fire has remained low on the fence, not even reaching half of its height.

Other phenomena apparent from the video itself include pieces of mulch that moved out of the bed under the structure and rolled on the pavement toward the fence or the sides of the experiment. The smoke and flames from the combination of fence and mulch bed generally extended toward the structure, while smoke and flames from the mulch bed at the base of the structure extended toward the fence. These observations are consistent with a horseshoe vortex that occurs at the base of a structure at right angles to a flow stream (Martinuzzi and Tropea 1993). Figure 4 shows this feature in a model of the experimental

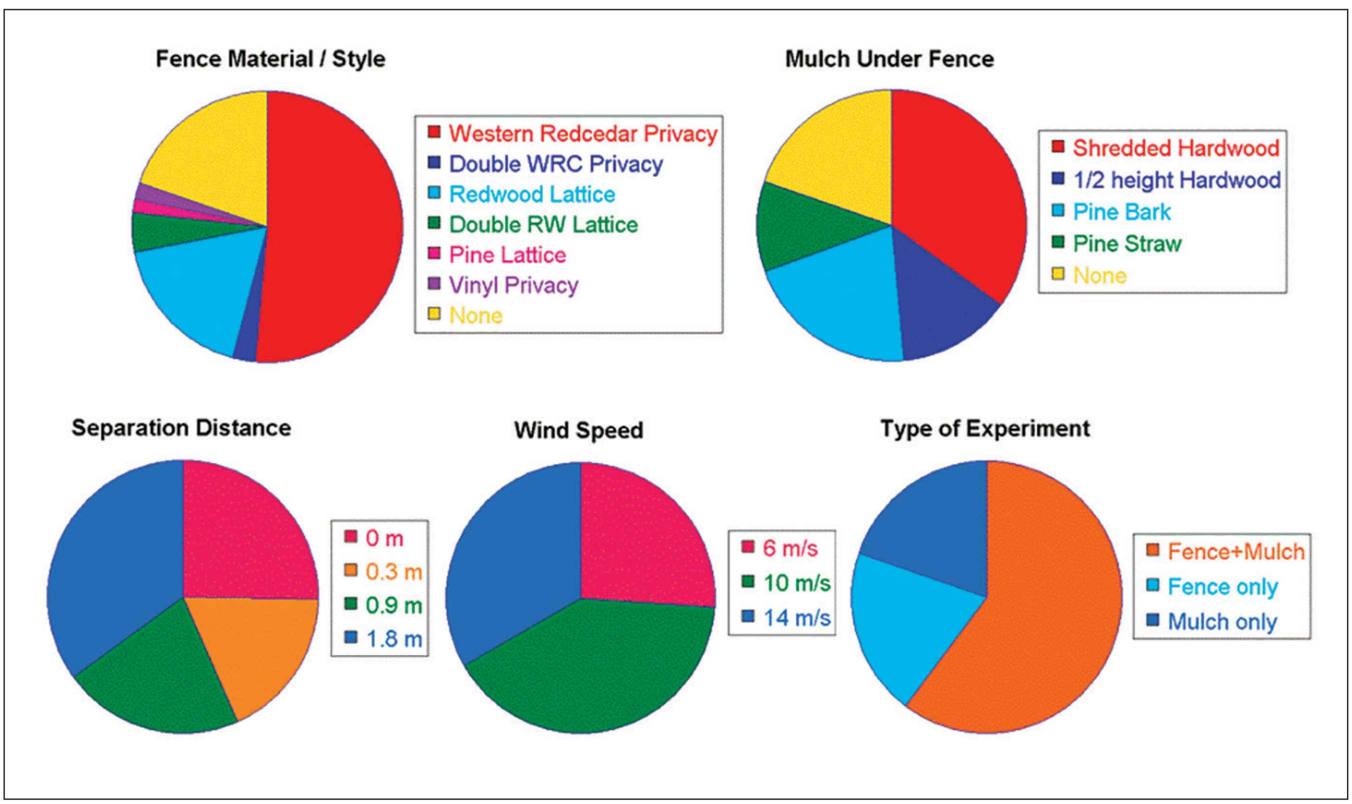

Figure 2—Distribution of experiments by fence type, mulch type, separation distance from wall, wind speed, and experiment type (fence with mulch beneath, fence only, or mulch only). WRC = western redcedar.

