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NIST Technical Note
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Abstract

A series of field experiments was conducted to examine the effects on fire spread toward a structure for combustible fences and mulch under conditions that may be encountered in a wildland-urban interface (WUI) fire. The fire behavior of a variety of materials, designs, and configurations were studied under various wind conditions. The 187 experiments were split into five categories: mulch only, fence only, fence plus mulch, parallel fences, and long range firebrand experiments. Fence materials included western redcedar, California redwood, pine, vinyl, and wood-plastic composites, and fence styles included privacy, lattice, and good neighbor (board on board). The tested mulch types were shredded hardwood, mini pine bark nuggets, pine straw, rubber, and artificial turf. A wind machine provided a mean wind speed between 6 m/s and 14 m/s (13 mi/h to 31 mi/h). The fence and/or mulch bed was ignited by a propane burner on the ground at the end farthest from the structure. A small structure was located between 0 m and 1.83 m (0 ft to 6 ft) downwind of the fence or mulch bed as a target for flames and firebrands. A target mulch bed at the base of the structure tested the ability of firebrands produced by the burning fence and mulch bed to ignite spot fires that threatened the structure.

The experiments in this study demonstrated that combustible fences can be rapid conduits for fire and can potentially spread fire to attached or adjacent structures. Combinations of combustible items were found to increase the fire hazard disproportionately. Fire behavior was classified as very high, high, medium, and low hazard. Rapid fire growth and large flames were found for parallel fences and one type of wood-plastic composite fence. Good neighbor fences carried flames from the ground to the top of the fence. Combustible fences with mulch at their base were found to be high hazard, transporting fire through the community and providing a steady source of firebrands. Fire spread continuously over mulch beds, with progress sometimes enhanced by the ignition of spot fires downwind. Medium fire hazard was found for wood fences in the absence of mulch, with slow fire spread dominated by glowing combustion with occasional small flames. Low fire hazard was expected for noncombustible fences, with maintenance required to minimize the accumulation of fine combustible materials along the fence.

In all cases the fire progress was affected by the wind field; the structure created both upward flow (enhanced by buoyancy) and a vortex that both deposited firebrands next to the structure and slowed flame spread on the ground. During most experiments, the burning mulch and fences produced firebrands that ignited spot fires in the target mulch bed. In long range experiments, firebrands from fences and mulch beds caused ignitions over 47 m (155 ft) downwind.

This study of fence fire spread is part of a series designed to better inform standards and codes regarding placement of landscape features around homes that are at risk of exposure to wildland-urban interface fires.

Keywords

Embers; fence fires; fences; firebrands; fire spread; mulch; parallel fences; structural ignition; structure vulnerability; wildland urban interface fires; wind-driven fires; WUI fires.

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List of Abbreviations and Acronyms

AHJ	Authority Having Jurisdiction
BRI	Building Research Institute
FDS	Fire Dynamics Simulator
GUI	Graphic User Interface
HOA	Homeowners Association
HMM	Hazard Mitigation Methodology
HRR	Heat release rate
HWM	Shredded hardwood mulch
IBHS	Insurance Institute for Business & Home Safety
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
PHRR	Peak heat release rate
PBM	Pine bark mulch
PSM	Pine straw mulch
PVC	Polyvinyl chloride, commonly referred to as vinyl
RH	Relative humidity
RSS	Root sum square
RW	Redwood
WPC	Wood-plastic composite
WRC	Western redcedar
WUI	Wildland-urban interface

Executive Summary

Wildland-urban interface (WUI) fires threaten communities in many locations around the world. Fences and mulch have been identified as contributors to the spread of WUI fires within communities. Once ignited, these fuels become sources that may ignite nearby objects through direct flame contact, radiation, convection, and firebrands. The hazard of wind-driven fire propagation and spread associated with fences varies greatly depending on their design, material composition, configuration with respect to nearby materials and objects, and maintenance.

It is important to understand the mechanisms by which these combustible landscaping elements can transport fire to a home in order to find ways to address the hazard. Such knowledge helps with proactive design, implementation, and maintenance within the community. It informs homeowners on what they can do to protect themselves and their properties. It also helps fire departments to plan defensive strategies, placing resources and assigning tasks where they will be the most effective. The goal is to enhance the safety of members of the public and first responders and to reduce structural fire losses.

CONTRIBUTION OF FENCES AND MULCH TO THE FIRE PROBLEM

WUI fire case studies performed by the National Institute of Standards and Technology (NIST) have identified fences and mulch as common contributors to the spread of WUI fires within communities. In the Tanglewood Complex Fire, over 2.4 km of fences were found to be damaged or destroyed within a community of 47 residential structures in which 17 homes were destroyed and 4 were damaged. Instances of fires spreading along fences to structures were observed in the Witch Creek Fire and the Waldo Canyon Fire. Post-fire field observations have found that wood fences are often totally consumed, leaving behind only the metal hardware (nails and screws) used during their assembly. In high fire and ember exposure locations, fences that are partially burned have often been linked to specific defensive actions, as related by first responders. In many WUI fires, firefighters have removed fences as part of their defensive strategy aimed at containing the fire or preventing it from reaching a nearby structure. Such activities reduce resources allocated to life safety operations and direct structure protection.

Fences, mulch, and other combustible landscaping elements can act as both potential ignition sites from existing fires and sources of fire spread themselves. These materials can be ignited by a wildfire through direct flame contact, radiation and convection from the flames, or firebrands. Firebrands, also referred to as embers, are carried by the wind and may ignite combustible materials in a community far downwind of the fire front. Once ignited, fences and mulch may themselves ignite nearby objects, including a home, through the same mechanisms of direct flame contact, radiation, convection, and firebrands.

Fences are typically placed along the perimeter of parcels, and they can be connected directly to neighboring fences or sit in close proximity to other fuels such as combustible sheds or woodpiles. The way the fence is connected to a residential structure can also impact how the fire spreads from a burning fence and the probability of ignition.

Some fences release little or no energy while others burn vigorously. Fence and mulch combinations can be divided into four fire spread hazard categories: very high, high,

medium, and low. Very high fire hazard fence configurations are those that threaten a structure through rapid fire spread and large flames extending above the fence. This study found that parallel combustible surfaces fell into this category, as did certain wood-plastic composite fences.

High fire hazard combinations of fence and mulch release a considerable amount of energy while burning, igniting nearby combustibles through direct flame contact or radiation and convection from the flames. This category also includes fences and mulch that generate firebrands capable of igniting spot fires downwind. Most combustible fences, mulch, and fence-mulch combinations fell into this category, with the capability of acting as a wick to spread fire toward a structure in the time of minutes to an hour or so.

Fences and mulch are classified as medium fire hazard if they are combustible but do not typically ignite nearby combustibles and do not cause significant downwind fire spread. In this category were vinyl fences and single wood fences in the complete absence of adjacent fine fuels.

Although fences made of noncombustible materials such as stone, brick, or steel were not included in this study, they can be classified as low fire hazard. They do not burn on their own but can trap and accumulate windblown debris along their length. If not removed, combustible materials at the base of even noncombustible fences can transport fire.

Because of the linear character of fences, they can contribute to multiple fire pathways, resulting in fire propagation both within and beyond the parcel of origin. This linearity and the resulting extensive spatial fire and ember exposure can potentially increase the hazard to multiple parcels and multiple structures in the vicinity of very high and high fire hazard fences.

FENCE USAGE AND MAINTENANCE

Multiple considerations affect fence design and implementation. In addition to obvious factors such as function, esthetics, and cost, permitting and installation requirements may be imposed by Authorities Having Jurisdiction (AHJs) and homeowners associations (HOAs). Some of these considerations impact the ignition propensity and fire behavior of fences.

Fences are often installed in contact with the ground to keep pets in a yard or unwanted animals out. Unfortunately, this configuration may put those fences in proximity to flammable mulch and to windblown debris accumulating at the base.

Fences are exposed to outdoor conditions, including extremes in temperature, precipitation, and UV radiation, over long time periods, typically with little or no fire prevention maintenance. Leaf litter and other combustible debris may accumulate at the base, creating a fine, dry, continuous fuel source analogous to the mulch beds in this study.

Vegetation planted near the fence may dry out, ignite in a WUI fire, and ignite the fence in turn. Interactions between the burning vegetation and fence may increase the intensity of the fence and enhance the fire spread.

Homeowners using fences to enclose their yards may erect fences near or at the property line. When this practice is followed by two adjoining neighbors, it can result in a parallel fence configuration that this study finds to be particularly hazardous.

EXPERIMENTAL DESIGN

This report presents a study of fire spread from combustible fences and mulch beds to a nearby structure in a wind field. The goal of the study was to assess the severity of the fire hazard that fences and mulch posed to structures. The fire behavior of these fuels, including flame spread rate, spotting due to firebrands, and downwind ignition potential, was observed under various conditions of applied wind and proximity to a structure.

In these field experiments, a fence section, mulch bed or fence/mulch bed combination was arranged perpendicular to the wall of a small structure and separated from it by a distance up to the length of a fence panel. Beyond the fence and/or mulch bed was a large fan that generated a wind field directed toward the structure. A fire was ignited using a propane burner at the end of the object closest to the fan, and the fire was observed as it spread toward the structure through flame contact and firebrand spotting.

In early experiments, the wall of the structure was covered by a sacrificial combustible layer and structure ignition was characterized. Only firebrands caught in the narrow space between the structure and the pavement were found to cause incipient ignitions in these experiments. To better characterize the ability of firebrands generated by the burning fence or mulch bed to ignite combustible materials near the house, a second mulch bed was placed along the base of the structure as a target. The wall was noncombustible in these experiments, and the structure was considered threatened when the spot fire reached the wall. In every case, the experiment was terminated using water suppression when fire reached the base of the structure and before the structure itself ignited. The eaves and roof of the structure were manually cooled when pyrolysis (smoking) was observed. The contributions of structure geometry, wall cladding, and construction to structure ignition were not the focus of this study.

Video analysis provided data to measure the progress of the fire along the mulch and fence. The time for a firebrand to ignite a spot fire in the target mulch bed was recorded, along with the time for the spot fire to reach the wall. Ambient wind and temperature were measured, and bidirectional probes recorded the speed of the wind reaching the test object.

A variety of fence and mulch materials, designs, and combinations were tested at three wind speed levels and four separation distances between the fuel source and the structure. The four basic configurations that were studied are illustrated in Fig. ES.1. Shown from left to right are test setups for mulch only, fence only, fence plus mulch, and parallel fences. Fence materials included western redcedar, redwood, pine, weathered wood, vinyl, and wood-plastic composite. Privacy, lattice, and good neighbor (board on board) fence styles were studied. Mulch types included shredded hardwood mulch, pine bark mulch, pine straw mulch, rubber mulch, and artificial turf. Most fence experiments were performed with a length of one fence panel; a few experiments added a second fence panel length to test whether the fire spread mechanisms had been fully captured. The three wind speed levels were categorized as low (6 m/s or 13 mi/h), medium (10 m/s or 22 mi/h), and high (14 m/s or 31 mi/h). The four separation distances were 0 m, 0.30 m (1 ft), 0.91 m (3 ft), and 1.83 m (6 ft). Long-range firebrand spotting was studied in a small number of experiments without the shed in place and with the target mulch bed at least 40 m (130 ft) downwind from the firebrand source.

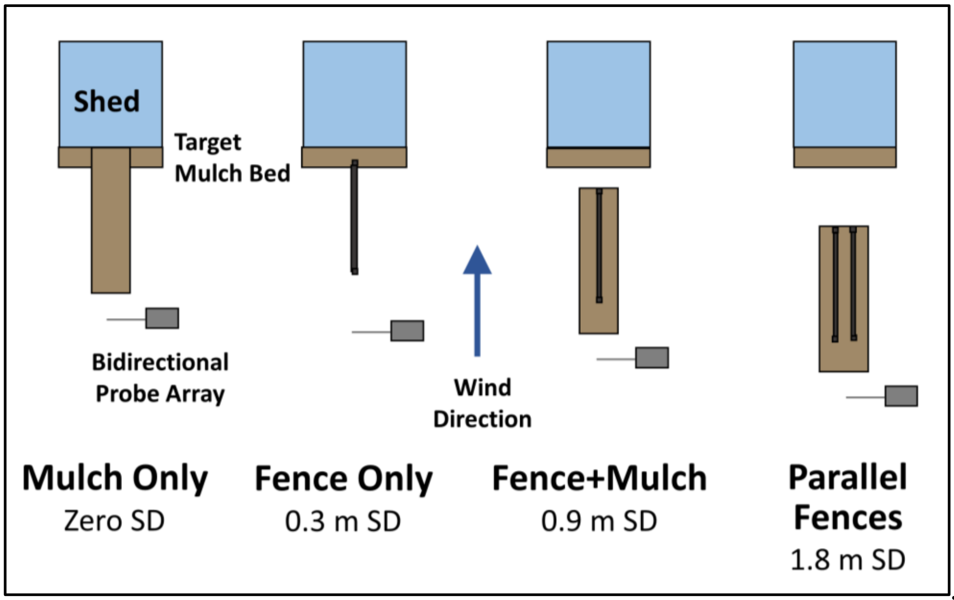

Fig. ES.1. Configurations tested in this study at various separation distances (SD).

LIMITATIONS

This study was a survey of the fire behavior in wind of a variety of combustible fences and mulches near a structure. It illuminated the differences in behavior for selected materials and fence designs and demonstrated certain trends.

Limitations of this research include the following:

- Combinations of fuels were limited.
- Few experiments were repeated.
- Distance downwind was limited for long-range spotting study.
- Fuels were ignited at a single location on or near the ground.
- Ignition was by gas burner rather than a natural source.
- The orientation of wind to the structure wall was limited.
- The mulch was preheated by heat conduction through the steel pan.
- Accumulation of windblown debris was not considered in Fence Only experiments.
- Effects of terrain were not studied.
- Smoke toxicity was not included.

KEY FINDINGS

The experiments in this study demonstrated a range of fire spread hazards from various types and configurations of fences and mulch ignited close to a structure in a wind field. General findings are listed first and followed by findings for configurations classified as very high hazard, high hazard, medium, and low hazard. The findings are labelled according to the following categories:

- FH Fire Hazard
- LS Life Safety
- HR Hazard Reduction – materials, assemblies, implementation/housekeeping
- IC Improved Characterization – recommended future work to characterize these fuels more fully

General findings

The results from these experiments on fire spread demonstrated that:

F1. As combustible materials are combined, the hazard increases disproportionately. (FH)

Fuel agglomeration provides significant increase in energy release and increases fire and ember exposures. For a single combustible fence panel by itself, the fire behavior was limited to glowing combustion near the area of ignition, with firebrands generating spot fires only on rare occasions. When a combination of a wood fence and shredded hardwood mulch was ignited at the base, the flames remained over the lower half of the fence and progressed steadily in the direction of the wind. Adding a second wood fence parallel to the first resulted in flames engulfing the fences within a few minutes of ignition.

F2. Fences may impact egress. (LS)

In a WUI fire, high and very high hazard fence configurations may result in a line of flames close to egress paths from a house or auxiliary dwelling. In one set of experiments on a wood-plastic composite fence, the top and bottom frames distorted and allowed burning boards to fall to either side. This created a 4 m (12 ft) wide zone of flames along the fence line.

F3. Fire spread rates vary with fence material and design, wind speed, and fuel configuration, including the presence or absence of mulch. (FH)

This report provides data on a variety of fence and mulch materials, designs, and configurations.

F4. Spot fires due to firebrands may ignite within a few minutes, even over a distance of 47.6 m (156 ft) or more from the burning item, and may continue to ignite long after the initial flaming combustion has subsided. (FH)

Firebrands capable of igniting spot fires downwind were generated by nearly all combinations of fence and mulch tested in this study. All wood fences with mulch at the base caused spot fires in the target mulch bed. Spot fires were often ignited within a few minutes of mulch and fence ignition. Shredded hardwood mulch and pine bark mulch burned and emitted firebrands for longer than an hour. Ignition of spot fires was also demonstrated from firebrands transported by the wind over distances as far as 47.6 m (156 ft) from the burning item under high wind conditions and over a paved surface. The wind field may deposit firebrands close to the wall of the structure. If a home is undefended during a WUI fire and not properly hardened, these firebrands may pose a serious threat to the home.

F5. A standard test method is needed to evaluate the fire characteristics of fences. (IC)

A standard test method is needed to assess the fire performance of fences. The method should consider not only materials but assemblies and be carried out in a vertical orientation. It should be able to distinguish the fire behavior of various materials, including wood-plastic composites, wood, and vinyl, and designs, including privacy, lattice, and good neighbor.

Very High Fire Hazard Configurations

Certain fence and mulch combinations were found to result in rapid fire spread and large flames. In a region subject to WUI fires it's advisable to remove these fuel sources if possible. Standard tests used to evaluate the fire characteristics of fences should be developed. Illustrations of the fire behavior of Very High Hazard fence and mulch configurations are shown in Fig. ES.2.

The fire behavior of configurations of fences and mulch identified in this study as Very High Hazard supported the following findings:

F6. Rapid fire growth and large flames were found for parallel fences and one type of wood-plastic composite fence. (FH)

- *Parallel wood privacy fences* and *double wood lattice fences* were engulfed in flames within a few minutes of ignition. Radiative exchange between the parallel burning surfaces and convection of the hot gases trapped in the bounded space caused rapid intensification of combustion and eruptive fire behavior. A large fire occurred even when wood privacy fences were separated by 91 cm (3 ft). A parallel fence configuration can arise when neighbors erect fences along both sides of a property line.
- For a *western redcedar privacy fence next to a pine lattice fence,* the fire behavior depended on spacing. Rapid fire growth and intense flames were found for a spacing of 31 cm (12 in). The char patterns on each fence were similar to those for the fences individually when the spacing between them was 46 cm (18 in).
- Limited testing indicates that ignition of certain *wood-plastic composite fences* can result in high intensity fire behavior. For one of the two types tested, the fence burned intensely, with large flames extending above the fence. The warped frame allowed vertical boards 1.8 m (6 ft) tall to fall to both sides, creating a 3.7 m (12 ft) wide zone of flames that could block egress and threaten property.

F7. Good neighbor fences serve as a ladder fuel to carry flames from the ground to the top of the fence. (FH)

- For *good neighbor fences* at low wind speed, the flames reached the top of the fence downwind from the ignition point. This is due to radiative and convective heat transfer between the boards connected to alternating sides of the stringer, the same mechanisms that caused rapid flame growth between parallel fences. At higher wind speeds the maximum height of the fire stayed below the center stringer of the fence.

F8. Rubber mulch generates large flames initially and when disturbed. (FH)

– *Rubber mulch* burned with black smoke and large initial flames, followed by a long period of sporadic flaming as a top layer of crumbly solid residue slowed the flow of oxygen to the unburned fuel beneath. Disturbing the mulch bed renewed the flaming as the unburned fuel was exposed to air.

Fig. ES.2. Examples of Very High Hazard fences and mulch: a) parallel privacy fences, b) double lattice fences, c) wood-plastic composite #1 fence, d) good neighbor fence, e) rubber mulch.

High Fire Hazard Configurations. Many fence and mulch combinations exhibited fire behavior in the medium hazard range, supporting fire spread and generating firebrands but not progressing to full involvement with large flames. This section describes the behavior of some configurations that fall into this category. Illustrations of the fire behavior of High Hazard fences and mulch are shown in Fig. ES.3.

The fire behavior of configurations of fences and mulch identified in this study as High Hazard supported the following findings:

F9. A fence with mulch at its base transports fire through the community and provides a steady source of firebrands to ignite combustible material downwind. (FH)

- *Wood privacy or lattice fences combined with mulch* were more hazardous than either the fence or the mulch bed separately. Adding fine combustible materials to the base of a fence promoted fire spread along the base of the fence, allowing the combination of fence and mulch to act as a wick transporting fire along the entire length of the fence. With ignition at the base of the fence, flames remained below half of the fence height. In every case, firebrands ignited spot fires in the target mulch bed.
- Stringers slowed the upward fire spread in these experiments by limiting the flame height on one side of the fence. In a WUI fire, however, they could provide locations for firebrands to lodge and ignite new fires on the fence.
- The flame spread rate in the horizontal direction was similar for all wood fences, including privacy, lattice, and good neighbor fences. Away from the wind field near the structure, the fire spread from the ignition point to the end of the single fence panel was 2 min to 5 min for high and medium wind speeds and 7 min to 12 min for low wind speeds.
- For one type of *wood-composite fence*, the fire remained below the halfway point of the fence height. Horizontal boards fell out of the frame and burned in line with the fence.
- Lifting a fence 15 cm (6 in) above shredded hardwood mulch decoupled the burning behavior of the fence from the mulch between posts. This conclusion may not hold for mulches that burn with higher flames, such as pine straw or rubber mulch. The benefits of raising the fence above the mulch may not be realized if a barrier is placed between them to keep wildlife out or pets in. Combustible debris such as leaves or needles that collect along the barrier will reduce the advantages of this design in a fire.

F10. Fire spreads easily across the fine overlapping particulates of a mulch bed. The fire intensity, rate of fire spread, production and size of firebrands depend on the material properties and physical characteristics of the mulch. (FH)

- *Rubber mulch* burned with black smoke and large flame initially and when disturbed. See description under Very High Hazard.
- *Pine straw mulch* burned rapidly with high intensity. By itself, the pine straw mulch was consumed without igniting spot fires. However, embedded combustible objects were easily ignited by the intense flames. When combined with a western redcedar privacy fence, the fire in the pine straw mulch ignited the fence quickly and spread to the end of the panel within one minute. The burning wood fence then generated firebrands capable of igniting spot fires.
- The fire spread behavior in a *shredded hardwood mulch* bed was affected by the flow field, ignition of spot fires downwind, and the geometry of the mulch bed and structure. Fire progressed in hardwood mulch beds through both continuous flame spread and firebrand spotting. Spot fires allowed the fire to jump in the direction of the wind.

– Fire spread more slowly over the *mini pine bark mulch* than over the shredded hardwood mulch, often taking at least twice as long to reach the end of the mulch bed. This likely results from the difference in texture – the chunks of mini pine bark mulch do not ignite as easily as the long, thin particles that characterize the shredded hardwood mulch.

F11. More information is needed on the fire behavior of a combustible fence next to an auxiliary structure. (IC)

– A *WRC privacy fence separated from a noncombustible cement board* by 31 cm (12 in) resulted in a char pattern similar to that of a single panel WRC privacy fence, with flame spread about three times faster. For a spacing of 46 cm (18 in), the fire behavior was less intense for a WRC privacy fence in combination with either a cement board or a vinyl privacy fence, as compared to a single panel WRC fence. The char pattern remained below the bottom stringer, and the flame spread was at the same rate or slower.

Fig. ES.3. Examples of High Hazard fence and mulch configurations: a) western redcedar (WRC) privacy fence with pine straw mulch, b) redwood lattice fence with shredded hardwood (HW) mulch, c) wood-plastic composite #2 fence with HW mulch, d) WRC privacy fence parallel to vinyl privacy fence, e) HW mulch f) pine straw mulch.