Figure 3—Image from video of western redcedar fence combined with shredded hardwood mulch.

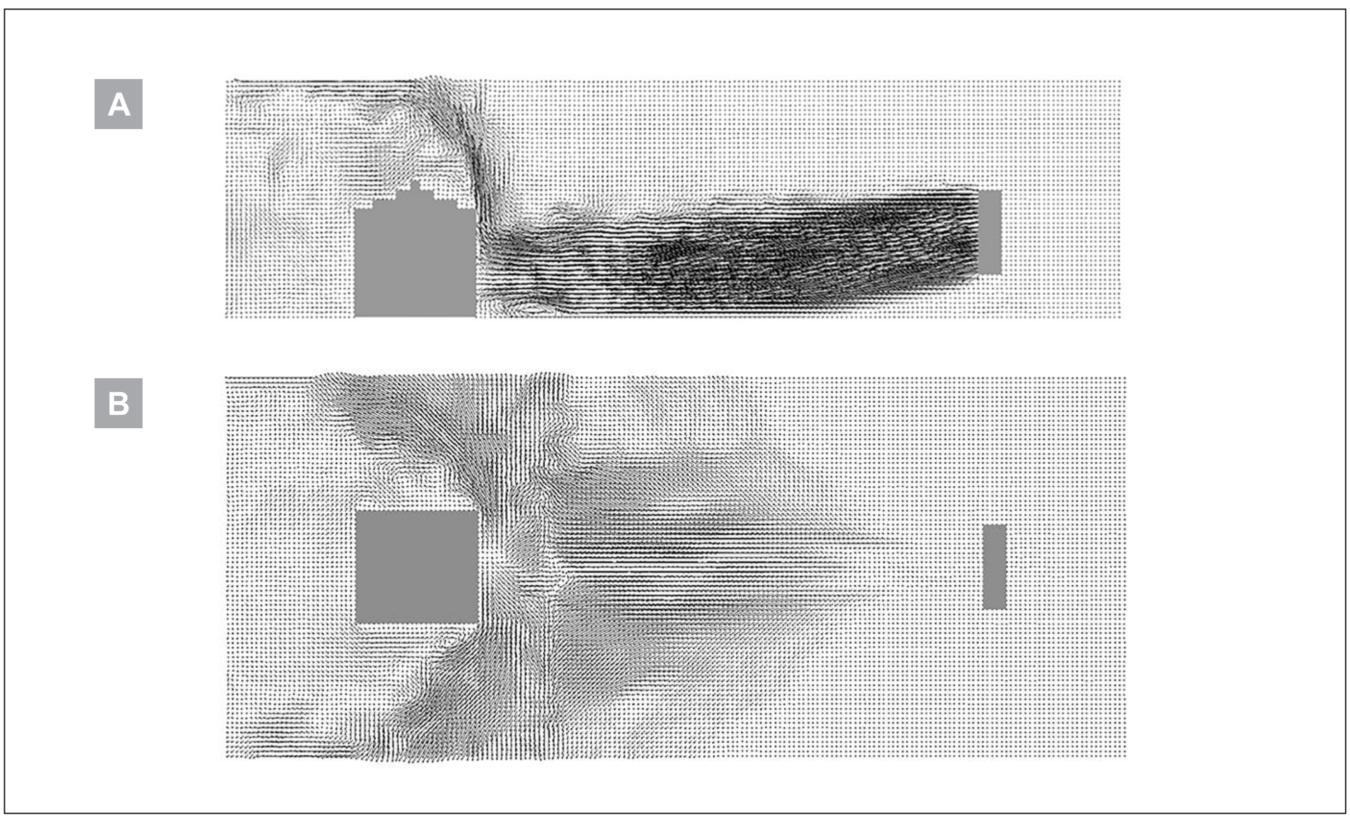

Figure 4—Instantaneous flow field from Fire Dynamic Simulator model, showing (A) side view and (B) top view in a plane close to the ground. Note the recirculation zone near the base of the structure wall.

setup using the NIST Fire Dynamic Simulator (FDS) (McGrattan et al. 2013). The vortex causes particles and smoke in the mulch bed at the base of the structure to be generally transported away from the wall and to the sides. Firebrands that are lofted, however, may be carried along the top of the vortex or drop out of the flow directed over the top of the structure, to be deposited at the base of the structure where they can ignite combustible materials close to the wall.

Spotting Time

This set of experiments represents a survey of the effects of fences and mulch on the spread of fire to a structure, directly or through firebrands and in a variety of conditions. Few experiments have been replicated, and many phenomena involved in firebrand spotting, such as generation of firebrands and ignition processes, are stochastic in nature. The analysis of this data was therefore based on uncovering trends and on discovering different modes of behavior, rather than on quantitative results.

One of the simple measures that has been determined from the video records is the length of time between turning on the fan and ignition within the target mulch bed at the base of the structure of the first spot fire that eventually reached the wall. Ignition was detected by the first sign of smoke.

Effects of Wind Speed and Separation Distance

In figure 5, the time to spot is plotted as a function of the nominal wind speed of the fan. The experiments represented in this plot are the 22 experiments performed on mulch alone and 67 experiments on fence and mulch combinations that are included in the pie charts of figure 2.

Figure 5 demonstrates several trends. First, the time to spot generally decreases as a function of wind speed. Second, the spotting times for fences in combination with mulch beds tend to be shorter than for mulch alone. Third, the spotting times are on the order of minutes. For 6 m second-1 winds, spotting occurs in 30 minutes or less, while for 14 m second^{-1} winds, spotting occurs in less than 7 minutes in every case. If a home is undefended during a WUI fire, these firebrands pose a serious threat to the home.

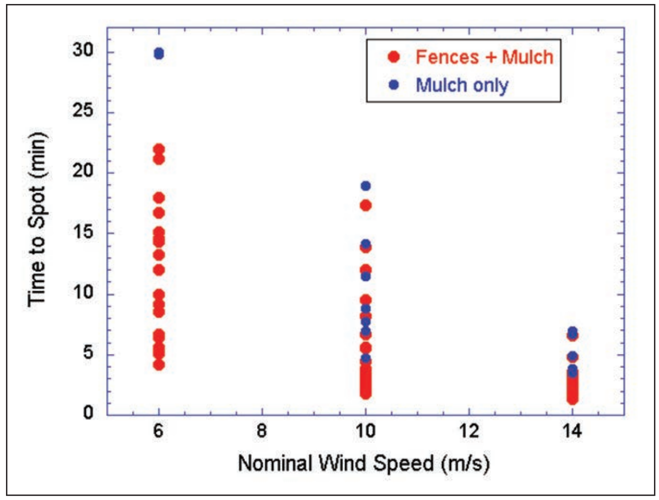

Figure 5—Spotting time as a function of nominal wind speed for experiments on mulch beds only (blue) and combinations of fence and mulch bed (red).

Firebrand spotting consists of three mechanisms: firebrand generation, firebrand transport, and ignition of the surrounding fuels (Koo et al. 2010). High speed winds break off and loft firebrands more readily. They also transport firebrands faster and farther. The ability of firebrands to ignite a spot fire in the mulch bed depends on many factors, including the characteristics of the firebrand and mulch bed, the contact between firebrand and mulch, and the local environment at the location of the firebrand. Higher speed winds deliver more oxygen to the ignition site and support smoldering (Filkov et al. 2016). However, if a critical wind speed is exceeded, the firebrand may be quenched by the cooling effect (Song et al. 2017).

Figure 6 shows that there is not a strong relationship between the time to spot and the separation distance between the end of the fence or mulch bed and the wall of the structure. This suggests that the spotting time is controlled by either firebrand generation or ignition, and that transport is not an important factor in this set of experiments, where the distance between fence and structure was relatively short.

In these experiments, spot fires appeared to be ignited by single firebrands. Not every firebrand landing in the target mulch bed found conditions favorable for ignition. Typically, a handful of spot fires (seldom more than 10) were ignited in the time period before 1 of those fires reached the wall.