Medium Fire Hazard Configurations: Some fences and mulch experiments demonstrated very slow fire spread without flaming and little or no generation of firebrands. Illustrations of the fire behavior of Medium Hazard fences and mulch are shown in Fig. ES.4.

The fire behavior of configurations of fences and mulch identified in this study as Medium Hazard supported the following findings:

Without nearby fine combustible materials, the fire spread over a single combustible fence is slow and dominated by glowing combustion. (HR)

– The fire spread over wood fences in the absence of fine combustibles was generally slow and dominated by glowing combustion with occasional small flames. Wood fences produced large firebrands from pieces of the fence breaking off and small firebrands from glowing combustion. However, spotting in the target mulch bed was rare in these experiments. It should be noted that it may be difficult to keep a wood fence sufficiently clear of fine combustible materials to achieve the slow-growth fire behavior. Windblown debris such as leaves and pine needles may accumulate before and during a WUI event.

F12. Fence and groundcovers with added or inherent fire resistance reduce the flame spread rate and the hazard due to flames and firebrands. (HR)

– *Vinyl privacy fences* did not support significant burning under the tested wind conditions. With mulch at its base, vinyl privacy fences, including panel, bottom frame, and fence post, blackened and distorted along the entire length of the fence. Distortion allowed the boards to fall out of the bottom frame. No firebrands were generated.

– The single type of *artificial turf* tested in this study, with synthetic fibers made from polypropylene with a urethane-coated backing, was difficult to ignite and exhibited slow flame spread.

Fig. ES.4. Examples of Medium Hazard fences and mulch: a) western redcedar privacy fence without mulch, b) redwood lattice fence without mulch, c) vinyl privacy fence with shredded hardwood mulch, d) artificial turf.

Low Fire Hazard Configurations. Although fences made of noncombustible materials such as stone, brick, or steel were not included in this study, they can be classified as low fire hazard. They do not burn on their own and have been shown to provide protection against radiant heat. However, any fence in contact with the ground can trap and accumulate windblown debris along their length. If not removed, combustible materials at the base of even noncombustible fences could potentially allow fire to spread.

F13. Noncombustible fences free of leaf litter and other combustible debris will not spread fire. (HR)

Maintenance is required to reduce the accumulation of fine combustible materials along a fence. This minimizes the amount of windblown debris such as leaves and pine needles that can ignite during a WUI event.

PRIMARY RECOMMENDATIONS

The following recommendations for members of a residential community are intended to address both ember and fire (radiation, convection, and direct flame contact) exposure hazards generated by combustible fences. Although the recommendations are intended primarily for moderate to very high hazard WUI locations, they are expected to reduce local fire hazards in any community.

For more detailed recommendations on spacings of combustible elements and hardening of structures and parcels, refer to the WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology report.[1]

R1. Avoid parallel fences, to reduce exposure to large flames. Parallel fences can result in highly hazardous fuel accumulation corridors that are difficult to access and maintain. Spacing of 0.9 m (3 ft) between fences is not sufficient.

R2. Avoid combustible fences where they can impact egress, to protect life safety.

R3. Avoid proximity to other combustible fuels, to reduce fire intensity and limit fire spread. This includes fuels above the fence and fuels across parcel boundaries. Avoid mulch at base of fence.

R4. Avoid proximity of combustible fences to residence, including neighboring residence, to prevent direct ignition. The relationship between spacing and structure to prevent structure ignition is a function of structure construction materials/assembly and fence materials/design.

R5. Replace combustible landscape features with noncombustible or low fire hazard features when possible. Fire spread is more likely with wood and wood-plastic composite fences than with fences made of vinyl or noncombustible materials such as stone, brick, or steel.

R6. Keep fence and yard clear of debris, to reduce the amount of fuel and potential pathways for fire.

[1] A. Maranghides, E. Link, S. Hawks, J. McDougald, S. Quarles, D. Gorham and S. Nazare, "WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology," NIST Technical Note 2205, National Institute of Standards and Technology, Gaithersburg, MD, 2022.

R7. Harden structures against firebrands, to prevent structure ignition from embers produced by fences or other combustible sources.

RECOMMENDATIONS FOR FUTURE WORK

More research is needed to determine the vulnerabilities of structures to fence fires relative to fence types and materials, the proximity and connection of the fence to the structure, and the design and exterior materials of the structure itself. Once the vulnerabilities are better understood, mitigation techniques such as material treatments and coatings can be explored beyond the simple solutions of increased separation and replacement of materials with noncombustible options.

S1. Study the effects on fire behavior of closely spaced parallel wall surfaces in communities.

The same radiation exchange and convective transport of hot gases between burning parallel surfaces that led to eruptive behavior for parallel wood fences can potentially result in highly hazardous situations for other closely spaced parallel surfaces, including residences. As one approach, the Structure Separation Experiments project at NIST[2,3] is addressing the question of how far apart residences should be from other nearby structures.

S2. Continue to study the fire behavior of landscape features and potential mitigation methods.

There are many combustible landscape features that may contribute to fire hazards in a parcel or community. Work is ongoing at NIST to understand the interactions of fires on woodpiles, landscape timbers, creosote-treated timber, and sheds. The work will include strategies for mitigation. Together, these studies will inform existing and new codes and standards with quantitative fire spread mitigation and structure protection strategies based on experimental data.

S3. Improve data collection methods.

The range of fire behaviors found for a variety of materials, designs, and configurations suggests improvements in data collection methods that would be useful for future targeted studies. For fence and mulch configurations resulting in large flames and very high hazard conditions, the radiative and convective heat flux received at vulnerable locations could be evaluated by heat flux sensors and/or infrared (IR) imaging. Firebrand fluxes, sizes, and energy content could be assessed in future studies by new measurement technology, including a three-dimensional firebrand tracking system under development at NIST.

S4. Use fire modeling to better understand the physics behind the fire behavior.

Modeling can be used to extend the understanding from this study to other configurations of fences, mulch beds, structures, and other fuels, in order to identify other high hazard

[2] A. Maranghides, S. Nazare, E. Link, K. Prasad, M. Hoehler, M. Bundy, S. Hawks, F. Bigelow, W. Mell, A. Bova, D. McNamara, T. Milac, D. Gorham, F. Hedayati, B. Raymer, F. Frievalt and W. Walton, "Structure Separation Experiments: Phase 1 Preliminary Test Plan," NIST TN 2161, National Institute of Standards and Technology, Gaithersburg, MD, 2021.

[3] A. Maranghides, S. Nazare, E. Link, M. Bundy, A. Chernovsky, E. Johnsson, K. Butler, S. Hawks, F. Bigelow, W. Mell, A. Bova, D. McNamara, T. Milac, D. Gorham, F. Hedayati, B. Raymer, F. Frievalt and W. Walton, "NIST Outdoor Structure Separation Experiments (NOSSE): Preliminary Test Plan," NIST TN 2199, National Institute of Standards and Technology, Gaithersburg, MD, 2022.

configurations. The results in this report may be helpful in validating a physics-based fire model, including:

- Fire behavior of fences as a function of material properties and design.
- Fire behavior of parallel fences compared to single fences.
- Dependence on parallel fence spacing for time at which flames engulf the fences.
- Dependence of fire behavior on parallel fence length, including the spacing for which a second panel length results in explosive fire growth, and the time for fire to spread down a long fence.
- Char patterns for wood privacy fences, both individually and in parallel with combustible and noncombustible fences and walls.

S5. Develop fire test(s) for evaluating fences and fence materials that represent the actual fire hazard.

A standard test method is needed to assess the fire performance of fences. The method should consider not only materials but assemblies and be carried out in a vertical orientation. It should be able to distinguish the fire behavior of various materials, including wood-plastic composites, wood, and vinyl, and designs, including privacy, lattice, and good neighbor.

1. Introduction

The trees, grass, brush, and organic debris that make up wildland vegetation are not the only source of fuel for wildland-urban interface (WUI) fires. Once such a fire reaches a community, its structures and landscape features add to and may come to dominate the fire sources, magnifying the risk. Combustible elements in a neighborhood may transform from being the targets of flames and embers to fire sources themselves that threaten surrounding properties and the people who live there. How and where we build, then, affects the progression of a WUI fire.

The National Institute of Standards and Technology (NIST) is working to assess fire hazards in our built environment and to develop mitigation methodology to harden it against ember and flame exposures. This report on fences and mulch builds on a growing body of NIST research studying fire behavior and how the materials, designs, and configurations present in a community influence a WUI fire.

1.1. Motivation

The wildland-urban interface refers to areas where houses are adjacent to or intermixed with wildland vegetation. The regions where the WUI overlaps with high risk of wildland fires due to fuel, weather, terrain, and sources of ignition are where these wildland fires pose the greatest risk to lives and property. Effective methods are needed in these areas for protecting people, homes, and communities from wildfires.

A large and growing number of people live in WUI areas in the United States. In 2010, the WUI covered 9.5 % of the total area of the conterminous U.S. and contained 43 million homes (about 1 in every 3) sheltering 98 million people, or 32 % of the U.S. population [1]. This represented an increase of 33 % in land area and 41 % in the number of homes since 1990, due almost exclusively to construction of new houses in or close to wildland vegetation [1]. Residents are attracted to the WUI due to the closeness to natural settings and amenities and to the relative affordability of housing farther from urban centers. Demographic forces, including retirement, population growth, and population shifts, are expected to continue expanding the WUI in the U.S. [2].

Residence in the WUI does not in itself put one at risk from WUI fires. Wildfires threaten communities where the WUI intersects with areas where there is a significant risk of wildfire ignition and spread. A fire can also ignite in wildland areas surrounded by a community, then rapidly grow to put one or more communities at risk. Drought, wind, terrain, vegetation type and health, and the presence of ignition sources contribute to the probability of development of WUI fires. Conditions for wildfires are expected to worsen as climate change continues to enhance fuel abundance and drought conditions [3]. Humans have greatly expanded both the spatial range of wildfires and the length of the fire season, now accounting for 84 % of the total number of wildfires [4]. Balch et al. developed a map of fire risk for populated places by combining population densities with wildfire risk [5]. The map shows that high and medium WUI fire risk areas are scattered across the U.S., including New Jersey, Kentucky, Tennessee, Florida, and the south Atlantic Seaboard in addition to midwestern and western states such as Texas and California.

WUI fires can occur when wildland fires cannot be controlled, often due to extreme wind and fuel conditions, and spread into communities. Such fires have caused significant losses to life and property in the U.S., Canada, and other parts of the world including Australia and Mediterranean Europe. The costs have increased in time; of the 20 most destructive fires in California history, more than half occurred since 2017 [6]. At the top of this list is the Camp Fire of November 2018, which resulted in 85 fatalities and destroyed over 18 000 structures, including 90 % of the homes in Paradise, CA. The Camp Fire was one of the costliest natural disasters of 2018, with an overall loss of $16.5 billion as estimated by multinational insurance company Munich Re [7]. The second most destructive fire on the same list was the Tubbs Fire in Sonoma County in October 2017, which resulted in 22 deaths and over 5 000 structures destroyed. Research is urgently needed to better understand WUI fire-structure interactions and to support changes to building and community designs and codes in order to mitigate the increasing losses from the growing number of WUI fire incidents.

NIST has carried out studies on several WUI fires, including the 2009 Witch Creek Fire in California [8, 9], the 2011 Tanglewood Complex Fire near Amarillo, Texas [10, 11], and the 2012 Waldo Canyon Fire in Colorado [12]. NIST is currently studying emergency communications during the Chimney Tops 2 Fire near Gatlinburg, Tennessee, which killed 14 people and destroyed or damaged 2 500 structures in November 2016 [13]. The NIST Camp Fire WUI case study is currently ongoing, with the Camp Fire fire progression timeline already published [14]. The current focus of the multi-year case study is on notification, evacuation, and temporary refuge areas (NETRA), and the final major report will focus on responder actions and structure survivability.

Fences and mulch have been identified as common contributors to the spread of WUI fires within communities. In the Tanglewood Complex Fire, over 2.4 km of fences were found to be damaged or destroyed within a community of 47 residential structures (in which 17 homes were destroyed and 4 were damaged) [10]. Instances of fires spreading to structures along fences were observed in the Witch Creek Fire [8] and the Waldo Canyon Fire [12]. Figure 1 shows the progress of a fire from a wood privacy fence to a structure during the 2018 Camp Fire in California. Figure 2 shows a length of fence burning in the same fire. Because of their linear nature, it is possible for fences to spread fire over long distances. In the Waldo Canyon Fire and many others, firefighters removed fences as part of their defensive strategy aimed at containing the fire [12], as shown in Fig. 3, reducing resources allocated to direct structure protection. Mulch and other groundcovers also provide a continuous pathway for fire. A report on 21 structures that were damaged by burning wildland vegetation in Virginia over a two-year period found that the fire spread to most structures by means of leaf and tree litter that covered the ground with a thickness between 8 cm and 13 cm [15].

Fig. 1. Fence burning in Magalia, California during Camp Fire, 8 November 2018. Photographs taken two minutes apart. CAL FIRE, used by permission.

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Fig. 2. Fence burning during Camp Fire as viewed from an ambulance. American Medical Response (AMR) – Shasta County, used by permission.

Fig. 3. Ignited wood fencing in Waldo Canyon Fire in Colorado, 2012. Photo from Colorado Springs Fire Department, used by permission.

Fences, mulch, and other combustible landscaping elements can act as both potential ignition sites from existing fires (targets) and sources of fire spread themselves. These materials can be ignited by a fire through direct flame contact, radiation, convection, or firebrands. Firebrands, also referred to as embers, are carried by the wind and may ignite combustible materials in a community far downwind of the fire front. Once ignited, fences and mulch may ignite nearby objects, including a home, through direct flame contact or firebrands.

The protection of people and property in the WUI depends in part on improvements to building and landscape materials, design, and maintenance practices. Efforts to improve community resistance to fire include: WUI building code organizations, such as the International Code Council (ICC), the National Fire Protection Association (NFPA), and the California State Fire Marshal Chapter 7A WUI Task Group; and voluntary fire outreach programs, such as Firewise, Fire Adapted Communities, and the Fire Learning Network. Concepts like defensible space and the home ignition zone educate the public on how to protect their homes. Recently, a fire hazard mitigation methodology has been developed based on the relationships among fuel layout, fire hazard, and structure hardening [16].

For maximum effectiveness, these efforts require science-based data and guidance. Increased understanding of the vulnerabilities of structures in WUI communities and the potential pathways for flames and firebrands will help to enhance life safety and to improve community resistance to these fires. The hazard may be reduced through improvements in materials, designs, and configurations. Homeowners and community planners can recognize ways in which neighbors can work together to reduce the fire threat. Strategies may be developed for both existing communities and new construction.

The goal of this work is to improve our understanding of the mechanisms by which fences and mulch can transport fire to a home. Better understanding of the role of these features as conduits of fire spread to structures, identification of particularly hazardous configurations, and determination of effective hazard mitigation approaches promote efforts to protect against ignition and fire spread. Helping fire departments to identify very high hazard situations will enhance first responder safety and effectiveness. The results of this work will be used to improve codes and standards and to provide guidance to homeowners, community designers, and first responders.

1.2. Background

WUI fires ignite the exteriors of structures through flame radiation and convection, direct flame impingement, and firebrands. In contrast to the large body of knowledge on ignition and fire growth within buildings, reflecting decades of fire research, the complexities of the interactions between the built environment and exterior fire exposure are in the early stages of exploration. Our understanding of WUI fire behavior is confounded by the large number of potential fire and firebrand exposure scenarios, the wide variety of WUI fuels (vegetative and structural), and the extensive assortment of exterior construction materials and assemblies. The research presented in this report joins other efforts to better understand structure vulnerabilities to fires on nearby fences and mulch beds.

1.2.1. Structure Vulnerabilities

Fire may ignite a structure through numerous pathways. At close range, exposed combustible materials may ignite through radiation/convection or direct flame contact. Ignitions may also occur through firebrands. These burning particles break off from a larger object in a fire and are blown or lofted to a new location, where they can ignite spot fires. Firebrands may ignite susceptible parts of the building exterior and may penetrate into interior spaces through vulnerable openings in the building envelope. An object ignited by flames or firebrands may itself become a fire source of firebrands and additional radiation and flame exposures to surrounding fuels (targets).

1.2.2. Fence Studies

Fences are a linear landscaping feature. Fences frequently “link” multiple parcels, as one fence connects to an adjacent fence. If they are combustible, they may provide a linear path for fire from one end of the fence to the other. They may also produce firebrands capable of igniting spot fires downwind. Several studies have looked at how fences may ignite in a WUI fire and how the fire may behave.

The fire performance of commercial fencing systems in common use in Australia was studied by CSIRO [17]. A bushfire flame front simulator was constructed using a grid of liquid propane burners. Hardwood and treated pine fences were exposed to a range of bushfire exposures, from burning leaf litter through structural fire. Ignition and fire behavior were studied under ambient wind conditions of approximately 5 km/h to 8 km/h (1.4 m/s to 2.2 m/s, or 3 mi/h to 5 mi/h). When burning leaf litter was distributed along the base and rails of treated pine fences, the fire spread slowly laterally along the fencing, eventually causing collapse. Hardwood fences (yellow stringybark eucalyptus and southern mahogany) resisted ignition by leaf litter and radiative heat exposure typical of an approaching bushfire. They ignited under flame immersion from a propane burner but did not support lateral flame spread under the conditions tested. In cone calorimeter studies, the surface moisture content was found to determine fire behavior more than average moisture content, suggesting that weather conditions on the day of the fire will have a significant impact. Sample conditioning at a lower temperature and higher relative humidity (RH) led to longer ignition times.

The CSIRO study [17] found that noncombustible pre-painted and metallic-coated sheet steel fences provided significant protection against radiant heat, preventing combustible items near the fencing from igniting and reducing the radiant heat exposure on a nearby structure. Gaps between boards of hardwood and treated pine fences reduced their ability to shield radiant heat, and the barrier failed completely when fences burned through or collapsed.

A study of the ignition of fences and wood shields by a grass fire [18] showed that fences with narrow gaps between spruce boards ignited, while those with widely separated boards did not. This was likely because the fire front attacked the tightly spaced fence for almost twice as long as the fence with wide gaps. The experiments were carried out in ambient winds of 1 m/s to 6 m/s (2 mi/h to 13 mi/h).

Wood fencing assemblies were exposed to wind-driven firebrand showers by NIST researchers and colleagues at the BRI facility. With no nearby fine fuels, the fencing assemblies experienced smoldering ignition that transitioned to flaming [19]. Flaming ignition occurred when shredded hardwood mulch was arranged at the base of the fencing assemblies. A study of double redwood lattice fencing assemblies on mulch beds subjected to firebrand showers at wind speeds of 4 m/s to 9 m/s (9 mi/h to 20 mi/h) showed rapid growth of flames over the entire assembly [20].

Research was carried out by IBHS on combustible fences in wind-driven firebrand showers [21]. A Wildfire Research Fact Sheet jointly published by NFPA and IBHS [22] includes the following conclusions, primarily derived from the IBHS study: (1) noncombustible fencing should be used where the fence attaches to a building; (2) the area at the base of the fence should be kept clear of debris, including fine vegetative fuels and mulch; (3) a fence design that allows for greater air flow makes windblown ember accumulation and lateral flame spread more difficult, and fence ignitions from windblown firebrands are more likely to occur where vertical fencing planks attach to horizontal support members; (4) fences built from lattice attached to both sides of the support posts should be avoided in wildfire-prone areas, and (5) vinyl fencing burns when subjected to flaming exposures from burning debris and deforms if subjected to radiant heat. Conclusion (4) is a preliminary result from this NIST study that will be discussed in detail in Section 4.4.

A previous NIST study conducted experiments to examine the fire spread along privacy fences relative to wind speed and angle [23]. Western redcedar (Thuja plicata) was the primary fence material, although comparisons were made to California redwood and vinyl fences. The presence of a combustible layer of mulch beneath the fence was significant; in these experiments, fire did not spread without mulch. With mulch, fire was found to spread horizontally along privacy fences as fast as 1.44 m/min, with the fastest rate occurring when winds were in line with the fence. At this angle, moderately high winds of about 13.5 m/s (30 mi/h) produced the fastest spread rate, while higher winds of about 18 m/s (40 mi/h) caused complex competition between sustained spread and extinguishment. No significant differences in fire spread rate were found between cedar and redwood fence fires, and wood preservative applied to the fence resulted in qualitative but not quantitative differences in burning behavior. The vinyl fence fire differed substantially from the wood fence fires due to differences in the fence structure and to the melting behavior of the vinyl when heated. Downwind mulch targets were found to be susceptible to ignition by fence firebrands, with smoldering ignitions occurring at a distance of 18 m (59 ft) from the fence.

In summary, the following findings were obtained:

1) Combustible mulch beneath the privacy fence was necessary for significant fire spread.
2) Fire spread was fastest when the wind was in line with the fence (versus 45° and 90°).
3) Winds of 13.5 m/s (30 mi/h) produced the fastest fire spread of 1.44 m/min (4.7 ft/min).
4) Redwood and western redcedar fire spread rates were not significantly different.
5) A wood preservative did not significantly change fire spread rate.

For these experiments, an airboat propeller was used to generate a wind field that was found to be uniform horizontally and vertically within 2.5 m/s. A flow straightener angled downward by about 9° improved the distribution of wind at the leading edge of the base of the fence.

1.2.3. Mulch Studies

Combustible landscaping mulch may provide a continuous pathway for fire over the ground. Once ignited, it may also act as a source of firebrands. Several studies have looked at ignition and flame spread over mulch materials.

In a wind field, mulch is easily ignited by single flaming firebrands and multiple glowing firebrands [24]. Firebrand experiments showed that smoldering ignition by firebrands always transitioned to flaming on shredded hardwood mulch, Japanese Cypress wood chips, and pine bark nuggets [25]. For a mulch bed adjacent to a re-entrant corner with oriented strand board (OSB) walls, the fire propagated to the back side of the assembly in all cases with wind speeds from 6 m/s to 8 m/s. When vinyl siding was attached, fire propagation showed dependence on mulch type, vertical separation distance, and wind speed.

A study on the ease of ignition of landscaping mulch found differences in the ignition response to high-temperature flames (propane torches for 15 s) and smoldering sources (cigarettes) for several combustible mulches [26]. Thirteen types of mulch were spread over circular test areas at a thickness of 10 cm (4 in) and allowed to weather. The mulch was exposed to lit cigarettes after settling for two weeks or nine months, or to 15 s of propane torch flame after settling for one year. All experiments were performed in mild ambient temperatures with low winds below 2.2 m/s (5.0 mi/h). Under brief high-temperature ignition, the ground rubber mulch consistently ignited and was hard to extinguish, with flames spreading rapidly. Pine straw ignited and propagated easily. Shredded hardwood bark and pine bark nuggets ignited but generally self-extinguished under the experimental conditions.

Four landscaping mulches were used to develop test protocols to measure ignition and flame spread over beds of mulch and forest litter [27]. These tests were performed in the absence of wind. Pine straw mulch readily ignited with a Class C wood crib, the smallest ignition source studied. In the flame spread tests, only pine straw mulch sustained spread to the end of the test bed. Both the flame spread rate and the flame height decreased when the mulch depth was reduced in half, from 76 mm to 38 mm. Pine bark nuggets were reliably ignited by the Class B wood crib, while shredded hardwood and pine bark mulches required Class A wood cribs, the largest source. For these three mulch types, with no wind, the flames self-extinguished shortly after the propane area burner used for ignition was shut off.