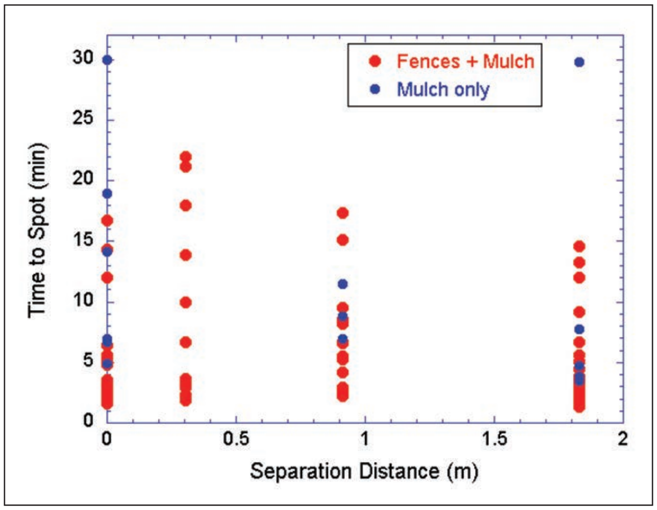

Figure 6—Spotting time as a function of separation distance for experiments on mulch beds only (blue) and combinations of fence and mulch bed (red).

Fences Without Mulch

In the absence of mulch beneath the fence, firebrand spotting was generally considerably slower, if it occurred at all; spotting occurred in only 8 of the 22 experiments with fences alone. The times to spot for these experiments are shown in figure 7.

Without mulch, the ignited fences tended to smolder rather than flame. This was a slow process that in the majority of cases did not result in spot fires. An exception is shown in figure 8, in which a smoldering piece of the fence has broken off at high wind speeds and ignited a spot fire near the wall.

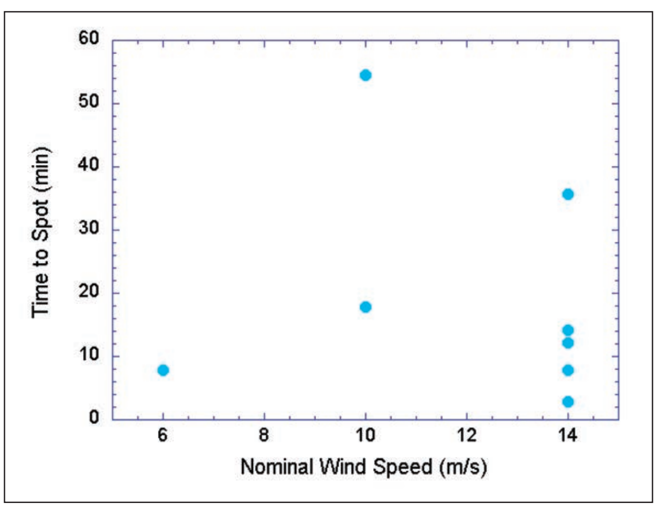

Figure 7—Spotting time as a function of nominal wind speed for experiments on fences only in which spotting occurs.

Exceptional Cases

This set of experiments demonstrated some special cases for which the fire behavior differed significantly from similar experiments.

Double Lattice Fences

A single redwood lattice fence combined with a shredded hardwood mulch bed burned with flames staying close to the ground, as shown in figure 9. This image was taken 12 minutes into the experiment. The behavior is similar to that seen with the privacy fence in figure 3.

Compare this to figure 10, in which redwood lattice fence panels have been attached to both sides of the end posts, with a spacing of 0.09 m between them. This image was taken 3 minutes into the experiment, at which point the double lattice fence is fully engulfed. The space between the fences is partially shielded from the wind field, which promotes flame attachment and spread. The changes in convective heat transfer introduced by the second fence, plus the radiative exchange between the fences, act to intensify the fire.

The time to spotting was 15 minutes in the case of the single lattice fence and 7 minutes for the double lattice fence, after the peak fire behavior in each case.

The fire behavior of the double lattice fence is sufficiently enhanced that the mulch bed beneath the fences is not necessary. Figure 11 shows a double lattice fence without mulch beneath, at 4 minutes into the experiment. Spotting in the target mulch bed occurred at 7 minutes, after the fence had collapsed into a burning pile on the ground.