A study on the combustibility of landscape mulches evaluated flame height, fire spread rate, and temperature at 10.2 cm (4 in) and 40.6 cm (16 in) heights for eight mulch types [28]. Mulches were arranged in circular plots with 2.4 m (8 ft) diameter and allowed to weather for 79 days. The plots were ignited on a hot dry day, with a fan producing winds of about 4.5 m/s to 6.7 m/s (10 mi/h to 15 mi/h) in the middle of each plot. Of the mulches tested, shredded rubber mulch was rated most hazardous, with the greatest flame height and temperatures. Pine needles and shredded western redcedar bark were only slightly less hazardous, with fast rates of flame spread. Shredded western redcedar bark produced embers that ignited mulch in adjacent beds. Medium pine bark nuggets were moderate in flame height and temperatures, and the flame spread rate was low. Composted wood chips were found to be the least hazardous of the mulch types tested, with slow smoldering combustion, low flames that were rarely seen, and the second lowest temperature readings.

In general, studies that include wind find that fire spreads over combustible mulch, even for mulch types that tend to self-extinguish without wind.

1.3. Approach

A series of field experiments on the fire spread behavior of ignited wood fences and mulch has been conducted by NIST. The experiments examined the spread of fire along wood fences and mulch beds toward a structure in the presence of wind at various speeds. The ability of firebrands generated by these burning materials to ignite spot fires at the base of the structure was observed. Early descriptions of this work were presented at conferences [29, 30, 31].

In each of these experiments, a portable, airboat-style fan was used to direct a wind field with a prescribed speed in the direction of a small shed. A fence panel, mulch bed, or combination was positioned between the fan and the shed at a prescribed location, aligned with the wind. The fence panel or mulch bed was ignited with a propane burner at the end near the fan, and the fire spread due to flames, smoldering, and firebrands was observed. Comparing the fire behavior of a fence with and without mulch provided insights into the contribution to WUI fire spread made by fine fuels that accumulate at the base of fences, such as leaves, needles and other debris. The small shed was used as a target structure for flame spread and firebrands. For most experiments, a target mulch bed was placed along the base of the wall to observe spot fire ignitions from firebrands.

Fence types used in the experiments included western redcedar privacy fences, vinyl privacy fences, California redwood lattice fences, pressure treated pine lattice fences, western redcedar good neighbor fences, and wood-plastic composite fences. Mulch types included shredded hardwood, mini pine bark nuggets, pine straw, and shredded rubber. Experiments were also performed on artificial turf.

1.4. Objectives

The overall goal of the work described in this report is to assess the severity of the fire hazard that fences and mulch pose to structures. This is accomplished by studying the rate and mechanisms of fire spread in the presence of wind, both as the fire progresses along the fence or mulch bed and as it jumps via firebrands from the fence or mulch bed to combustible materials at the base of the shed. The main objectives of the experiments are:

- To observe the burning behavior of wind-driven fires along fences and mulch beds;
- To understand the rate of fire spread along fences and mulch beds as related to wind speed;
- To determine the impact of fence style, fence material type, and type of mulch on the fire spread rate;
- To determine whether a fire along a fence or mulch bed poses a potential ignition danger to an attached or adjacent structure; and
- To ascertain whether a burning fence installation or mulch bed produces significant firebrands capable of igniting downwind combustibles.

It is anticipated that this work will contribute technical knowledge to improve codes and standards for auxiliary structures and to support efforts to address the WUI fire problem by hardening structures and creating defensible space. Future reports will describe the expansion of this study to fire spread over other home landscape features, including woodpiles, railway ties, and landscape timbers. A device to measure firebrand flux and size will provide quantitative data in the near future. Research is also anticipated to explore methods of hardening, such as noncombustible components or flashing, coatings, and design options that reduce the vulnerability.

2. Experimental Description

To investigate the spread of fire through direct flame impingement or firebrand spotting, a series of outdoor experiments was performed on fences and mulch beds arranged in front of a structure in a generated wind field. Figure 4 shows a schematic of the experimental setup for fences and mulch beds. A wind machine, consisting of a gasoline engine turning a 2.11 m (83 in) propeller mounted on a trailer, was directed toward a small structure. A flow straightener was employed to remove large-scale swirl from the supplied wind and to direct the wind downward slightly toward the ground. A fence section, with or without a mulch bed beneath, was arranged perpendicular to the wall of the structure and parallel to the wind flow. The fence and/or mulch bed were placed in contact with the wall of the structure or separated from it by one of three fixed distances. To study the potential for firebrands to ignite the structure, a target pan of hardwood mulch was usually positioned at the base of the structure wall. This mulch bed served as a surrogate for any combustible material next to a structure.

The fence, mulch bed, or combination was ignited with a propane burner to simulate prior ignition via one or more firebrands. Wind was directed at the fence and structure with the wind aligned with the plane of the fence in all but two cases. Three wind speeds were used in the study, with nominal values of 6 m/s (13 mi/h) for low, 10 m/s (22 mi/h) for medium, and 14 m/s (31 mi/h) for high wind speed levels. The fire spread behaviors of multiple fence types, materials, and configurations were investigated, and several mulch types and arrangements were tested. The following sections will detail the experimental setup, equipment, measurements, conditions, and the parameters explored. Many of the uncertainties in the experimental setup and measurements are covered in Appendix A.

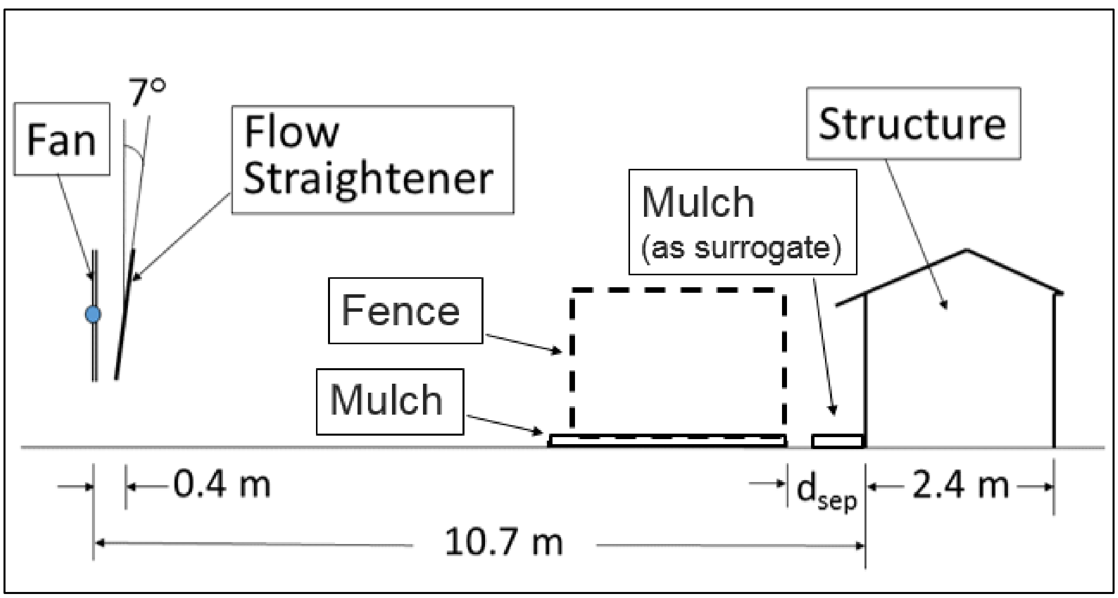

Fig. 4. Major components of the experiment (not to scale).

2.1. Research Location and Site Description

The experiments were conducted in Frederick, MD at the Frederick County Public Safety Training Facility. A large, nearly flat asphalt and concrete area near a water-supply pond was utilized. The pond and its wall provided a noncombustible background downwind of the firebrand-generating experiments. Water for extinguishment was provided through a nearby hydrant and a diesel pump, which provided a high-pressure source of pond water.

An aerial view of the site is shown in Fig. 5, marked up with locations of the target shed, equipment/conditioning building, and wind machine. For the usual configuration, as shown, the wind flow was applied from the wind machine from the SSW direction at an angle of 200° ± 1°. The long-range firebrand experiments described in Section 4.5 were performed in a pathway extended along the wall next to the pond, with wind applied from the SSE direction at an angle of 148° ± 0.5°.

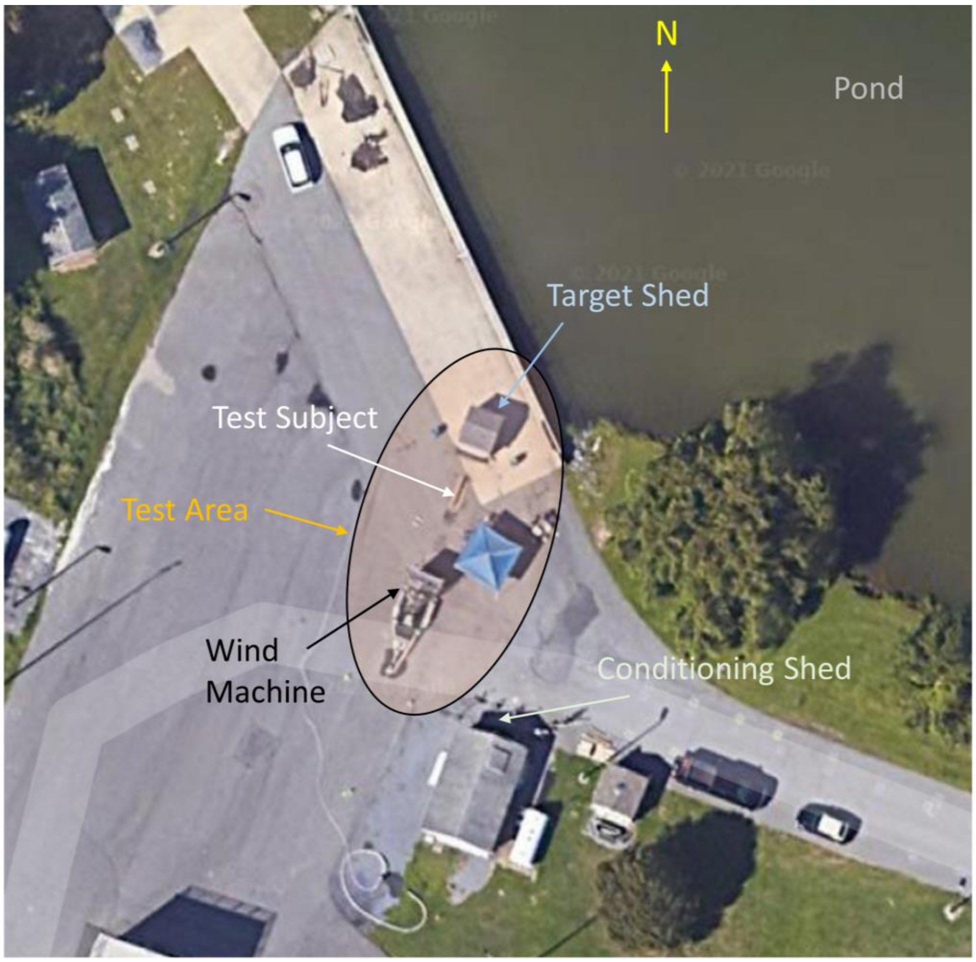

Fig. 5. Aerial view of site used for experiments. Google Earth image with NIST overlay.

2.2. Wind Field Generation

2.2.1. Wind Machine

The wind machine used to impose a wind field on the target structures, shown in the foreground of Fig. 6, was assembled and mounted on a trailer by American Airboat. The power was provided by a 6.0 L displacement, 450 HP rated marine engine with multi-port fuel injection. The wind machine utilized Whirlwind Propellers model AB300ex-WT79, which had three quiet-design, graphite composite blades with a width of 33 cm (13 in) and a sweep diameter of 2.11 m (83 in). The wind machine incorporated a high performance positive drive belt with 2.3:1 reduction. A manual “cruise control” mechanism was designed and added to the single lever binnacle-style throttle control in order to allow maintenance of selected engine speeds, which were monitored with a built-in tachometer.

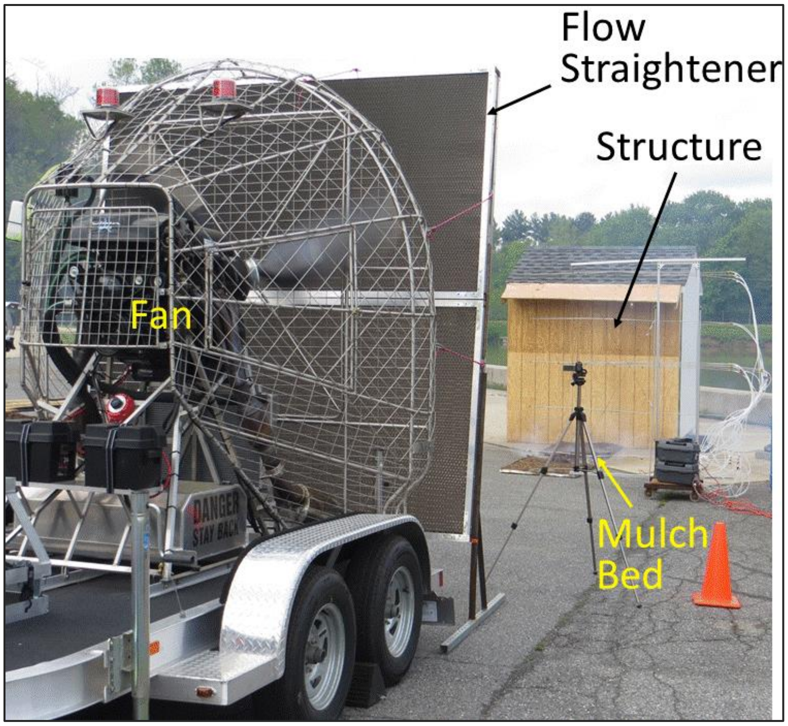

Fig. 6. Photo of test site showing fan, flow straightener and target shed in an experiment on a mulch bed without a fence.

2.2.2. Flow Straightener

A flow straightener was used to remove large-scale swirl from the supplied wind and adjust the wind direction. The flow straightener consisted of two framed sections of aluminum honeycomb with cells 19 mm (3/4 in) across and 11 cm (4.4 in) thick. The two framed sections, each measuring 1.2 m × 2.4 m (4 ft × 8 ft), were stacked as shown in Fig. 6, with the front plane of the flow straightener positioned 45 cm (18 in) in front of the fan at the height of the fan center. Since the lowest sweep extent of the wind machine propellers is 1 m above the ground, the column of air moved horizontally by the wind machine by itself would not begin to be felt at the ground for a distance of several meters. To enable the generated wind field to reach the base of any combustible object being tested, such as a fence and/or mulch bed, with substantial velocity, the flow straightener was angled downward by approximately 7°.

2.2.3. Velocity Profiles

The wind field from an axial fan, such as the wind machine used in these experiments, changes with position downwind [32]. At the outlet of an axial fan, the velocity profile shows a minimum in the central hub region of the propellers. The profile then smooths out with distance from the fan. According to the Air Movement and Control Association International (AMCA), a uniform velocity profile is achieved at a distance of about 2.5 duct diameters from the outlet of the fan, for ducted flows with velocities up to 12.7 m/s (28 mi/h). This provides a general guideline for the minimum distance of the wind machine from the fence or mulch bed being tested, recognizing that the free outlet condition and the presence of the flow straightener modify both the distance necessary to obtain a uniform velocity profile and the radial extent of the high velocity region downwind.

Further discussion of the flow field is provided in Section 2.7.1 and in Appendix C.

2.3. Target Shed

Experiments were classified as Series 1, 2, or 3, depending on the nature of the firebrand target downwind of the fence or mulch being tested. A target shed was used for Series 1 and Series 2 experiments. Series 1 experiments looked at the possibility of direct ignition of a combustible shed wall by firebrands. In Series 2 experiments, a mulch bed at the base of the shed served as a surrogate for combustible materials (such as leaves or pine needles in addition to mulch) that could ignite and carry a fire to the shed wall. Series 3 experiments were performed without a shed, with a mulch bed located far downwind from the test subject to examine long distance ignition by firebrands.

A shed with a 2.43 m (8 ft) square footprint and a height of 2.43 m (8 ft) along the front and rear faces can be seen in the background of Fig. 6. The shed was positioned 10.67 m (35 ft) away from the plane of the wind machine propellers. An artificial eave was added to the shed on the windward side, extending 45 cm (18 in) outward at the same 30° angle as the roofline. The eave was constructed from standard pressure treated pine 2×4s[4] and 1.5 cm (0.59 in) thick T1-11 weather-resistant southern yellow pine plywood panel siding.

A false wall was attached to the shed on the windward side to allow replacement of burned wall layers without damaging the original shed wall. The design of the false wall included layers (from the shed outward) of 1.6 cm (5/8 in) gypsum board, standard pressure treated pine 2×4s (the same type used for the eave), 1.6 cm (5/8 in) gypsum board, and 1.5 cm (0.59 in) thick southern yellow pine plywood panel siding.

For Series 1 experiments, a second layer of plywood panel siding was attached to the lower part of the false wall, as shown in Fig. 7 (a), providing a sacrificial layer that was easily replaced. For Series 2 experiments, James Hardie fiber cement siding was added to the bottom of the false wall, as shown in Fig. 7 (b), as a noncombustible layer that prevented the false wall from getting burned and requiring replacement. The plywood panel siding and fiber cement siding were each 1.22 m (4 ft) tall by 2.44 m (8 ft) wide, with thicknesses of 1.5 cm (0.59 in) and 6.4 mm (¼ in), respectively.

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[4] The term “2×4” is used to refer to dimensional lumber, also known as framing lumber. The cross-sections of lumber are referred to by their nominal size, in this case 2 in by 4 in, but the actual depth and width (the “dressed” size) after cutting and smoothing are 3.8 cm by 8.9 cm (1 ½ in by 3 ½ in) [68]. Similarly, 4×4s measure 8.9 cm by 8.9 cm (3 ½ in by 3 ½ in), and 1×6s measure 1.9 cm by 14.0 cm (¾ in by 5 ½ in).

The false wall and siding layer added approximately 15 cm to the shed depth, for a final shed footprint of 2.43 m wide by 2.58 m deep. The vertical gray strip appearing in Fig. 7 is a metal corner bead protecting the edge of the shed.

Fig. 7. Target shed configurations for a) Series 1 and b) Series 2 experiments.

2.4. Mulch Types and Preparation

For each experiment, a pan was placed on the ground to hold mulch and/or fences and to collect the burned debris. A mulch bed was often placed under the fence to allow testing of the effect of the presence of mulch on flame spread and spot fires. The mulch was considered a surrogate for any fine combustible fuel next to or beneath a fence. Mulch was also tested alone, without a fence, to explore its fire spread and spotting behavior and differentiate it from that of mulch combined with fences.

2.4.1. Mulch Pans

To accommodate a bed of mulch 5 cm deep, two pans were fabricated from 26 gauge [0.454 mm (0.0179 in) thick] galvanized steel sheets. Each steel sheet pan was 87.6 cm (34.5 in) wide and 1.83 m (6 ft) long with 2.5 cm (1 in) high side walls. The two pans were overlapped and connected at the walls with two small C-clamps, for a total combined length of 3.35 m (11 ft). When mulch was placed in the pan, it was generally spread at a compressed depth of 5 cm ± 1 cm. The mulch depth was tapered over roughly the outermost 20 cm to meet the side walls at a depth of 2.5 cm, and also tapered toward the front of the pan to a depth of 2.5 cm. This slight sloping at the edges was done to decrease the step change from ground to full-depth mulch and reduce the effect of the pan and mulch on the wind field near the ground.

After a fence was placed at the correct location in the pan, the fence panel was raised to the prescribed height above the ground and attached to the end posts. If, as in all but a few cases, the height above the ground was 0 m, then the mulch was checked to make sure that it barely contacted the bottom of the fence and was adjusted where necessary. Downwind edges of the mulch pan and the fence post furthest from the wind machine were both located at the prescribed separation distance from the shed wall. Since the combination of fence panel and posts was typically 2.62 m (8.6 ft) or less in length, the excess pan length extended upwind from the leading fence post and included a 30 cm to 60 cm length of mulch to allow the observation of counterflow flame spread on the mulch upwind of the fence. Approximately 0.17 m^3 (6 ft^3) of uncompressed mulch was required to fill the mulch bed. The shredded hardwood mulch was compressed by stepping on it, with pressure of up to about 34 kPa (5 psi), based on the weight and contact area of the researchers. The resulting density of the mulch measured after compression was 253 kg/m^3 (15.8 lb/ft^3) ± 3 %.

The mulch pans tended to warp after exposure to repeated fires and handling to dispose of debris. Two solid steel bars with dimensions of 10.2 cm × 20.3 cm × 2.5 cm (4 in × 8 in × 1 in) were placed in the pans toward the outside where they overlapped to keep the pans compressed to the ground. Two additional bars with dimensions of 7.6 cm × 12.7 cm × 2.5 cm (3 in × 5 in × 1 in) were used in the windward corners of the pan to prevent the wind from lifting the edge off the ground and affecting the wind flow over the bed. During early experiments, low-profile heavy rocks found at the test site were used for the same functions.

For the experiments on two fence panels connected end-to-end, three pans were attached with clamps for a combined length of about 5.33 m (17.5 ft).

An exception to the use of steel pans under the mulch or fence was made for the experiments on artificial turf. As a synthetic groundcover that rolled out like a carpet, artificial turf did not require containment to hold it in place. Noncombustible Durock cement board [33], with a low thermal conductivity (0.18 W/m-K) of the same order of magnitude as soil [34], was used for these experiments. Two cement boards measuring ½ in thick, 3 ft wide, and 5 ft long were arranged end-to-end, with the artificial turf unrolled on top. Steel bars were used to keep the artificial turf from curling up.

2.4.2. Mulch Types

Mulch types used in these experiments included shredded hardwood, mini pine bark nuggets, pine straw, and shredded rubber. Photographs of these mulches are presented in Fig. 8.

The predominant mulch used in these experiments was shredded hardwood, shown in Fig. 8 (a). The shredded hardwood mulch was procured in 56.6 L (2 ft^3) bags. Shredded hardwood mulch was tested at the full 5 cm depth most of the time, although an abbreviated series of experiments with 2.5 cm depth was also conducted to see what effect the depth of combustible mulch might have on flame spread.

Mini pine bark nugget mulch was also procured in 56.6 L (2 ft^3) bags. A photograph is shown in Fig. 8 (b).

Pine straw mulch is commonly utilized for landscaping in the U.S. southeastern states. Multiple needle lengths and quality are available. The pine straw mulch used in these experiments was slash pine (Pinus Elliottii) with nominal 23 cm (9 in) length needles and of A-grade quality (low level of non-pine-needle debris). The mulch was obtained from two vendors in South Carolina; the products appeared to be identical. A photograph of the pine straw mulch is shown in Fig. 8 (c). For medium and high wind conditions, a chicken-wire mesh with 2.5 cm (1 in) openings was used to hold the pine straw mulch down and prevent it from blowing away prior to burning. This was deemed a realistic measure given that a typical pine straw mulch bed installation would stay in place naturally after it had been compressed and interwoven together due to cyclical exposure to wind and rain. No other mulches were susceptible to being blown away in significant quantities.

Fig. 8. Mulch types: a) shredded hardwood mulch, b) mini pine bark nuggets, c) pine straw, and d) shredded rubber mulch.

Experiments were also performed on shredded rubber mulch, shown in Fig. 8 (d). No experiments were performed on this mulch in combination with a fence. The brand used was Rubberific Red Rubber Mulch, which was purchased in 22.7 L (0.8 ft^3) bags.

In addition to the above types of mulch, two experiments looked at the fire behavior of a single variety of artificial turf. The synthetic fibers were made from polypropylene with a urethane-coated backing. The turf was cut to a width of 0.91 m (3 ft) ± 8 mm and rolled onto the cement board substrate described in the previous section. There are a wide variety of materials and designs for artificial turf – the experimental results for the single type selected for this study should not be considered as representative of the fire behavior for all varieties.

2.4.3. Mulch Conditioning

All natural mulches used in these experiments were dried to 6.5 % ± 1 % moisture content. Three alternative drying processes were utilized during the study: natural heating and drying in the sun on an outdoor raised mesh platform, mesh bags placed on wire shelving in a wood-drying kiln at NIST, and thin layers placed in an indoor space conditioned to 30 % relative humidity (RH). A moisture content of 6.5 % was selected because it is on the order of values seen in wood in summertime in the American Southwest [35] – a low value, yet more realistic than the far lower moisture content that could have been achieved through oven-drying.

Mulch moisture content was measured with an Arizona Instruments Computrac MAX 1000 moisture analyzer (see Fig. 9). After drying, the mulch was placed in plastic bins that could hold between 56.6 L (2 ft^3) and 113.3 L (4 ft^3) for storage and transport. The bins were stored either in the conditioned (30 % RH) indoor space or in sealed bins in a building at the test site. The dehumidifying equipment at the latter site was unable to reduce the water vapor content below 35 % RH; however, with sealed bins, large amounts of mulch, and a small moisture gradient, the moisture content was not expected to change significantly when moved from 30 % to 35 % relative humidity conditions. A chart of equilibrium moisture content (EMC) of wood as a function of relative humidity and temperature shows that EMC ranges from 5.6 % to 6.3 % at 30 % RH and 6.3 % to 7.1 % at 35 % RH, for temperatures from 43.3 °C to -1.1 °C (110 °F to 30 °F) [35, 36]. Therefore, a moisture content estimate of 6.5 % ± 1 % encompasses the sets of conditions at both sites, as well as the effects of variations in initial drying.

Fig. 9. Moisture analyzer used for measuring moisture content of mulch.

The rubber mulch was not carefully conditioned. Each 28 L (1 ft^3) bag was emptied into two large bins such that the depth of mulch was about 10 cm (4 in). These were only stored in the conditioned environment for about one day, so some residual moisture remained in the mulch.

2.4.4. Target Mulch Bed

To study whether the fence or mulch bed being tested was capable of generating firebrands that could threaten a structure through spot fires, many experiments included a target bed of shredded hardwood mulch placed along the base of the shed wall, as shown in Fig. 10. These experiments were classified as Series 2 experiments. The target mulch bed was 0.46 m (18 in) wide and 2.44 m (8 ft) long. Two steel pans, each 1.37 m (4.5 ft) long, were overlapped in the middle to create the 2.44 m total length. The pans had 2.5 cm (1 in) walls on the far ends and on the back edge that abutted the shed wall.

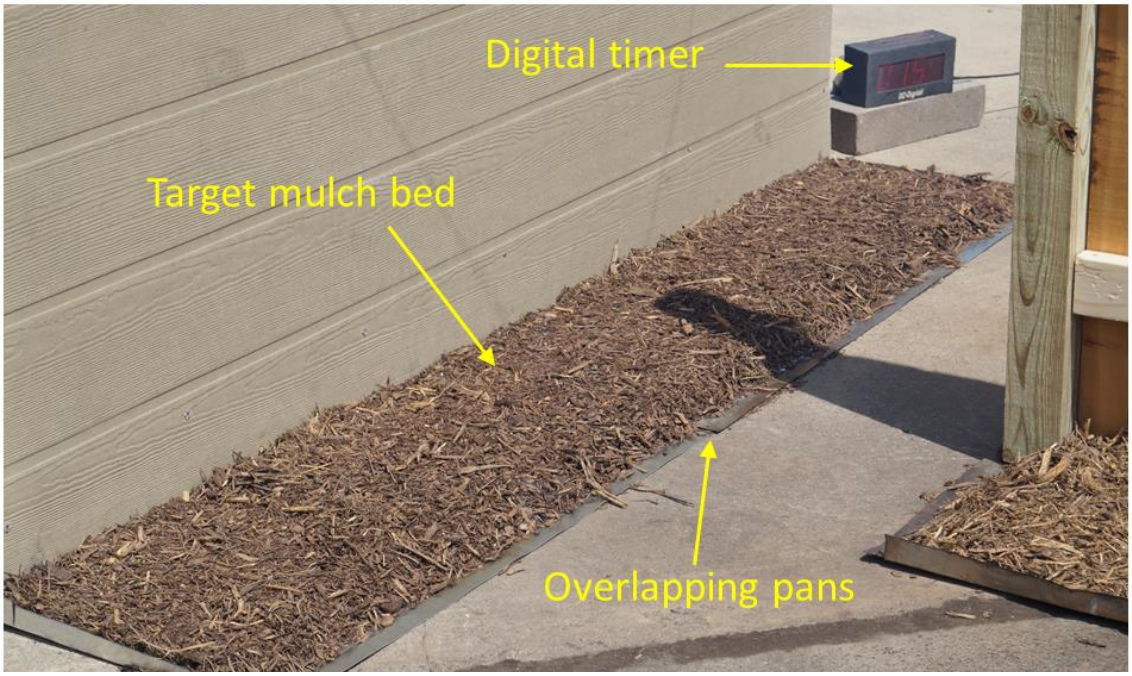

Fig. 10. Target mulch bed and digital timer.

The target mulch bed served as a surrogate for any combustible material next to a structure. Because of its rough texture, any firebrands landing on this surface tended to stay in place. Shredded hardwood mulch was selected as a conservative worst-case for combustibles near the structure: dry, consisting of easily ignited small pieces, and comprised of innumerable crevices in which firebrands could lodge. The mulch was conditioned to 6.5 % ± 1 % moisture content, as described in Section 2.4.3.

The mulch bed was prepared by filling the pans with an even layer of mulch and compressing the mulch by foot, as described in Section 2.4.1. The target mulch bed was 2.5 cm thick, with the first 3 cm of the leading edge slightly tapered down to about 1.5 cm thick to decrease the severity of the abrupt change in height from the ground and to reduce the number of sliding firebrands that were caught at the front edge of the bed.

2.5. Fence Types, Materials, and Preparation

2.5.1. Privacy Fences

An informal survey of southern California and northern Texas fence companies performed for the previous NIST fence study [23] found that privacy fences are the most common type constructed in those areas. A variety of top styles are used (e.g., cap, dog-ear, lattice). The simplest style privacy fence (plain flat top) was selected for that initial series of experiments as well as for this more in-depth investigation. The survey also found that western redcedar, California redwood, and vinyl were the most common fence materials, leading to the selection of those materials for the preliminary study. Since redwood and western redcedar displayed very similar fire behavior, the current series of experiments focused on western redcedar. A photo of a western redcedar privacy fence is shown in Fig. 11 (a).

Fig. 11. Fence types: a) western redcedar privacy, b) aged privacy, c) vinyl privacy, d) redwood lattice, e) pressure treated pine lattice, f) western redcedar good neighbor, g) wood-plastic composite #1, and h) wood-plastic composite #2.

The western redcedar (WRC) privacy fence panels in this study were made primarily with vertical boards of 1×6 lumber, measuring 1.9 cm (3/4 in) thick, 14.0 cm (5.5 in) wide, and 1.83 m (6 ft) tall. These boards were chosen because their usage appears to be more predominant than the narrower 1×4 boards, whose width is 8.9 cm (3.5 in). The density of the wood boards was 360 kg/m^3.

The fence panels were manufactured locally by two fence construction companies to maintain commercial standards and consistency, with overall dimensions of 2.44 m (8 ft) long by 1.83 m (6 ft) tall. To achieve the 2.44 m length, sixteen 1×6 boards and two 1×4 boards were arranged side by side. The boards were nailed to three 2×4 horizontal stringers or rails made of pressure treated pine, with cross-sectional dimensions 3.8 cm (1.5 in) thick by 8.9 cm (3.5 in) high and density of 930 kg/m^3. The bottom stringer was attached 21 cm (8.25 in) above the ground, the top stringer was attached either flush with the top of the fence (for tests A-48 through A-91) or 21 cm (8.25 in) below the top, and the middle stringer was attached midway between top and bottom stringers. Spacing between the vertical boards varied from 1 mm (0.04 in) to 6 mm (0.24 in) and averaged 3.5 mm (0.14 in). Uncertainties for the dimensions of fence components and the assembled fence are discussed in Appendix A.1.

In order to evaluate the effects of age on fire spread on a western redcedar privacy fence, four fences were recovered from a dump in Colorado Springs by the Colorado Springs Fire Department. All four panels were from the same fence assembly, which was estimated to be well over ten years old. The type of wood was not determined conclusively, but western redcedar is a common fence material in the area, and the fence appearance was consistent with this type of wood after weathering. Due to broken or damaged boards, the four deficient fence panels were combined into three complete ones. The fences also included weathered pressure treated pine 2×4s. Much of the wood had signs of dry-rot and was relatively fragile compared to new fences. The aged fence panels were 2.34 m (92 in) long as compared to 2.44 mm (8 ft) for the new WRC panels; otherwise, the dimensions were identical. Figure 11 (b) shows a photo of one of the aged privacy fences as it was ignited.

A few experiments were performed on polyvinyl chloride (PVC) privacy fences, commonly referred to as vinyl fences. Unlike the wood fences, vinyl panels were provided with their own vinyl posts. The total length of these test subjects including posts was 2.44 m (8 ft). As shown in Fig. 11 (c), vinyl fence assemblies consisted of the two end posts with two horizontal rails flush with the top and bottom. The rails had continuous slots to hold the ends of the inserted vertical boards. The vertical sections nested with each other with a tongue and groove design.

2.5.2. Lattice Fences

A second type of fence investigated was the diagonal lattice fence. Photos in Fig. 11 (d) and (e) show redwood and pressure treated pine diagonal lattice fences, respectively. Lattice fence panels were included in this study as an example of a decorative fence type often used to border gardens or patios. Redwood was the material used for most of the lattice experiments. The dimensions of the diagonal lattice wood slats were 3.8 cm (1.5 in) wide and 7.9 mm (5/16) in thick. The diagonally crossed slats produced diamonds that were 7.0 cm (2.75 in) across. The size of a lattice panel was 1.22 m (4 ft) high by 2.44 m (8 ft) long, making them 0.609 m (2 ft) shorter in height than the privacy fences.

Lattice fences required two horizontal stringers or rails for strength. The material for these boards was interior (untreated) pine, with the same transverse dimensions as the privacy fence stringers (nominal 2×4 lumber) but oriented with the wider dimension horizontal to the ground as shown in Fig. 11. The stringers were cut to a length of 2.34 m (92 in) to allow the 2.44 m (8 ft) long lattice panel to overlap the posts by 5 cm (2 in) at either end. The stringers were located 8.9 cm (3.5 in) from the bottom of the fence panel and 21.6 cm (8.5 in) from the top.

Pressure treated pine lattice fences were tested as a comparison with the more expensive redwood, which is more readily available near the U.S. west coast. The pine lattice wood was slightly thinner at 6.4 mm (1/4 in) thick, so any differences in fire performance could be due to mass as well as material.

2.5.3. Good Neighbor Fences

Good neighbor fences are fences that look the same from both sides of the fence, so that both neighbors see the finished, “pretty side” of the fence. The good neighbor fences used in this study, shown in Fig. 11 (f), also go by the name board-on-board. They are characterized by boards that are attached to alternating sides of the horizontal stringers, allowing neighbors to enjoy both privacy and an identical appearance. Due to the interesting fire behavior found for double lattice fences and parallel privacy fences (described in Section 4.4), the good neighbor style privacy fence was investigated for three experiments. It was anticipated that this fence might exhibit a hybrid of the fire behaviors of single and parallel privacy fences, since the boards are in view of each other's faces for radiative heat transfer, although at an angle. This fence style used the same western redcedar boards as described for the standard privacy fence in Section 2.5.1, but the vertical boards were mounted on alternating sides of the horizontal stringers or rails. The good neighbor fence used the same type, arrangement, and spacing of horizontal stringers as used for the privacy fences. On each side of the fence, boards alternated with 8.9 cm (3.5 in) width spaces, and each board faced a space on the opposite side of the fence. This spacing typically resulted in ten vertical boards on one side and eleven on the other.

2.5.4. Wood-Plastic Composite Fences

Two wood-plastic composite fences were tested in this study. Both fences were designed to look the same on both sides of the fence, similar to the good neighbor fence.

In the case of WPC1, shown in Fig. 11 (g), the extruded composite boards were designed to interlink, leaving no gaps between boards. The assembly primarily consisted of top and bottom rails holding the interlinked vertical boards. The vertical boards, made of 5.6 mm (7/32 in) thick composite, stood in the slot running along the entire length of the bottom rail made of 2.5 mm (0.1 in) thick aluminum, which was 15 cm (6 in) tall and wrapped with 5.6 mm (7/32 in) thick composite rail covers. The tops of the boards were also inserted into the 15 cm (6 in) tall, 13 mm (1/2 in) thick top rail. Both rails were suspended from brackets attached between their ends and the posts. Bare treated 4×4 pine posts were used instead of the sleeves sold with the assembly.

The boards for the WPC2 fence were arranged horizontally, as shown in Fig. 11 (h). Hollow aluminum posts 10 cm (4 in) wide were mounted on stands at each end of the fence. An aluminum bottom rail 30 mm (1.2 in) high was inserted into slots on the posts, followed by a set of eight fence boards each 21 cm (8.3 in) tall and topped by an aluminum upper rail 30 mm (1.2 in) high. Each board was hollow with struts separating front and back surfaces, for a total board thickness of 17 mm (0.7 in).

2.5.5. Fence Support

All wood fences were mounted on two pressure treated pine posts with square cross sections 8.9 cm (3.5 in) on a side (nominal 4×4 lumber). The posts at each end added 17.8 cm (7 in) to the length of a single privacy fence panel, for a total length of 2.62 m (8 ft 7 in). Lattice fences were mounted on the sides of the posts, for a total single panel length of 2.51 m (8 ft 3 in).

Fence panel and post assemblies were supported by boring a 2.4 cm (0.94 in) diameter hole in the bottom of each post and inserting the 25 cm (10 in) long, 1.91 cm (0.75 in) diameter "leg" of a steel "foot" in the hole. Beneath the vertical rod, each foot was made with a cross of 4.8 mm (3/16 in) thick, 2.5 cm (1.0 in) wide steel bars. Sections of wood 4×4 posts 25 cm long were inserted into the vinyl posts to allow mounting on the same legs/feet used for wood fences.

Each end of the fence was connected to two partially filled 208 L (55 gal) barrels of water using 15-gauge (1.45 mm or 0.0571 in diameter) steel wires. The purpose of this was to provide stability and to prevent the wind from blowing the fence over or causing unrealistic vibration or other motion. When the separation distance from the shed was less than 3 ft, the nearest fence post was attached to the eaves of the shed rather than to a water barrel. The wire support system also allowed the fences to be adjusted for verticality.

2.5.6. Parallel Fences

During this study, rapid growth in fire spread and energy release was discovered for two fence panels erected adjacent to each other. This fire behavior led to a series of experiments to investigate two scenarios. In the double lattice fence scenario, two lattice fence panels are mounted on opposite sides of a 2×4 lumber frame, providing a more substantial boundary to delineate or partially enclose an area such as a garden. In the parallel fence scenario, two fences are erected by neighbors on either side of the shared property line. It is not uncommon to find parallel fences in communities, where a homeowner erects a second fence for a pleasing appearance or a functionality that is not provided by the neighbor’s existing fence. Fences are often installed fractions of a meter apart, as in the example in Fig. 12. A fence may also be constructed next to other types of vertical surfaces, such as auxiliary buildings.

Fig. 12. Parallel privacy fences. Colorado Springs Fire Department, used by permission.

Double lattice fences were fabricated with structural support similar to that used for single lattice panels. As can be seen in Fig. 13, two 3.8 cm × 8.9 cm (nominal 2×4 lumber) untreated pine rails were attached horizontally along the top and bottom of two lattice panels. The rails were oriented with the shortest dimension contacting the lattice panels, providing an 8.9 cm (3.5 in) separation distance between them. The upper frame board was located 21.6 cm (8.5 in) from the top of the lattice, and the lower one was located 8.9 cm (3.5 in) from the bottom. To provide more stability, keep the assembly square, and provide an attachment point to connect to the posts, four 10.2 cm (4 in) long corner braces made from the same untreated pine lumber were attached at the inside corners, extending upward or downward from the horizontal frame boards.

Fig. 13. Double lattice fence.

For the parallel privacy fence experiments, the two fences were each connected to their own independent posts. The fences were arranged with the smooth sides facing out and the horizontal stringer sides facing inward. Spacing of the fences was defined as the distance separating the vertical boards, although distances between horizontal stringers was less. Spacings included 20.3 cm (8 in), 30.5 cm (12 in), 45.7 cm (18 in), 61.0 cm (24 in), and 91.4 cm (36 in). For spacings of 61 cm (24 in) and greater, two adjacent sets of mulch pans were required. For stability, each fence was attached to two water barrels and to each other with steel wire. Parallel fences were tested similarly to single fences – with and without mulch beneath and raised or lowered on the posts as needed.

Most parallel privacy fence experiments were conducted with western redcedar fences, but additional experiments explored combinations of western redcedar privacy fences, vinyl privacy fences, pine lattice fences, and noncombustible cement board sheeting.

2.5.7. Fence Materials

Physical and flammability properties were obtained for the fence materials used in this study. Appendix B describes a cone calorimeter study comparing flammability measurements for western redcedar (WRC), vinyl (PVC), and wood-plastic composite (WPC) fence samples. The samples were cut from fence boards – the WRC and WPC samples were solid, with different thicknesses but comparable masses. The PVC sample consisted of two thin sheets separated by three thin sheets serving as braces and had the lowest mass. Wood-containing samples (WRC and WPC) ignited easily, and the duration of flaming was higher than that of PVC by a factor of two. The WPC samples burned intensely, with peak and total heat release values greatly exceeding those of the other two materials. The total heat release and the average heat release rates for WRC samples were significantly higher than for PVC.

Firebrand generation was observed in WRC samples during flaming and after flame extinction, with small wood firebrands flying away from the burning cone samples. No smoldering combustion was observed for PVC and WPC samples.

2.5.8. Wood Conditioning

Wood fences, posts, and the boards used to assemble double lattice fences were stored in the same conditioned spaces as the mulch (30 % to 35 % RH). Like the mulch, the moisture content for these components was 6.5 % ± 1 %, selected as a value that would provide more realistic conditions for fire spread than the enhanced conditions that would result from using oven- or kiln-dried wood [35].

2.6. Ignition Source

The test subject was ignited by one of three types of propane burners applied near the end farthest from the structure. The primary burner was a customized model that consisted of eight Venturi-style brass torch heads (Bernzomatic brand Pencil Flame model), arranged with four torch heads on each side of the test object. Two torches of each set pointed 45° upward toward the fence and the other two pointed 45° downward toward the mulch, as can be seen in the overhead view in Fig. 14. The torches were wrapped with Kaowool ceramic fiber blanket and then covered with aluminum foil as shown in Fig. 15 for protection from flames and radiation after ignition of the fence and/or mulch.

Fig. 14. Propane burner for igniting fence and/or mulch, with torches exposed.

Fig. 15. Propane burner protected by Kaowool blanket and aluminum foil.

An alternative ignition source was used on a small number of experiments with unusual fire behavior. Because of the rapidity of the fire growth on shredded rubber mulch, and because the vaporized rubber tended to clog the fence burner torches, a larger single propane torch was implemented. The larger torch was a Magna Industries MagFire MT5500 with a 6 cm diameter nozzle and maximum output of 150 kW. It was successfully used to ignite the rubber mulch quickly and uniformly across the width of the pan. The torch burner was also used for ignition of artificial turf.

For experiments in which the fence was raised above the mulch bed, described in Section 4.3.2.4, a ring burner with propane as the fuel was used for ignition. The Imperial model IMP1273 ring jet burner was 23 cm (9 in) in diameter and primarily made of cast iron. It consisted of nine hubs of one to four brass torch heads each, distributed around the perimeter and across the diameter.

2.7. Measurements

2.7.1. Wind Speed Profiles

The experiments were performed under imposed wind speed conditions from 6 m/s to 14 m/s (13 mi/h to 31 mi/h) in line with the fence. In order to measure the wind velocity field, an array of thirteen bidirectional probes was placed 1.22 m (4 ft) upwind of the fence post closest to the wind machine (or, for a mulch-only experiment, where that post would be). This location was selected to capture the wind field close to the fence/mulch that is the focus of the experiment without influencing the upwind measurement. Bidirectional pressure probes measure the difference between the total pressure on the windward side of the probe and the static pressure on the leeward side. The difference is the dynamic pressure caused by the wind, which can be combined with temperature and a probe factor to calculate the wind speed [37]. The leads of the probes were connected to Setra Model 264 bidirectional pressure transducers, which have a pressure range of ±373.6 Pa. Each transducer produced a voltage output from 0 V to 5 V, with 2.5 V output indicating zero pressure differential. Combining the pressure measurement with ambient temperature gave a corresponding velocity range of about ±23 m/s (±52 mi/h). The transducer calibrations were checked periodically with a pressure calibration system, and their sensitivities were found not to drift significantly. Voltage outputs measured during daily pneumatic zeroing (which will be described in Section 2.9.2) were used to account for any voltage offsets.

A photograph of the bidirectional probe array in front of a fence/mulch test combination is shown in Fig. 16, and the diagram in Fig. 17 indicates the locations of probes. The array consisted of five probes arranged vertically on the centerline of the experiment at heights of 0.30 m (1 ft), 0.76 m (2.5 ft), 1.22 m (4 ft), 1.68 m (5.5 ft) and 2.13 m (7 ft) measured from the ground; two sets of two probes each extending out from the centerline in 0.61 m (2 ft) intervals at both the lowest (0.30 m) and highest (2.13 m) positions; and an additional four probes extending out from the centerline in 0.30 m (1 ft) intervals at the middle (1.22 m) position. This allowed for collecting velocity data for a vertical velocity profile at the centerline and a horizontal velocity profile at the center height, and added several additional, more sparsely located, velocity measurements to provide a more complete picture of the velocity field generated by the wind machine.