Parallel Privacy Fences

The addition of a second western redcedar privacy fence parallel to the first changed the fire behavior in a similar way to the double lattice fence. Figure 12 shows a single privacy fence with hardwood mulch beneath after 20 minutes. In figure 13, a second privacy fence was arranged at a spacing of 0.20 m from the first. This could occur, for example, if two neighbors decided to build privacy fences on the property line of their respective parcels. This configuration greatly enhanced the fire behavior. Figure 13 shows the conditions 5 minutes into the experiment.

Figure 8—Firebrand spotting for western redcedar privacy fence with high wind speed (14 m second^{-1}) and at 1.8 m separation distance from wall.

Figure 9—Single redwood lattice fence in hardwood mulch at low wind speed (6 m second^{-1}).

Figure 10—Double redwood lattice fence in hardwood mulch at low wind speed (6 m second^{-1}).

Figure 11—Double redwood lattice fence without mulch at low wind speed (6 m second^{-1}).

Figure 12—Single western redcedar privacy fence in hardwood mulch at low wind speed (6 m second^{-1}).

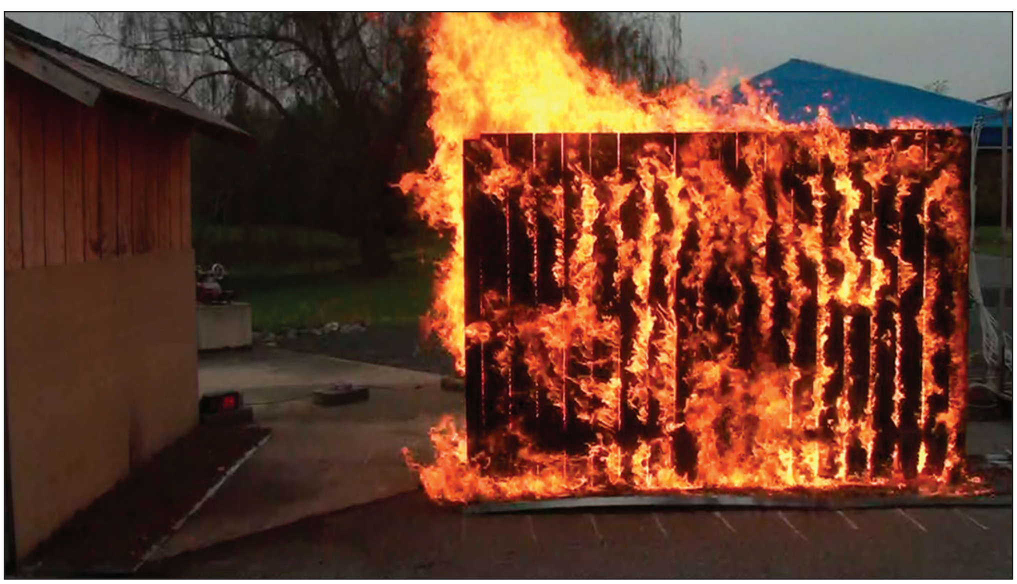

Figure 13—Parallel western redcedar privacy fences separated by 0.20 m in hardwood mulch at low wind speed (6 m second^{-1}).

The time to spotting was 13 minutes for the single privacy fence and 5 minutes for the parallel privacy fences.

Unlike the double lattice fences, a mulch bed beneath the parallel privacy fences was necessary for enhancing the fire behavior. Figure 14 shows that without the mulch bed the parallel fences smoldered slowly, similar to the behavior seen in figure 8 for a single privacy fence without a mulch bed beneath.

Pine Straw Mulch

A final example of unusual fire behavior was encountered with a bed of pine straw mulch. This mulch burned intensely and rapidly. However, the firebrands produced by pine straw mulch were too fine to ignite the target mulch bed. Figure 15 shows a pine straw mulch bed in direct contact with the target hardwood mulch bed at the base of the structure. Although the flames have reached the target mulch bed, no ignition took place.

If the pine straw mulch bed was combined with a western redcedar privacy fence, however, the pine straw quickly ignited the whole bottom of the fence, and spot fires were ignited in the target mulch bed by firebrands from the fence.

Figure 14—Parallel western redcedar privacy fences without mulch at low wind speed (6 m $second^{-1}$).

Figure 15—Pine straw mulch bed in contact with target hardwood mulch bed.