Fig. 16. Bidirectional probe array.

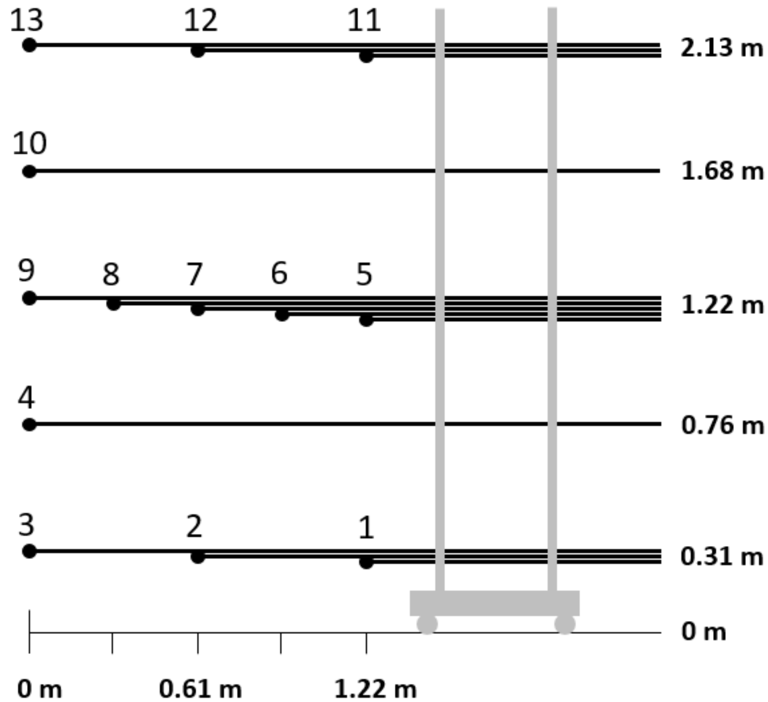

Fig. 17. Diagram of the bidirectional probe array used to measure the velocity field.

Ambient temperature was required along with the differential probe pressures to calculate the wind speed. Temperature was measured with a type K thermocouple bead made from 24 AWG wire (0.51 mm diameter). The temperature measurement location was about 2.5 m away from the probe array and shielded from thermal radiation from either the fire or sun.

The effect of wind angle had been studied in previous research on the fire behavior of fences [23]. Since an angle of 0° (parallel or in line with the wind) was previously found to produce the fastest fire spread, it was selected for the vast majority of experiments in order to provide worst-case fire hazard conditions. Two experiments performed with the wind at a 45° angle to the fences confirmed that the fire spread was slower compared to wind aligned with the fences.

The wind profile measured by the bidirectional probe array depends primarily on the wind speed and the distance from the wind machine, with a contribution from the component of ambient winds in the direction measured by the probes. Because the probe array is 1.22 m (4 ft) upwind from the fence and at least 3.84 m (12 ft 7 in) upwind from the shed, the effects of these objects on the measured wind field are minimal.

Appendix C.2 shows velocity profiles measured during experiments at four distances from the wind machine. The experiments in this study were divided into twelve sets corresponding to the three wind speeds and four probe array positions, and velocity measurements from each probe were averaged for each set. The resulting pseudocolor plots show that the velocity profile is reasonably uniform over the central region of the wind field in the region occupied by the fence. At ground level, the mulch bed sees a gradient in velocity from the centerline to the edge of the mulch pan. The center velocity is somewhat lower than the assigned wind speed and increases with distance along the mulch bed toward the shed due to the angled flow straightener.

For a given experiment, the average of the velocities of the lower four probes along the centerline was used to state the average wind velocity. This measure was selected after studying the velocity profiles along the centerline shown in Fig. C.6.

2.7.2. Ambient Wind Speed and Direction

The ambient wind speed and direction were measured by an anemometer mounted on a 3.7 m (12 ft) pole about 7.9 m (26 ft) south-southeast of the wind machine propellers and 17.7 m (58 ft) south-southwest of the target shed. The instrument was a Young model 86000 Ultrasonic Anemometer with 5 V output and 0.25 s response time for both wind speed and wind direction. Wind speed was measured with 0.01 m/s resolution and ± 2 % ± 0.1 m/s accuracy as stated by the manufacturer, and the wind direction was measured with 0.1° resolution and ± 2° accuracy. Wind direction accuracy was degraded to about ± 5° due to the estimation of true north during installation and slight positional drift due to high winds which was periodically corrected. The ambient wind measurement provided an approximate wind environment near but not exactly at the location of the experiments, so some focused wind gusts may have been located at the experiment and not the anemometer or vice versa.

2.8. Data Acquisition

2.8.1. Wind and Temperature Data

A data acquisition system was required to measure 16 channels of measurements from the bidirectional probe array located in front of the fence or mulch bed, an ambient temperature thermocouple, and the local wind speed and direction from the sonic anemometer. Voltage and thermocouple data from the sensors were collected using two National Instruments input modules, NI-9205 and NI-9213, respectively inserted in a National Instruments cDAQ-9174 CompactDAQ USB 4-slot chassis. The data were collected at 10 Hz and averaged over every second for each channel. The program saved the averages and standard deviations of the samples from each channel to the output file, which was stored on a laptop computer and later uploaded to a permanent data storage repository. The Labview program used to collect the data was also used to monitor data quality and spot check for sensor malfunctions.

2.8.2. Digital Video and Photographic Records

A minimum of four high-definition video cameras, Sony model HDR CX-350, were placed around the fence to capture the fire and smoke behavior. Two cameras located on opposite sides of the fence included the fence, shed wall, and shed mulch pan in their fields of view. These cameras captured fire spread and spot fire ignition data. An additional two cameras were located upwind of the fence next to the wind machine flow straightener, including the fence, shed, and shed mulch pans in their views. For experiments with parallel fences, a fifth camera was usually placed under the flow straightener on the centerline of the experiment to record the fire behavior between the two fences. Fig. 18 is a top view schematic of the experimental setup showing the relative positions of the video cameras.

To track experiment time, a DC-Digital timer, model DC-25UT, was placed in view of two or three of the video cameras (depending on line-of-sight blockage due to varying fence position). The timer, visible in Fig. 10 and Fig. 16, was started simultaneously with the wind machine. This allowed the video records of the left view and one or two of the front views of the test setup to also record the timer and thus synchronize with the remaining video camera(s), the two stopwatches used, and the wind data, which was referenced to computer time.

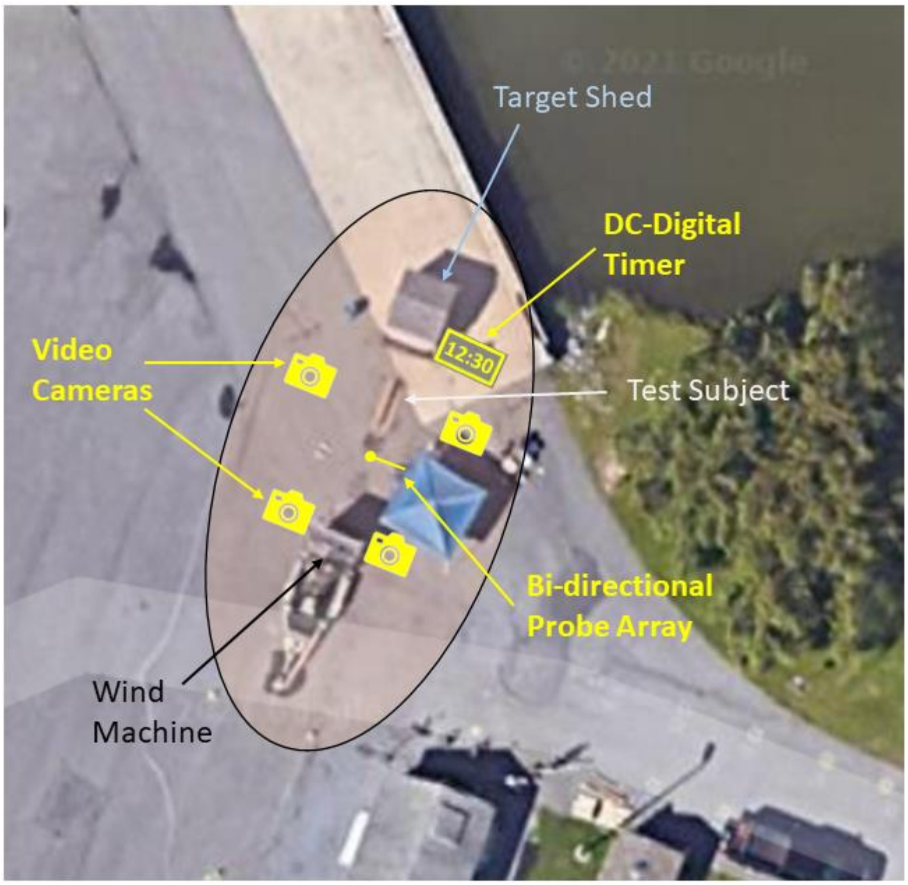

Fig. 18. Top view schematic of experimental setup showing placements of video cameras, timer, and bi-directional probe array. Google Earth image with NIST overlay.

Digital still photographs were taken throughout the testing period and afterward. The digital still camera used was Sony model SLT-A58. Periodically, the handheld camera was used to capture close-up video of interesting phenomena.

2.9. Experimental Procedures

2.9.1. Weather Conditions

The ambient wind speed was required to be less than 33 % of the nominal applied wind speed in order to carry out the experiment. If the ambient wind direction was forecast to be close to perpendicular to the direction of the generated wind, then ambient winds needed to be less than 25 % of the generated wind. Under these conditions, the impact of the ambient winds on the wind field generated by the fan was minimal. Winds from the North and Northwest were also avoided as they caused smoke and firebrands to overspread the experiment control area.

Testing was usually not scheduled when rain chances were likely during a substantial part of the morning or afternoon. Excessively hot or cold weather conditions also precluded testing. Generally, experiments were not scheduled if the heat index was expected to rise over 32 °C (90 °F) for a large part of the day, in order to avoid heat exhaustion. If temperatures were not expected to surpass 10 °C (50 °F), experiments were precluded by difficulties with handling tools, vaporizing propane, and drying the wet ground after fire extinguishment.

2.9.2. Preparation

Preparation for a typical experiment began with clearing the test area of debris. The mulch pans were connected and located at the prescribed distance from the shed and centered along the shed/wind machine centerline axis. Heavy steel bars were placed in the assembled pan at the leading edge and in the overlap region to weigh it down. If a fence was to be erected, holes were bored into one end of each post and the posts were placed on the post support legs close to their final location. The fence was then positioned for attachment to the posts. Shims were used to raise the fence if a mulch layer was to be laid beneath. The fence and posts were predrilled and then screwed together at each horizontal stringer. After the fence was secured to the posts, the shims were removed, and a mulch layer was laid evenly and compressed by foot throughout the pan. The posts were set perpendicular to the ground and secured with wire to two water-containing barrels located off to the side and also to the shed or shed eaves if located at 0 m or 0.30 m (1 ft) separation distance. After the fence was secured, the support wires were marked for safety with strips of tape or other material to prevent personnel from running into them. Mulch was then laid, spread evenly, and compressed in the target mulch pan at the base of the shed, if prescribed by the test plan.

Preparations for instrumentation included positioning of the four or five video cameras with framing of the appropriate views. The bidirectional probe array was positioned in front of the leading fence post. For fence experiments, a burner was connected to the propane gas cylinder and was positioned on both sides of the fence, with its leading torch head located 2.5 cm (1 in) beyond the trailing side of the leading fence post. Half of the torches on the burner were aimed upward to the face of the fence and the rest aimed downward toward the mulch (if mulch was present). If no fence was being tested, a layout table was checked to find out where on the mulch bed the burner should be positioned relative to the shed, as if a fence were there. The propane cylinder was opened and the burner line charged to check the burner for leaks, and then the gas was shut off with a valve. Before the first test on a given day, pneumatic zeroing of the pressure transducers was performed by connecting a short length of rubber tubing to each side of the bidirectional probes and recording the data. This also enabled observation of the pressure transducer voltages being read by the data acquisition system for troubleshooting problems. Voltages that were drifting indicated a poor connection, and voltages offset significantly from 2.5 V indicated a plumbing leak.

After a safety check of the surrounding area, the wind machine was warmed up for approximately 5 min prior to each experiment. A garden hose was attached to a fire hose, which was in turn connected to a hydrant. The hydrant was opened to charge the line, and a diesel pump was started up to pressurize the hydrant with water from the nearby pond.

Finally, a safety briefing was conducted to communicate the test procedure, participant roles, and safety reminders. Zeroing tubes were removed from the probe array, and the test description and filename were detailed in the logbook.

2.9.3. Operations

The following procedure was typical, although some minor aspects varied for some tests. The data acquisition system was initiated with the selected filename and description. Between 15 s to 60 s of background data were obtained before two stopwatches were started simultaneously and the program time was recorded. At that time, all video cameras were put into recording mode. After 50 s of stopwatch time, a small propane torch was ignited, and at 55 s the propane cylinder was opened. At 1 min, the ignition torch was held near the burner torches until they were all ignited. The times for initiating and completing burner ignition were recorded. For most experiments, the burner was sustained for 90 s on the fence and/or mulch in order to produce a self-sustaining fire that would not self-extinguish or go out in the wind. Some conditions such as cold (which diminished the propane flow) called for longer burner duration up to 3 min. Photographs of the fence or mulch fire were usually taken shortly after ignition.

A countdown to generating wind was performed, and a digital timer located next to the shed pan and visible in two or three of the video camera views was initiated at the same time as the wind machine was started. The wind level was adjusted by setting the tachometer to 950 rpm (revolutions/min) for low wind [6 m/s (13 mi/h)], 1500 rpm for medium wind [10 m/s (22 mi/h)], and 2000 rpm for high wind [14 m/s (31 mi/h)]. The times for initiating the wind and completing its adjustment were recorded in the log. As soon as the wind started, the burner was removed to protect it from the fire, and the propane valve was closed.

In addition to the continuous videos recorded on fixed cameras, photographs were taken from many angles and fields of view during the experiment. The photos included the overall views encompassing the entire fence and shed, the linear extent of the fire along the fence/mulch, spot fires in the target mulch bed, and unusual or interesting phenomena. Some interesting phenomena were captured using the video mode of the handheld digital camera. The experiment ended when a spot 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 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/mulch bed in order to capture the fire spread rate over the entire fence. At the end of the test, the fires were extinguished with a water hose and post-fire photographs were obtained.

2.10. Parameter Summary

From April 2016 through September 2021, 187 field experiments were carried out on fences and mulch. The experiments in this study were performed on a variety of combinations of fence panels and mulch under various conditions of wind and separation distance from the target shed or mulch bed. The distribution of the parameters in these experiments is shown in Fig. 19 and summarized in this section.

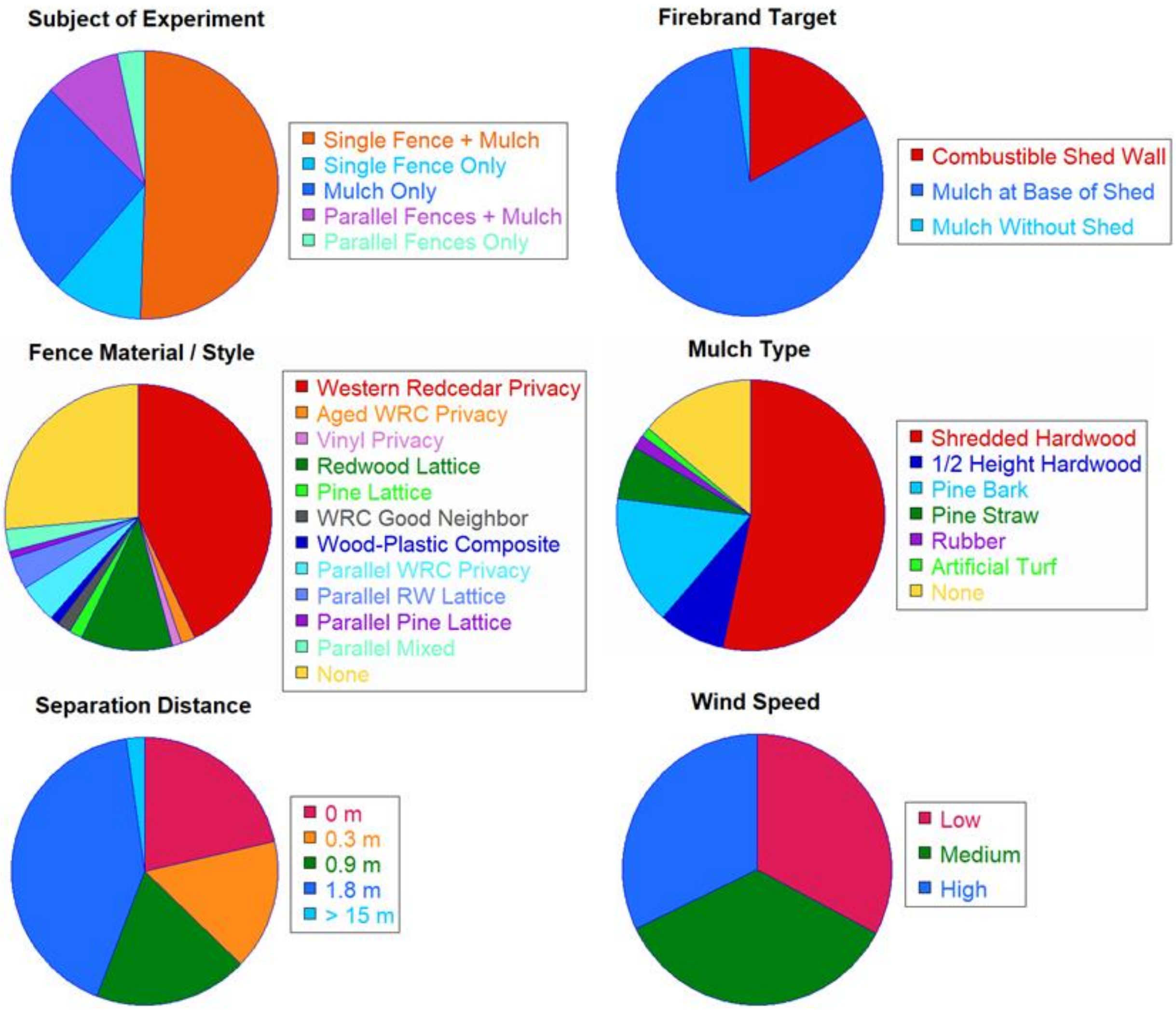

Fig. 19. Distribution of 187 experiments by subject of experiment, firebrand target, fence type, mulch type, separation distance from the wall, and wind speed.

2.10.1. Subject of Experiment

The experiments fell into four types based on the test subject: fence plus mulch, mulch alone, fence alone, and parallel fences (with and without mulch).

Approximately half of the experiments were performed on some combination of fence and mulch. This configuration was the main focus for this study, addressing the question whether fences could act as a wick to carry fire from one property to another within a community.

Combining the fence with mulch showed the effect of fine combustibles in contact with the base of the fence. Under the high wind conditions that may accompany a WUI fire, leaves or pine needles may collect next to the fence even when it is maintained free from combustible materials such as mulch and shrubbery. For most experiments the fence was erected as described in Section 2.5.5 at a height touching the surface of the mulch, which was arranged according to Section 2.4.1. A small number of experiments tested the effect of raising the fence panel above the mulch bed as a potential avenue for mitigation.

Mulch beds accounted for about a quarter of the experiments. The purpose of these experiments was to demonstrate the fire behavior of various types of mulch placed near a structure. Mulch beds were arranged as described in Section 2.4.1.

Experiments on fences in the absence of mulch addressed the question of how fences behave under perfectly clean conditions, with no contact with fine combustibles. These experiments acted as a control group to examine the effect of mulch on the fire behavior of fences. Under realistic fire conditions, it would be difficult to achieve a fence free of fine combustibles, since WUI fires are often accompanied by winds that blow loose materials such as leaves or pine needles into corners and crevices. The methods in Section 2.5.5 were used to erect these fences.

Parallel fences were separated from other fence categories after it became clear that their fire behavior was significantly more hazardous than that of other configurations. Combustible surfaces parallel to each other are subject to radiative and convective heat transfer mechanisms that produce rapid fire growth. Configurations that were considered in the experiments included double lattice fences, which may be used for a garden; parallel wood privacy fences, which may be erected by neighbors on either side of a property line; and wood privacy fences parallel to surfaces that represent a combustible or noncombustible shed wall. The preparation of parallel fences for these experiments is explained in Section 2.5.6.

Because of similarities in fire and firebrand behavior, the results for this report are organized by these four types of experimental subjects, as are the appendices that present the details of each experiment. The full set of experimental matrices is provided in Appendix D.

2.10.2. Firebrand Target

The experiments involved three configurations with respect to the target for flame spread and firebrands. A shed was arranged at right angles to the fan at a distance of 10.7 m (35 ft) for Series 1 and 2 experiments, as described in Section 2.3 and illustrated in Fig. 4. A small handful of experiments (Series 3) were performed without a shed in order to study the ignition of mulch by firebrands at a distance.

In Series 1 experiments, a sacrificial layer of southern yellow pine plywood panel siding with a thickness of 1.5 cm (0.59 in) was attached to the shed wall, as discussed in Section 2.3, extending to the ground with a crevice less than 2 mm. For these experiments, ignitions at the base of the wall were taken as a measure of vulnerability to firebrands. With a smooth surface at the base of the shed, the flow field at the base of the wall directed the firebrands toward the right or left of the shed, and few firebrands lodged in the small space between the plywood wall and the concrete.

About 80 % of the experiments were Series 2, with a narrow mulch bed positioned along the base of the shed and a noncombustible false wall to protect the shed. The mulch bed was used here as a surrogate for building ignition vulnerability or hazard. This configuration represented a worst case condition of fine combustible material in contact with the structure. The firebrands that landed in the target mulch bed tended to stay in the place they landed. If conditions were favorable, the firebrands ignited fires that then worked their way back toward the shed, at which time they were extinguished with water. This event usually marked the end of the experiment, unless the fire over the test subject had not yet reached the end closest to the shed or was spreading very slowly.

For Series 3 experiments the structure was removed, and the target mulch bed was placed 23 m to 47 m (75 ft to 153 ft) from the end of the fence and/or mulch that was ignited. The purpose of these experiments was to test the ability of firebrands generated by the mulch to ignite a fuel bed at a long distance from the source. These experiments are discussed in Section 4.5.

2.10.3. Fence Material, Style, and Configuration

As described in Section 2.5, privacy, lattice, and good neighbor fence styles were tested in this study. The boards for the privacy fences were made of western redcedar, vinyl, or wood-plastic composite, and the lattice fences were constructed of redwood or pine. Western redcedar boards were used to assemble the good neighbor fences. Aged western redcedar fences that were believed to have spent at least ten years outside in Colorado were also tested to see whether the fire behavior is significantly worse after long exposure to the elements.

Over half of the experiments with fences were performed with western redcedar privacy fences. These fences were studied at all values of wind speed and separation distance and provided a basis for comparing the fire behavior of different fences and mulches.