Removing the Structure

An additional three experiments were performed in which the small structure was removed from the area downwind of the firebrand source, the target mulch bed was moved to a distance 23 m from the source, and the burning source was subjected to a wind field of 14 m second^{-1}. The space between the source and target was asphalt and concrete, representing a worst case (i.e., favorable) scenario for transport of the firebrands over the ground. Roads and driveways make this a realistic condition for a WUI neighborhood. Figure 16 shows the experiment in which a double lattice fence has been ignited. A bed of shredded hardwood mulch and a woodpile were used in the other two long-range experiments. In each case, spot fires ignited in the target mulch bed 23 m from the firebrand source within 5 minutes after the wind machine was set to deliver high wind speeds. It should be noted that most of the spot fires occurred in the middle of the target mulch, indicating that the firebrands were lofted at some point rather than simply moving over the surface of the ground.

CONCLUSIONS

This limited series of field experiments on ignited mulch beds, fences, and combinations of fence and mulch bed in a wind field in front of a structure demonstrates that firebrand spotting may occur within 2 to 20 minutes of ignition. Spotting often occurred after peak flaming and was affected by wind fields near the structure.

For this set of wind velocities and approach angle, fence configurations, and materials, the time to spotting tended to decrease with increasing wind speed, but it did not show a strong relationship with separation distance. This is consistent with the wind having important effects on firebrand generation and on the local ignition environment.

For this series, the combination of a fence and a mulch bed appeared to decrease the time to spotting over either the mulch bed or the fence alone.

In the absence of a structure, firebrand spotting can occur within a few minutes even at long range.

Figure 16—Double lattice fence experiment without a structure and with a mulch bed situated 23 m from the far end of the fence.

Future experiments will include effects of mitigation, including coatings and fence height above the ground, and aging on the generation and spotting of firebrands from fences.

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REFERENCES

Filkov, Alexander; Kasymov, Denis; Zima, Vladislav; Matvienko, Oleg. 2016. Experimental investigation of surface litter ignition by bark firebrands. Advanced Materials in Technology and Construction; AIP Conf. Proc. 1698, 060004. https://doi.org/10.1063/1.4937859.

ICC and NARCD Councils. 2013. Communities dealing with wildland/urban interface fire; Wildfire Safe, Sound & Code Smart; WUI fact sheet. https://nanopdf.com/download/wssampcs-wui-fact-sheet-c-international-association-of-wildland-fire_pdf. [Accessed 2018 June 21].

Koo, Eunmo; Pagni, Patrick J.; Weise, David R.; Woycheese, John P. 2010. Firebrands and spotting ignition in large-scale fires. International Journal of Wildland Fire. 19: 818–843.

Maranghides, Alexander; McNamara, Derek. 2016. 2011 Wildland urban interface Amarillo Fires Report #2—Assessment of fire behavior and WUI measurement science. Technical Note NISTTN 1909. Gaithersburg, MD: National Institute of Standards and Technology. 153 p. https://doi.org/10.6028/NIST.TN.1909.

Maranghides, Alexander; McNamara, Derek; Vihnanek, Robert; [et al.]. 2015. A case study of a community affected by the Waldo Fire—Event timeline and defensive actions. Technical Note NISTTN 1910. Gaithersburg, MD: National Institute of Standards and Technology. 213 p. https://doi.org/10.6028/NIST.TN.1910.

Martinuzzi, R.; Tropea, C. 1993. The flow around surface-mounted, prismatic obstacles placed in a fully developed channel flow. Journal of Fluids Engineering. 115: 85–92.

McCaffrey, B.J.; Heskestad, G. 1976. A robust bidirectional low-velocity probe for flame and fire application. Combustion and Flame. 26: 125–127.

McGrattan, Kevin B.; McDermott, Randall J.; Weinschenk, Craig G.; [et al.]. 2013. Fire Dynamics Simulator Users Guide. Special Publ. NISTSP 1019, 6th ed. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.sp.1019.

Song, Jiayun; Huang, Xinyan; Liu, Naian; [et al.]. 2017. The wind effect on the transport and burning of firebrands. Fire Technology. 53: 1555–1568.

Taylor, Barry N.; Kuyatt, Chris E. 1994. Guidelines for evaluating and expressing the uncertainty of NIST measurement results. Technical Note NISTTN 1297, 1994 ed. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.tn.1297.