In two experiments, the length of the fences was doubled by arranging two panels end-to-end with a post between the panels and at each end. The purpose of these experiments was to determine whether the fire behavior had reached a steady-state flame condition in a single panel length.

Five experiments were performed with the wood privacy fence panel raised above a bed of shredded hardwood mulch. Vertical separation of the fence from the mulch was considered a possible mitigation technique.

2.10.4. Mulch Type

The mulches used in this study include shredded hardwood mulch, mini pine bark nuggets, pine straw, and synthetic (shredded rubber) mulch. In addition, two experiments were carried out on artificial turf. The majority of experiments were performed using shredded hardwood mulch, which also served as a common base for the comparison of different fence types and configurations. Details on each mulch type and its preparation for testing are presented in Section 2.4, with photos in Fig. 8. The standard mulch thickness was 5.0 cm, which was compressed by foot. The effects of a thinner mulch layer were investigated with a set of experiments on shredded hardwood mulch at half thickness, or 2.5 cm.

2.10.5. Separation Distance from Structure

When the shed was present, experiments were performed at distances between the shed wall and the nearest end of the fence or mulch bed ranging from 0 m to 1.83 m (0 ft to 6 ft). The four separation distances used in this study were 0 m, 0.30 m (1 ft), 0.91 m (3 ft), and 1.83 m (6 ft). Figure 20 shows a diagram of the four separation distances (SD) for Series 1 experiments, with a combustible wall attached to the shed as a target. Figure 21 shows a diagram for Series 2 experiments, in which a bed of shredded hardwood mulch served as the target for spot fires.

Because parallel fence experiments tended to produce large flames, they were all performed at a separation distance of 1.83 m (6 ft).

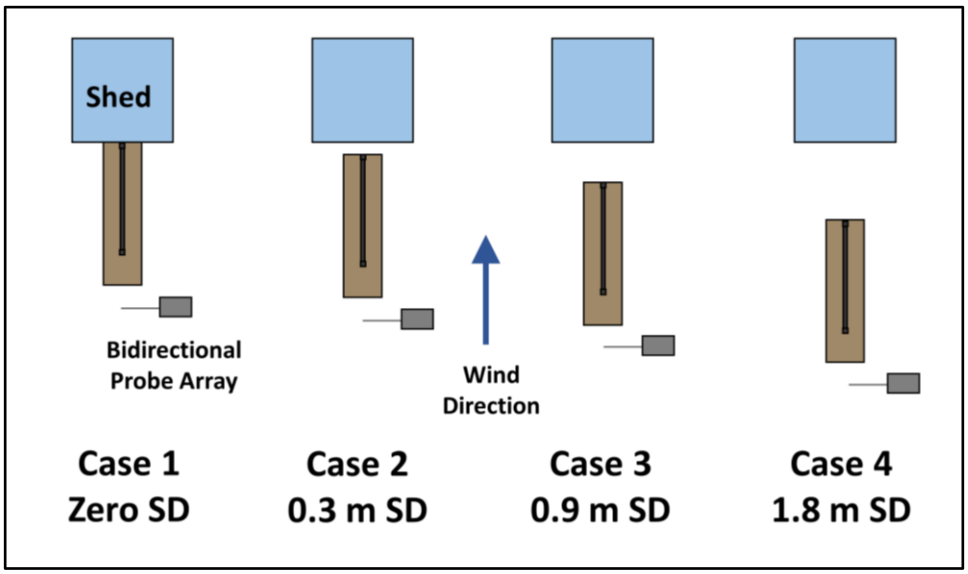

Fig. 20. Experimental configurations with combustible wall as target.

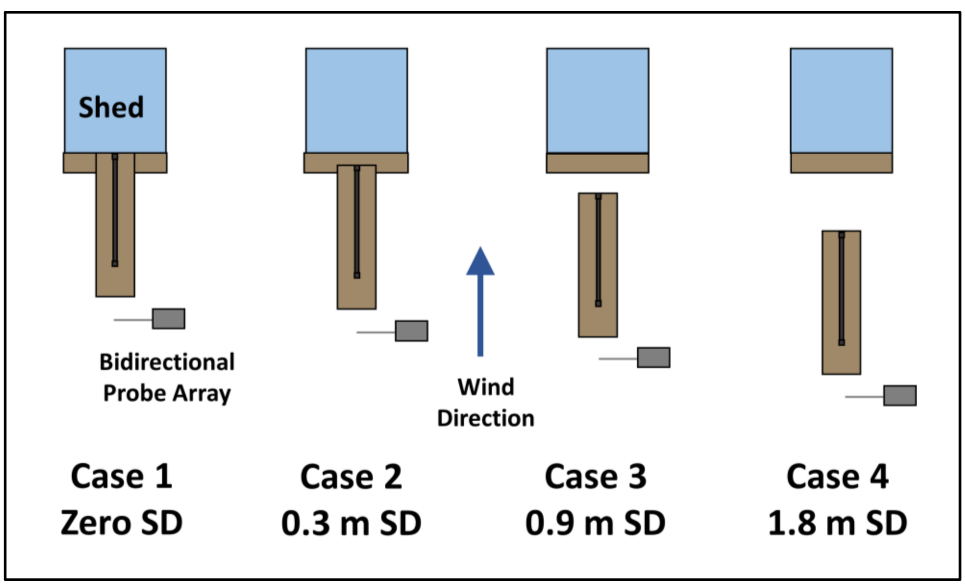

Fig. 21. Experimental configurations with shredded hardwood mulch bed at base of structure as target.

For Series 3 experiments, the shed was removed, and distances were measured from the end of the fence or mulch bed farthest from the fan to the leading edge of the target mulch bed. The long separation distances for these experiments were intended to test the distance over which firebrands were able to ignite spot fires in a mulch bed.

2.10.6. Wind Speed and Direction

Wind speeds through a community during a WUI event may range from nearly stagnant to prevailing wind speeds and possibly higher, depending on local shielding and channeling due to structures, vegetation, and terrain. The experiments in this study were performed under nominal imposed wind speed conditions from 6 m/s to 14 m/s (13 mi/h to 31 mi/h), generated by a large fan with tilted flow straightener as described in Section 2.2. Low, medium, and high wind speeds corresponded to average values along the centerline in the ranges 5 m/s to 9 m/s (11 mi/h to 20 mi/h), 10 m/s to 13 m/s (22 mi/h to 29 mi/h), and 14 m/s to 18 m/s (30 mi/h to 40 mi/h), respectively. The low wind speed category was selected to overlap with the conditions for experiments on fences performed by Manzello and colleagues in Japan [20].

Because a previous NIST fence study [23] concluded that the worst case fire behavior occurred with the wind flow in line with the fence, almost all experiments were performed in this configuration. The wind was at a 45° angle to the fence in two experiments. All experiments were performed with the shed perpendicular to the fence and/or mulch bed.

3. Analytical Tools

The data acquisition systems described in Section 2.8 provided raw data that needed to be analyzed and visualized to develop an understanding of the fire behavior in each experiment. This section describes the tools that were developed to analyze the video evidence and wind data collected from each experiment and the use of a computational fluid dynamics model to understand the flow field.

3.1. Video Analysis

The primary data to be collected from each experiment were flame spread and firebrand spotting. Every experiment employed four video cameras, with views from the left, right, left front, and right front of the object being tested, from the point of view of the fan (facing the shed). In some experiments, a fifth camera was used – to record a parallel fence experiment directly down the center between fences, for example, or to record a closeup of an interesting phenomenon. The videos recorded the progress of flames and charring and the ignition of spot fires, as well as events such as burner ignition, fan engine startup and shutdown, and the start of suppression. The frame rate was 29.97 frames/s.

Timing, flame spread, and spotting analyses were performed on videos from the left and right cameras. The MATLAB computing environment [38] was used to build tools for tracking the flame fronts over mulch beds and fences. The graphical user interfaces (GUIs) for selecting points on the video were developed using GUIDE in MATLAB to lay out the GUI components (such as push buttons, pop-up menus, and plots) and to set up the framework for event-driven programming. Several GUI applications were later migrated to MATLAB's App Designer interactive development environment.

3.1.1. Event Timing

All four video cameras monitoring the experiment were turned on shortly before the propane burner was applied to the test subject and turned off as the fire was being extinguished with water from a hose. Each camera view was fixed in place during the experiment after adjustment to capture the field of interest. To compare the views from multiple cameras, usually the right and left views, the timing was synchronized. The five events listed below were selected as the primary timing markers because they could be determined within a few video frames. Each event is illustrated in Fig. 22 under the matching letter.

a) *End of Gas Burner Ignition*
The End of Gas Burner Ignition event was the last moment that the small propane ignition torch was applied to the gas burner. The torch was often applied multiple times to each side of the burner, so this marker records the end of the final application. Although the fence sometimes blocked the view of the propane torch itself, the movement of the researcher's arm while removing the torch was usually apparent.

Fig. 22. Illustration of timing markers for Test A-29, showing a) end of ignition process, b) start to removal of propane burner, c) audio track for fan on, d) audio track for fan off, e) beginning of water application, and f) 5 s after the water is applied.

b) *Start to Remove Gas Igniters*
The Start to Remove Gas Igniters event was the moment when the gas igniters/burners began to be moved away from the point of ignition. This typically took place about 1 ½ minutes after the End of Gas Burner Ignition.

c) *Fan On*
The Fan On event marked the time at which the fan reached the initial maximum audio amplitude, as viewed in the audio track display. This point is indicated by the arrow in Fig. 22 (c). A precise frame number could be obtained by zooming in on the audio timeline and identifying the frame at which the audio signal stabilized to a periodic waveform. To the ear, this corresponded to the time at which the engine caught after turning over. Further adjustments of the fan rpm to reach the required set point (seen in the figure as variations in the amplitude to the right of the event arrow), which typically took between 15 s and 45 s, were not considered. Fan On marked the zero time for all analyses, and typically occurred 1 s to 5 s after the gas igniters were removed.

d) *Fan Off*
The Fan Off event was the moment at which there was a detectable decrease in the audio amplitude produced by the fan, as viewed in the audio track display. This point

near the end of the experiment is indicated by the arrow in Fig. 22 (d). A frame number could be determined by zooming in on the audio timeline and identifying the frame at which the audio track changed from a periodic waveform to a rougher signal. To the ear, this corresponded to a change in pitch as the fan was turned off.

e) *Water First Applied*
The Water First Applied event marked the first moment when water from the hose was observed to reach the burning object to extinguish the fire. In some videos the water could be seen leaving the hose and landing on the fence or mulch. In other cases, the application of water could be detected by the initiation of a cloud of steam mixed with smoke, as can be seen by comparing images (e) and (f) in Fig. 22. Early applications of water to contain spot fires near the target shed were not included in determination of the Water First Applied event.

In addition to the five events listed above, the initiation of the digital timer described in Section 2.9.3 was visible from the camera on the left side. The timer was started within a few seconds of the two events Start to Remove Gas Igniters and Fan On – all three events occurred in response to a countdown given by the team leader. In Fig. 22 (b), the person preparing to start the timer is visible near the orange traffic cone. The timer was useful for a small number of experiments in which one or more video recordings were interrupted in the middle of the test, resulting in two videos from those cameras. From the left camera, the timer could be used to determine the amount of time elapsed between the end of the first video and the beginning of the second. For interruptions of the right camera, the timings of Fan Off and Water First Applied events were calculated by comparison with event times from the left camera.

For Series 2 experiments, with a mulch bed target at the base of the shed, the timing of spot fires was measured. Three simple timing measures were recorded for each experiment: (1) the time at which the first spot fire ignited within the target mulch bed, (2) the time of ignition for the first spot fire to put flames against the wall, and (3) the time at which flames were first observed at the wall. Ignition was detected by the first visible sign of smoke. The right and/or left video recording was used to identify both the first spot fire ignited and the first spot fire resulting in flames on the wall. These two spot fires were then tracked back in time to determine the first time at which a puff of smoke from that location was distinguishable from the surroundings. The time when the first splash of orange was observed at the base of the wall or along its surface was recorded as the time of flames on the wall.

Uncertainties in the timing of these events are discussed in Appendix A.3.

Other times obtained from the videos included the times for flames or charring to reach both the halfway point on the fence and the end of the fence, which were used for preliminary flame spread rate comparisons. These were determined using the flame spread analysis discussed in Section 3.1.3 and Section 3.1.4.

Timing markers were obtained using VirtualDub [39, 40], VEGAS Pro [41], or AVS Video Converter [42] video processing software. Frame numbers or times of events were recorded in an Excel file. Some discrepancies in timing were observed among video handling tools, but markers obtained from these three software packages were found to be consistent within ±0.5 s. For the most accurate results, the same tool (VirtualDub) was recommended for both timing the videos and extracting images from them.

3.1.2. Conversion of Videos to Image Sequences

Videos from right and left cameras were used to determine flame spread as a function of time. The tools developed for this analysis required the videos to be converted into sequences of images. Each image needed to be as sharp as possible in order to estimate the location of the flame front in the mulch bed or on the surface of the fence. Other considerations included the digital size of the stored images and the length of time required to create them.

The software selected for this task was VirtualDub [39] equipped with Ut Video Codec Suite [43] to provide lossless compression and Smart Deinterlacer Filter [44] to eliminate interlacing artifacts. VirtualDub allowed the extraction of every 30 frames, resulting in a set of images spaced apart by 1.001001 s (corresponding to the video frame rate of 29.97 frames/s). This provided better image quality than other video handling tools that used averaging to create a sequence with one image per second. Ut Video Codec Suite, with fast lossless compression capabilities, was used to first convert the original digital video in .m2ts format to .avi format, using only one out of every 30 frames. For the final image sequence, every frame was then extracted from the .avi video. This procedure reduced the time required to extract images from the original video by more than an order of magnitude. Smart Deinterlacer Filter eliminated lines where there was frame-to-frame motion, such as in areas with flame or smoke, leaving the motionless parts at high resolution.

The initial conversion from .m2ts to .avi took approximately 1/5 the time of the original video duration, and the extraction of frames from the .avi video took approximately 1/3 of the time of the duration. In cases where videos from both left and right cameras were converted into image sequences, images from both sequences were compared to ensure that the timing matched.

3.1.3. Mulch Experiment Flame Front Tracking

After the sequence of images was extracted from a video recorded by camera to the right or left of the object being tested, the images were ready be analyzed to determine the position of the flame front as a function of time. A MATLAB GUI tool, mulch_test_analysis.m, was developed to track the char front for mulch experiments.

Figure 23 shows an example of the GUI for a mulch test. To begin the procedure, the user first clicked on Get Image File on the upper right of the interface. This prompted the user for a single image from the sequence for the experiment to be displayed and analyzed. Open Excel File allowed the user to either open a new file to contain the flame front data or to add to an existing file.

In order to measure the position of the flame front in a given image, a physical scale that took the perspective of the camera into account was required to define distances along the length and width of the mulch bed. The Set Perspective Lines button prompted the user for a series of points that defined the perspective lines on each end of the mulch bed, selected by placing the cursor on the screen and clicking the mouse. The user was asked to identify two points on the top of the mulch bed at the base of the shed – one close to the camera and one farther away – and two points on the top of the mulch bed at the opposite end from the shed. The user was also asked to identify points along the top edges of the mulch bed closest to and furthest from the camera. Finally, the user was asked for a point at a known physical distance

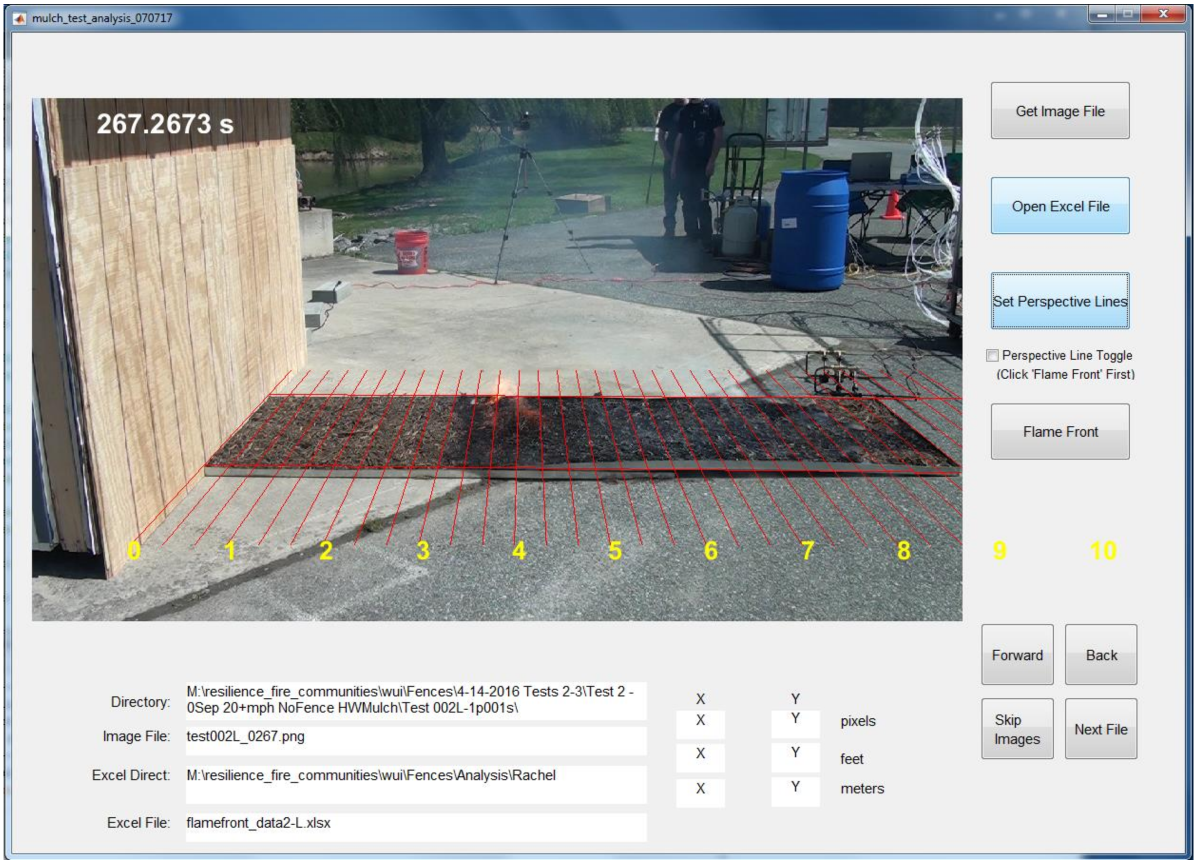

Fig. 23. Example of GUI with perspective lines for analyzing flame spread over a mulch bed with time.

from the shed wall. In the case shown in Fig. 23, the corner of the white square marking on the asphalt in the foreground was known to be 1.07 m (3.5 ft) from the shed wall. Other cases used the distance of the end of the mulch bed to the shed wall or other known lengths. The image in Fig. 23 shows the mulch bed delineated by the set of perspective lines, spaced at 10.2 cm (4 in) intervals, and the near and far edges of the mulch pan.

In later experiments, markings added to the pavement at 0.30 m (1 ft) intervals made it easier to determine both the physical scale and the angle of perspective lines along the length of the mulch bed. For camera views in which the upwind end of the mulch pan was not in the frame, as was the case for some of the experiments with 0.91 m (3 ft) and 1.83 m (6 ft) separation distances, the perspective line away from the structure was established using other information. On a sunny day, such as that shown in Fig. 23, the shadow cast by the bidirectional probe array could be used, assuming that the array had been positioned parallel to the shed wall. The location of the perspective line along the wall at mulch height was estimated in cases for which the mulch pan was separated from the wall.

Selecting the Flame Front button allowed the user to move among the video frames and use the mouse to click on the location of the flame front in each image. The frame time and the distances of the flame front from the shed wall and the centerline were automatically recorded in the Excel file for later plotting. Buttons on the lower right allowed the user to move forward and backward among the frames and to specify the number of frames to skip for experiments with slower flame spread.

The boundary between burned and unburned mulch was considered to be the location where the color of the mulch changed from brown to black. Flames attached to the mulch were observed in some video frames but were too sporadic to serve as an indicator of flame front location. The flame front was typically not a straight line. The leading edge of the flame front was therefore defined as the point of the continuous burn pattern closest to the structure. On occasion, burn spots appeared in the mulch bed downwind of the flame front due to firebrands. When a spot became connected to the main burned region, the location of the flame front jumped to the leading edge of the spot.

Uncertainties in the mulch flame front analysis are described in Appendix A.4.1.

3.1.4. Fence Experiment Flame Front Tracking

A second MATLAB GUI tool, fence_test_analysis.m, was developed to track the burned area of the fence as a function of time.

The procedure for defining the geometry for fence experiments was similar to that described in the previous section for the mulch tool, with flame front data collected over the surface of the fence rather than that of the mulch bed. Figure 24 shows the GUI for the fence flame front analysis. The Select Image button prompted the user for an image (preferably from early in the image sequence) that was displayed in the active window. The Open Excel File button allowed the user to either open a new file to contain the perspective line and flame front data or to overwrite an existing file. The Set Fence Perspective button prompted the user for information about the experiment, including four points defining a set of corners of the fence, the height and length between these markers, the time of the current image, and the time interval between images in the sequence. Each corner point was located using crosshairs and selected with the mouse button. As each point was selected, its 2-D location in the image was entered into a sheet of the Excel file, along with user-provided data defining the physical dimensions. The final fence outline was displayed as shown in Fig. 24.

After the fence was defined, the Get Points button allowed the user to define the flame front location at specific time intervals using the crosshairs and mouse button. The time interval could be changed using the Skip button. A suggested time interval for collecting 50 data points was provided by the Frame Skip Calculator function. Navigation Tools allowed the user to move forward and backward among the video frames.

Three points on the fence were expected for each image. The first point identified the location closest to the shed where the fence was charred, the second marked the height of the charred region in the ignition area, and the third marked the highest point of the char on the fence outside of the ignition region, defined as two boards or more downwind from the post farthest from the shed. The two definitions of char height enabled the separation of ignition effects, which included fire development before the fan was turned on, from the effects of flame spread downwind. After the three points were selected, the MATLAB code automatically moved to the next image in the sequence. The time and flame front locations were automatically recorded in the Excel file for later plotting.

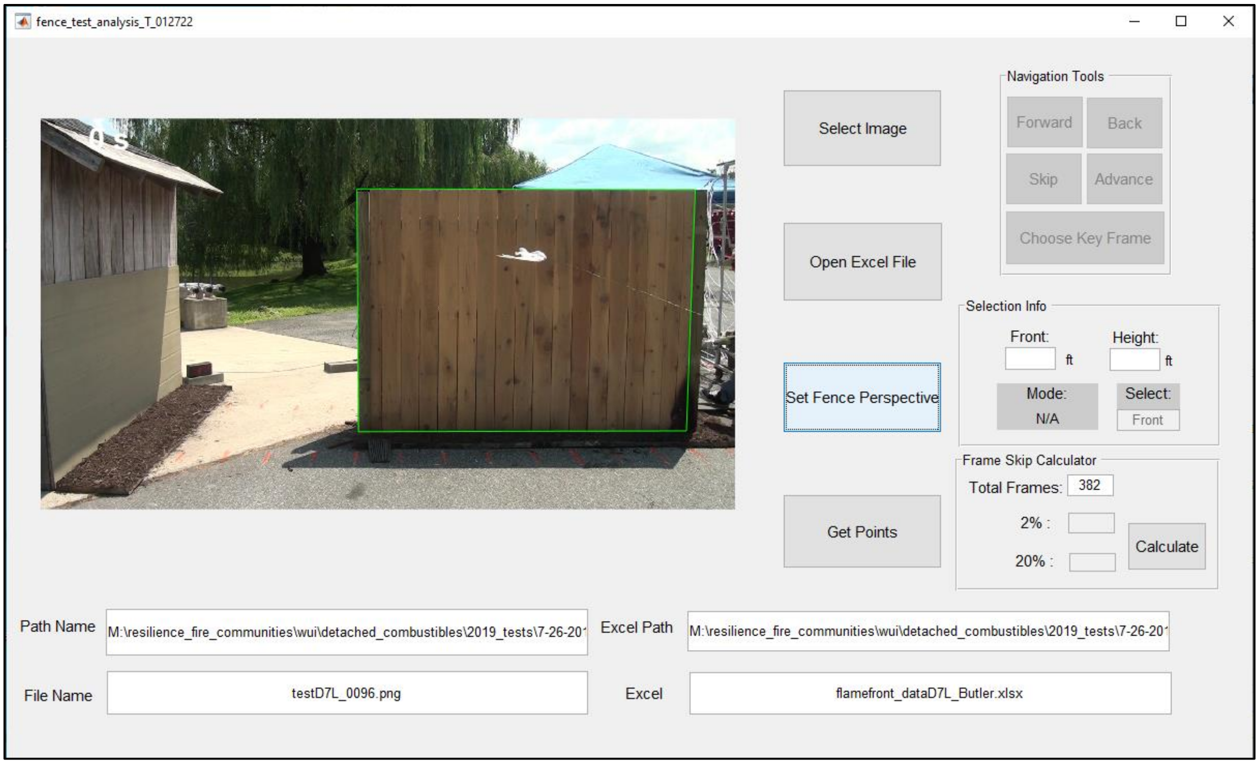

Fig. 24. GUI for selection of location points for fence video.

The MATLAB program also allowed the capture of two-dimensional char profiles on the fence. The Choose Key Frame button presented crosshairs to select points outlining the char region on the fence. Char profiles were typically captured at five times evenly distributed through the experiment.

Obscuration by flames and smoke, lighting, discontinuities in the char location where the boards met, and placement of the cursor all contributed to the uncertainty in the location of the char front on the fence. Uncertainties in the fence flame front analysis are described in greater detail in Appendix A.4.

3.2. Wind Analysis and Visualization

An interactive graphic user interface (GUI) program, windplots.mlapp, was written to convert the voltage files from the pressure transducers into wind velocities and display the results. This program was based on the MATLAB App Designer tool. As described in Section 2.7, the wind field just upwind of the fence or mulch bed was measured by an array of bidirectional probes, and ambient wind and temperature data were collected from a nearby sonic anemometer and a thermocouple. The process for zeroing the probes is explained in Section 2.9.2, while Section 2.8.1 describes the collection and initial processing of the wind and ambient weather data by using a Labview program to write the data to an Excel file.

Figure 25 and Fig. 26 show examples of the data visualization from windplots.mlapp. The first step in the wind analysis procedure was to obtain the zero voltage level for each probe, using the *Step 1: Zeros* button in the upper left corner. This prompted the selection of an Excel file containing measurements taken while the zeroing tubes were applied and before the fan was turned on. The data columns and plots populated by the data in one such file are shown in Fig. 25, with the following annotations:

A. Voltage data as a function of time. The time extended from the lower bound to the upper bound defined in the boxes below the plot, which could be changed to define a time range in which readings were stable. All data presented in the GUI plots and tables were from the specified time range. The voltage data typically lay between 2.4 V and 2.6 V. In the example shown, the data from one probe fluctuated significantly within this range, indicating that there may have been connection issues.

B. The probe array, with a number and radio button for each probe. Probes that were clearly faulty (i.e., with values well outside the expected range) could be turned off by clicking on the radio button.

C. Average value for each probe in the array. Black dots at the center of each color square indicate the location of the probe in the array by height and distance from the centerline. Probes that were faulty and had been turned off were assigned the color white.

D. Average values for the five probes along the centerline. Values were not plotted for faulty probes.

E. Average values for the five probes extending horizontally from the centerline to the outer edge of the array at a height of 1.22 m (4 ft) from the ground. Values were not plotted for faulty probes.

F. Table of probes, showing location, average value, and standard deviation of the data

G. Ambient temperature as a function of time.

H. Wind rose plot of wind speed and wind direction during the specified time range. Statistical calculations were performed with the CircStat MATLAB toolbox [45]. The green line indicates the orientation of the experiment, plotting the direction from the fan to the shed. The red line indicates the mean direction of the ambient wind.

I. Ambient wind speed measurements as a function of time.

J. Average values and standard deviations for temperature, wind speed, and wind direction.

Outliers could be filtered out by setting Max and Min values for the data set. Data for missing zero probe values could be downloaded from a previous analysis.

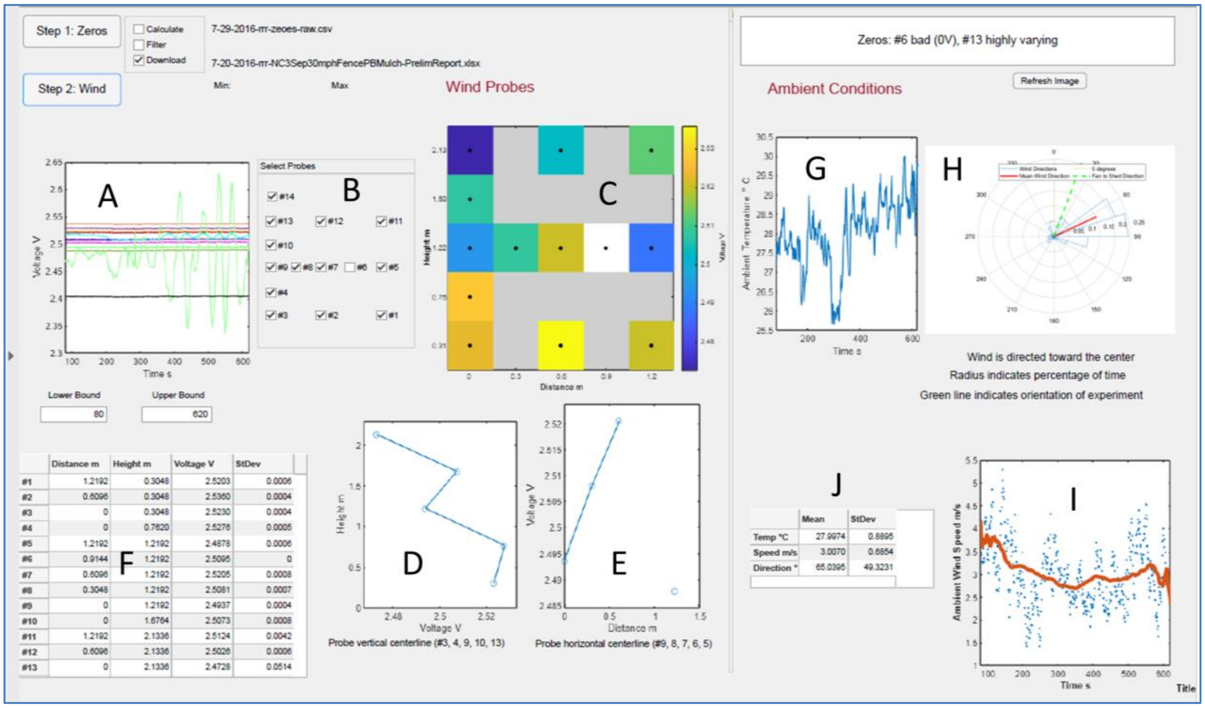

Fig. 25. Visualization of zeroing data for 29 July 2016, used for tests A-57 to A-60.

After the probe data from the zeroing analysis were available, the *Step 2: Wind* button was selected to determine the wind speeds during an experiment performed on the same day. Figure 26 shows an example of the data visualization of wind speed from Test A-57, which was carried out on the same day as the zero readings in Fig. 25. The plots and tables are the same, but the values from the probes are wind speeds rather than voltage. When the wind data from an experiment were read from the Excel file, the plot of wind speed as a function of time showed a step increase when the fan was turned on and a step decrease when it was turned off. The lower and upper bounds were then selected to encompass only the time range when the fan was on.

Finally, selecting *Step 3: Save* stored the statistical data in a separate Excel file and the plots in a dedicated subdirectory with the rest of the data for that experiment.

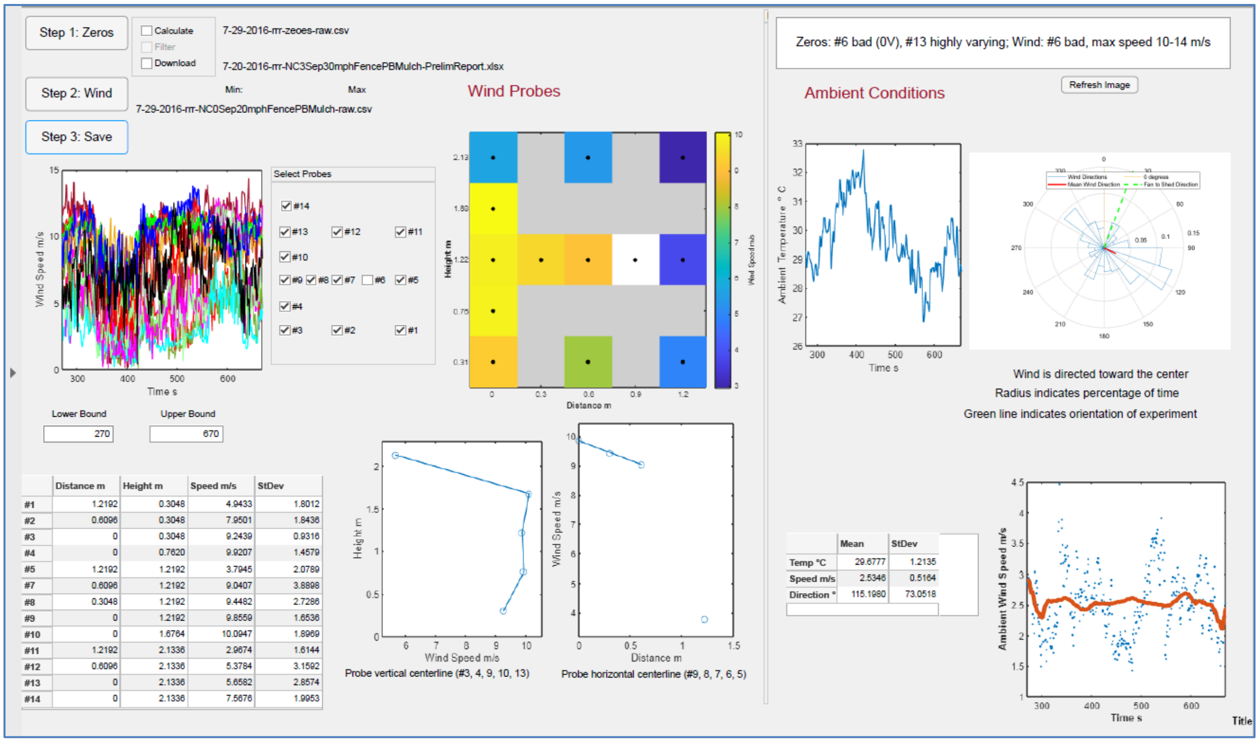

Fig. 26. Visualization of wind speed and ambient data for Test A-57.

3.3. Flow Simulations

Several observations, including the movement of mulch particles and firebrands and the slowing of flame spread velocity as the flame front approached the shed, suggested that the flow field could be playing an important role in these field experiments. To obtain insights into how the flow field might affect firebrand behavior and flame spread, the experimental setup was modelled using the NIST Fire Dynamic Simulator (FDS) [46]. FDS is a computational fluid dynamics software program that is typically used for calculating fire-driven fluid flow. Although the heat from a fire will modify the flow field due to buoyancy effects, these calculations considered only the wind flow in the absence of fire, sometimes referred to as “cold flow” calculations.

In addition to illustrating the basic flow field for the experimental setup, FDS simulations helped to establish the acceptable ambient wind speed limits for running experiments as given in Section 2.9.1. This was accomplished by adding a cross-flow wind to the model.

3.3.1. FDS Model of Mulch Experiments

As an initial exploration of the flow behavior in these field experiments, FDS was used for calculating fluid flow only (without fire) in an exterior computational space with open boundaries [29]. Subgrid mixing due to turbulence was represented by a Smagorinsky large eddy simulation (LES) model. Validation work [47] has shown that FDS is capable of good results when compared with experiments for similar problems, including building ventilation, wind impinging on the exterior of a structure, and transport of pollutants in an urban environment.

In the model of the mulch test, illustrated in Fig. 27, the fan and shed structure (in brown) were represented as obstacles. Since the intent of the model was to provide general insight rather than a quantitative comparison, the propeller-driven flow field and the geometries of the structure and the fan/flow straightener system were not represented in detail. The fan was simulated by a square block 1.8 m (6 ft) on a side and 0.5 m (1.6 ft) thick with a steady velocity boundary condition directed toward the structure at an angle of 7° to the horizontal. The distance of the fan from the structure was 10.7 m (35 ft) in agreement with the experimental setup. Boundary conditions at the exterior of the domain were open. Resolution in *x*, *y*, and *z* directions was 0.1 m (4 in).

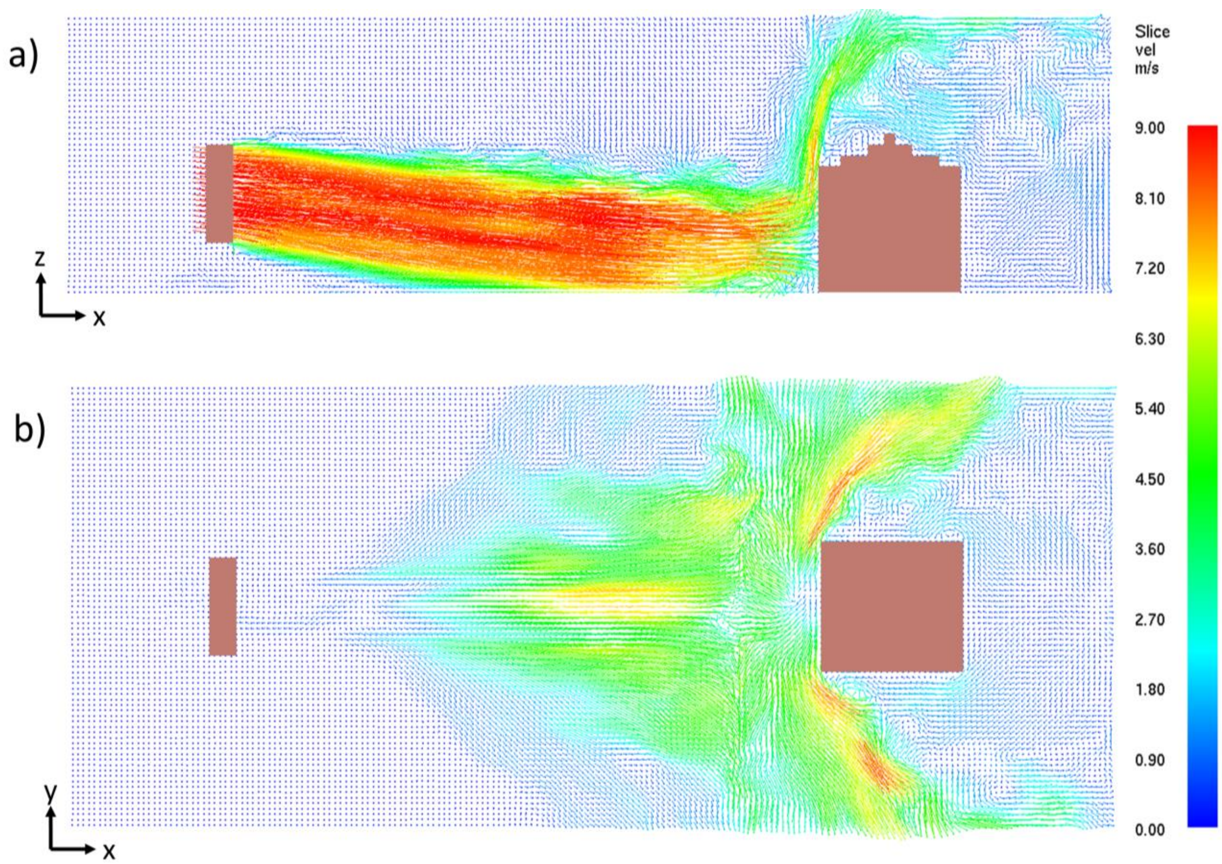

Fig. 27. FDS model results showing instantaneous velocity vectors, colored by wind speed. Side view (a) shows velocities along the center plane, and top view (b) shows velocities in a plane 0.1 m (4 in) above the ground.

3.3.2. Flow Field, including Vortex at Base of Shed

Instantaneous velocity vectors in Fig. 27 illustrate some of the features of the wind flow, which was highly turbulent. Figure 27 (a) and (b) show instantaneous velocity vectors along the center plane of the experimental geometry (side view) and in a plane 0.1 m (4 in) above the ground (top view), respectively. The vectors are colored by wind speed, with red corresponding to the wind speed of 9 m/s (20 mi/h) applied by the fan, as indicated in the color scale.

The velocity flow field shows that a vortex formed near the ground in front of the structure and wrapped around the sides, consistent with the horseshoe vortex observed for a surface-mounted cube at right angles to a flow stream that is described in the scientific literature [48]. The behavior of the wind near the ground is of particular interest for the mulch experiments. The side view in Fig. 27 (a) shows the vortex near the ground in front of the structure. From the top view in Fig. 27 (b), the wind velocity slightly above the ground was directed toward the structure at distances between one and two structure heights (about 2 m to 7 m) from the structure. Within one structure height distance (about 2 m) from the structure, the wind velocity was lower and directed away from the structure and toward the fan.

Figure 28 shows time averages for the component of velocity in the direction toward or away from the shed, v_x. Between the fan and the structure, the wind was directed toward the shed (positive values of v_x, red) except for a region close to the ground just in front of the structure, where v_x was strongly negative (blue). This marks the counterflow region of the vortex. The vortex extended toward the fan a distance of 1.7 m (5.6 ft), approximately 0.7 times the dimensions of the shed, which is roughly consistent with the literature on flow around surface-mounted cubes at high Reynolds number [49, 50].

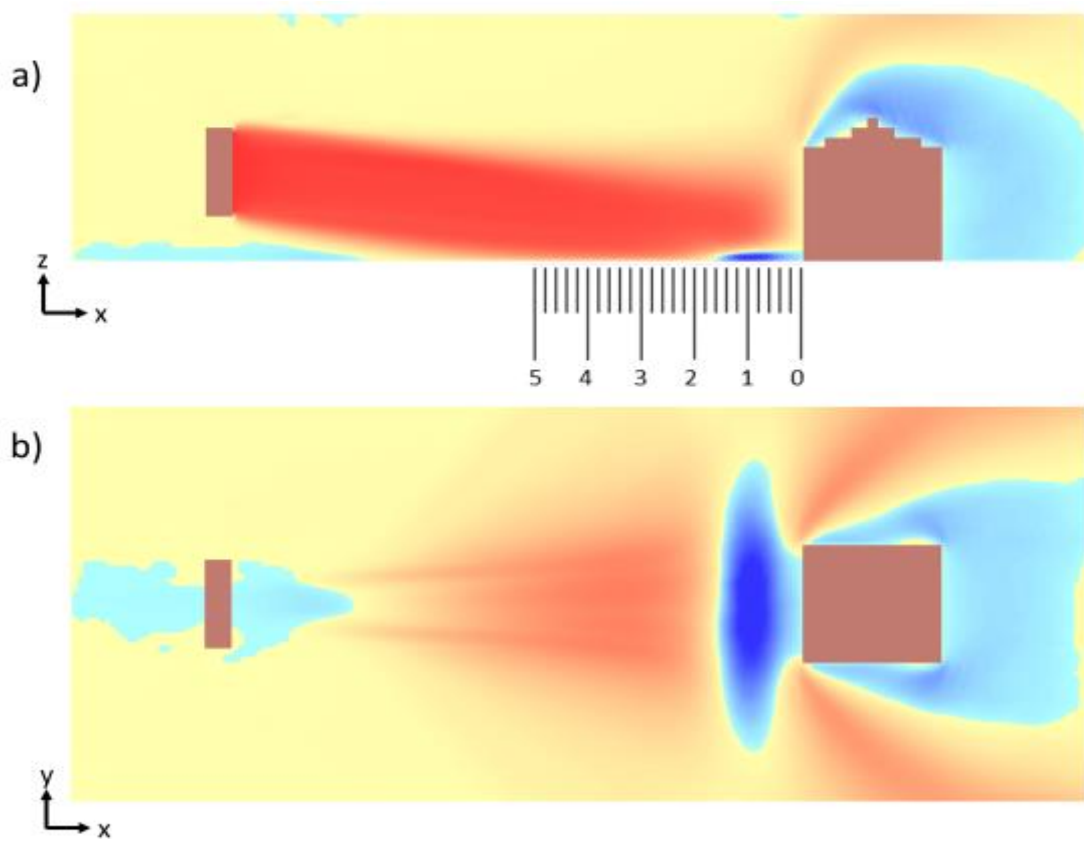

Fig. 28. FDS model results showing time-averaged contours of wind speeds in the *x*-direction. Side view (a) shows contours along the center plane, and top view (b) shows contours in a plane 0.1 m (4 in) above the ground.

Simulations at imposed wind speeds from 6 m/s (13 mi/h) to 14 m/s (31 mi/h) indicated that the vortex size was relatively independent of wind speed in this range. Vortex intensity and concurrent and opposed flow velocities were strongly affected by wind speed.

FDS simulations were also performed for fence experiments. The geometry was the same with the addition of a thin obstacle representing a single fence panel at a separation distance of either 0 m or 0.9 m (3 ft) from the structure. The results were qualitatively the same as for the mulch simulations, with a vortex forming in front of the structure in all cases.

3.3.3. Wind Effects on Firebrands and Fire Spread

The flow field strongly influences the behavior of firebrands generated in the mulch bed.

When the fan was on during the experiments, larger pieces of mulch from the target bed could be observed rolling on the pavement away from the shed wall or towards the sides of the shed. The vortex motion could also be observed from the directionality of the smoke and flames. For the spot fires in the target mulch bed at the base of the shed, the smoke and flames generally extended away from the shed, while for the burning object (fence and/or mulch bed) the smoke and flames extended toward the shed.

Firebrands produced near the ground experience the opposing flow from the vortex, which acts to keep them away from the structure and directs them into the high velocity flow around the left or right side of the structure shown in Fig. 27 (b). These firebrands may ignite combustible materials at a distance from the structure. In these field experiments, spot fires were occasionally observed to ignite at the outer edge of the target mulch bed.

Firebrands that are either produced at or lofted to an intermediate height of 0.1 m (4 in) to 1 m (3.3 ft) may be caught in the vortex flow and deposited close to the wall of the structure, where they can ignite combustible wall material or mulch adjacent to the wall. Firebrands that approach the structure at a height greater than a meter may enter an updraft that transports them over the top of the structure; open vents could allow these firebrands to enter the structure.

The flow field also affects the flame spread over the fence or mulch bed. Depending on how far away from the shed the mulch bed is ignited, the flames spreading toward the structure may initially experience concurrent flow, with wind velocity in the same direction as the flame spread. As the flame front enters the vortex region, however, the flame spread changes to opposed flow mode and may slow considerably. If a firebrand ignites a spot fire in the mulch within the vortex region, the flame spread from the point of ignition back to the main flame front is concurrent with the vortex flow field and is thus rapid. An example of this behavior will be shown in Section 4.1.2.3.

4. Experimental Results

The set of 187 experiments described in this report represents a survey of the effects of certain fences and mulch on the spread of fire to a structure, given various wind conditions and separation distances. Both direct flame spread and spot fires ignited by firebrands were studied. A variety of fences and mulches were tested under a range of conditions; the parameters were described in Section 2.10. Because of the large number of combinations and limitations on performing the experiments, only a few of the experiments were replicated. The comparison of quantitative data was made more difficult by the fact that many phenomena involved in firebrand spotting, such as generation of firebrands and ignition processes, are stochastic in nature. The analysis of the data from this set of experiments was therefore focused on uncovering trends and on discovering different modes of behavior, rather than on quantitative results.

Appendix D shows the experimental matrix, divided into categories of Fence Only (without mulch below the fence), Mulch Only (without a fence), Fence Plus Mulch, and Parallel Fences. The number of each experiment corresponds to cases whose details are presented in Appendix F through Appendix I. Appendix E explains the contents of each case writeup, which include a description of the experiment, photographs from before and during the experiment, flame spread plots, critical times, and ambient and applied winds.

4.1. Mulch Only Experiments

This section reports on the fire behavior observed in mulch bed experiments. A variety of mulch types were studied, including shredded hardwood mulch, pine bark mulch, pine straw mulch, and rubber mulch. The experiments were performed at nominal imposed wind speed conditions from 6 m/s to 14 m/s (13 mi/h to 31 mi/h), categorized as low, medium, and high as described in Section 2.10.6. Separation distances from the nearby structure were between 0 m and 1.83 m (6 ft), as shown in Section 2.10.5.

The test matrix for Mulch Only experiments is shown in Table D.1 in Appendix D. The details of each experiment, including parameter values, images, flame spread data, wind plots, and summary values, can be found in Appendix F. In each case, timing was measured from the point after ignition when the fan was turned on.

4.1.1. Example

Some aspects of fire behavior over a combustible mulch bed are demonstrated in Fig. 29. In this experiment (Test A-83), a fire was ignited in a bed of shredded hardwood mulch separated from the structure wall by 0.91 m (3 ft). A target mulch bed was placed along the base of the structure to catch firebrands generated by the burning mulch bed. At t = 0 min, the fan was turned on to generate a wind field in the medium range with an average wind speed along the centerline of 9.3 m/s (20.8 mi/h), and the gas burners were removed. White lines mark off distance from the wall at 0.30 m (1 ft) intervals.

The first three frames in the sequence in Fig. 29 show that the fire progressed at a steady rate, with the mulch darkening as it charred and with orange flames appearing sporadically. As the mulch burned, ash accumulated and changed the surface color to gray. After 4 min, the flame front slowed as it encountered the vortex at the base of the shed described in Section 3.3.2. A firebrand from the burning mulch ignited a fire in the middle of the target mulch bed shortly before t = 10 min, as indicated by the smoke rising from this site. The smoke at this location was observed to blow away from the wall, showing the direction of the wind (and the presence of the vortex). By t = 12 min, the spot fire had increased in size, reaching both the wall of the structure and the front edge of the target mulch bed.

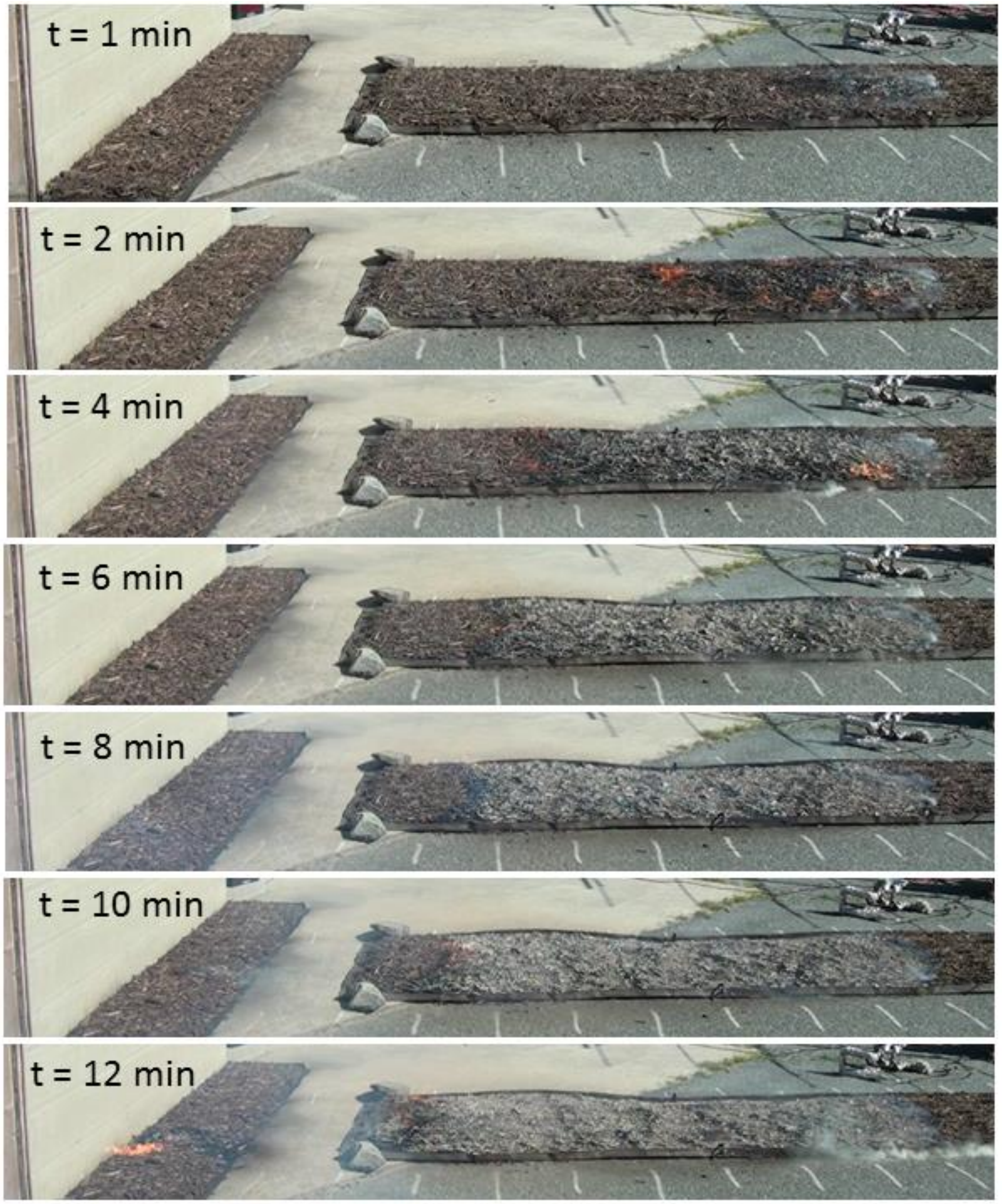

Fig. 29. Time sequence of shredded hardwood mulch bed at medium wind speed separated from shed wall by 0.91 m (3 ft) [Test A-83].

The flame spread plot in Fig. 30 shows the flame front location as a function of time (green line) for this case. In order to keep track of the location of the flame front within the mulch bed, the plot includes black horizontal lines to mark the distance of each end of the mulch bed from the shed wall. The line at 0.91 m (3 ft) represents the closest proximity of the mulch bed to the wall, and the line at 4.27 m (14 ft) marks the approximate location of the far end. The initial location of the flame front (at time t = 0 min when the fan was turned on) was 3.35 m (11 ft) from the shed wall, or 2.44 m (8 ft) from the end of the mulch bed closest to the shed wall.

The green line showing flame front location with time illustrates the decrease in the rate of spread as the flame in this experiment approached the shed wall. During the first three minutes of the experiment, the flame front progressed from 3.35 m (11 ft) to 1.83 m (6 ft) from the shed wall, for a flame spread rate of 0.54 m/min. In the time period from 5 min to 10 min, the flame front progressed from 1.44 m (4.7 ft) to 1.23 m (4.0 ft), with a flame spread rate of 0.044 m/min. The distance from the wall at which flame spread started to slow significantly is consistent with the extent of the vortex described in Section 3.3.2.

The black error bars in Fig. 30 show the expanded uncertainty for each of these points, based on the uncertainty analysis for mulch in Appendix A.4.1 and the uncertainties from Table A.5. For Test A-83, the separation distance was greater than zero and markers on the ground helped to set the distance scale, so the expanded uncertainty (95 % confidence level) was ±6.9 cm.

The main flame front united with a spot fire at about 10.5 min into the experiment, resulting in a sudden jump to the end of the mulch bed.

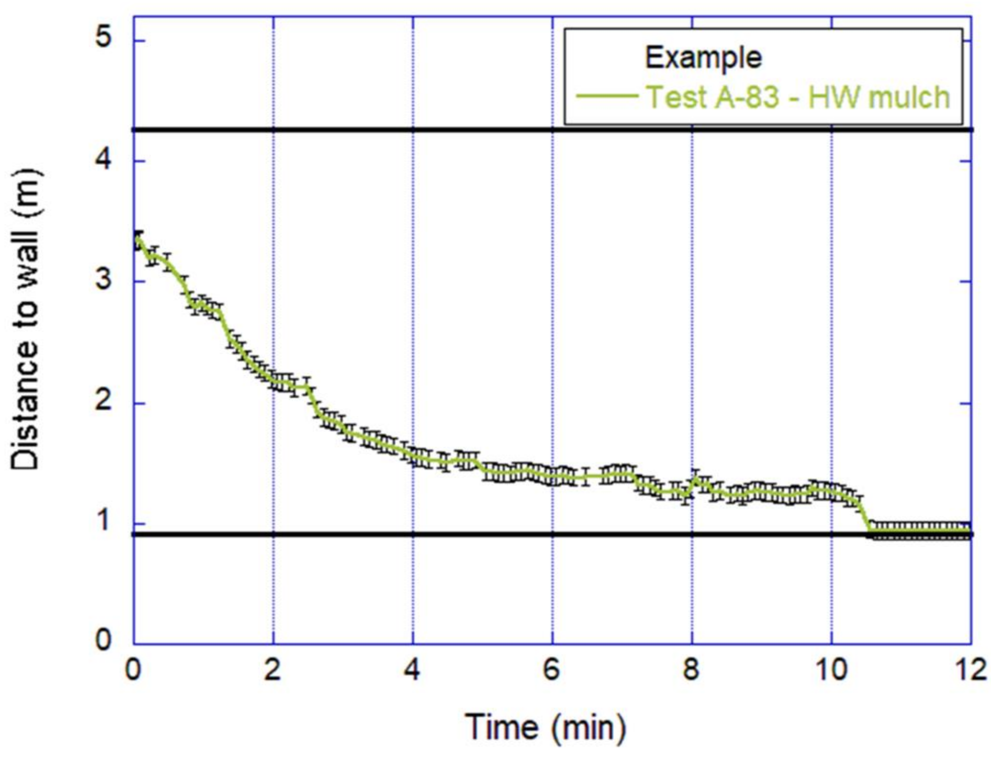

Fig. 30. Flame front location vs. time for Test A-83, with HW mulch at medium wind speed and 0.91 m (3 ft) separation distance from structure, showing expanded uncertainty.

4.1.2. Fire Spread Behavior

This section describes observed effects of spot fires, wind speed, and separation distance on fire spread rate. Shredded hardwood mulch beds were used to study these effects.

4.1.2.1. Effects of spotting along mulch bed

The fire spread behavior along mulch beds containing shredded hardwood mulch showed variability even under seemingly identical conditions. One significant factor was the spotting behavior along the length of the mulch bed. In some experiments, the flame front moved approximately evenly across the entire width of the bed. Figure 29 displayed one example of this mode of fire spread behavior; other examples are shown in Fig. 31 (a) and (c) under medium and high wind speed conditions, respectively. In other experiments, such as those shown in Fig. 31 (b) and (d), the fire front did not widen to the sides of the mulch bed but remained highly irregular in shape. These experiments typically started with a narrow burning profile leading from the point of ignition by the burners. Firebrands ignited the mulch downwind of the main flame front, creating spot fires that expanded with time until the individual flame fronts merged. Curved patterns within the burned areas of (b) and (d) indicate the irregular burning in these two experiments, in which spotting played a large role in flame spread.

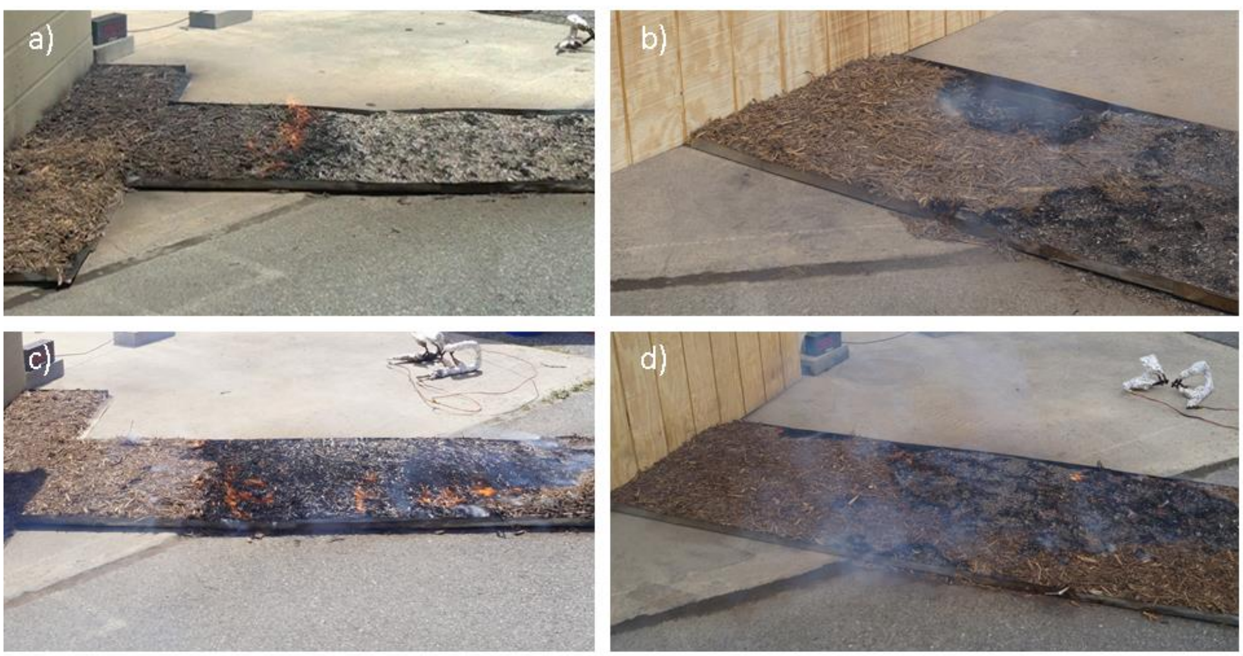

Fig. 31. Two modes of fire spread behavior in HW mulch beds: uniform flame fronts for a) medium [Test A-42] and c) high [Test A-27] wind speeds, and flame spread through spotting for b) medium [Test A-8] and d) high [Test A-10] wind speeds.

The experiments portrayed in Fig. 31 (a) and (b) were run under similar medium wind speed conditions, and (c) and (d) were both run under high wind speed conditions. The reasons behind the differences in fire spread behavior are unknown. Figure 32 shows plots of flame front location as a function of time for the experiments displayed in Fig. 31, along with an additional experiment performed at low wind speed (Test B-72) that was dominated by spotting behavior along the length of the mulch bed. Higher wind speeds resulted in faster fire spread rates and shorter experimental time durations. However, for each wind speed there was significant variability. The experiments that were dominated by firebrand spotting progressed more slowly than those that maintained a more uniform flame front. The vertical jumps in the plots in Fig. 32 indicate the times at which the main flame front merged with a spot fire downwind, instantly moving the flame front location to the maximum downwind extent of the spot fire. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

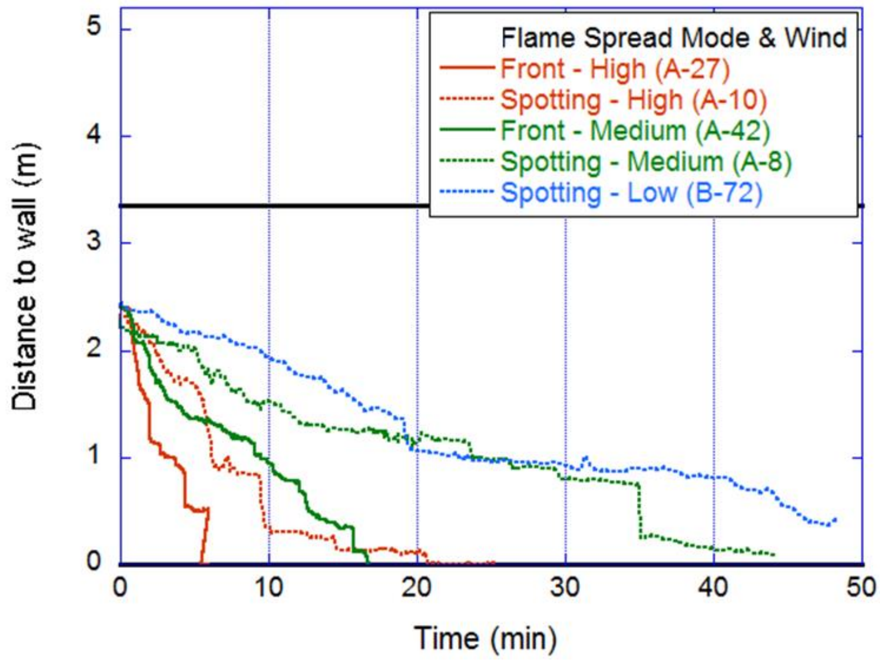

Fig. 32. Effects of dominant spread mode and wind speed on flame front location vs. time for HW mulch beds at zero separation distance from structure.

For the experiments in Fig. 32, the mulch bed was against the shed wall, so the black lines at 0 m and 3.35 m (0 ft and 11 ft) mark the nearest and farthest distances of the mulch bed to the wall respectively. The initial location of the flame front (at time t = 0 min when the fan was turned on) was between 2.2 m and 2.4 m (7.2 ft to 7.9 ft) from the end of the mulch bed closest to the shed wall. This variation reflected both the uncertainty in placement of the propane burner and the variation in flame spread toward the wall between propane burner ignition and the time at which the fan was turned on.

The scientific literature on fire behavior may be able to provide some basic insight into the differences in mulch flame spread when either fronts or spot fires are dominant. In a concurrent wind-driven fire, with the fire spreading downwind, a uniform flame front allows the flames to be close to the fuel for effective preheating. Higher wind speeds increase the flame spread rate by driving the flame closer to the unburnt fuel in its path, increasing the rate of heat transfer [51]. The slower flame spread for experiments with an irregular flame front may reflect the higher fireline curvature in these cases. Fireline curvature is a factor in spread rate over grasslands, where fires with a narrow, pointed head burn more slowly than those with a broad parabolic shape [52, 53]. In addition, the large downwind spot fires in these experiments may increase the turbulence of the air flow across the surface of the mulch bed. An increase in turbulence intensity decreases the spread rate by enhancing the mixing of air and fuel gases, which decreases the flame length, or by lifting the flame higher from the fuel surface [54, 55].

4.1.2.2. Effects of wind speed

Figure 32 shows that increasing wind speed was associated with higher fire spread rates and lower experiment durations for the two dominant flame spread modes: uniform spread and spotting. This plot gathered data from experiments at zero separation from the shed wall. Figure 33 (a) and (b) show that the same trend with wind speed was observed for separation distances of 0.91 m (3 ft) and 1.83 m (6 ft) respectively. For each separation distance, the experiments performed at high wind speeds were the fastest. Experiments performed at low wind speeds required a considerably longer time for the flame front to reach the end of the mulch bed closest to the shed wall. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

The flame spread plots from multiple experiments carried out under basically identical conditions show the range of behavior encountered when the field experiments were repeated.

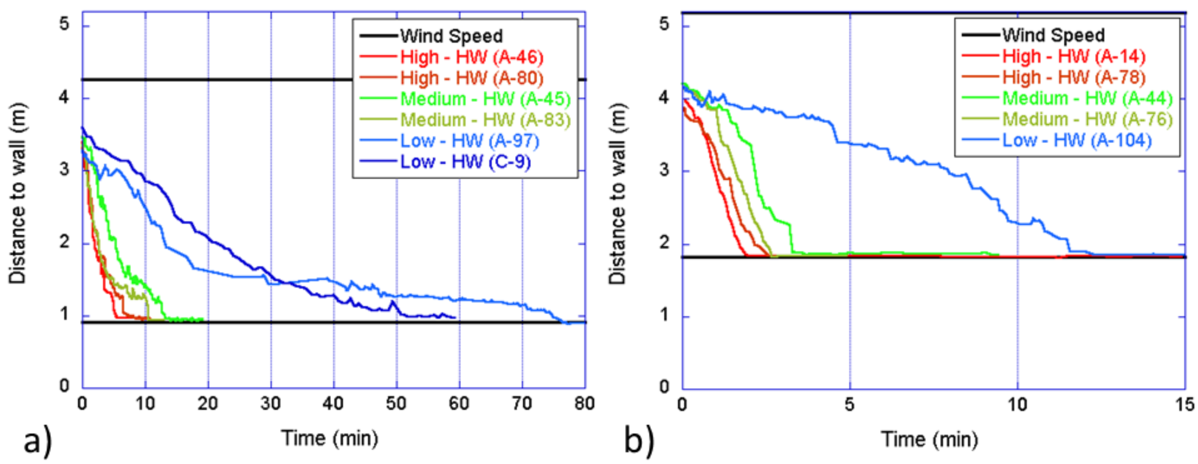

Fig. 33. Effects of wind speed on flame spread for HW mulch at separation distances of a) 0.91 m (3 ft) and b) 1.83 m (6 ft).

4.1.2.3. Effects of wind vortex

As discussed in Section 3.3.3, the wind vortex at the base of the shed has a strong influence on the behavior of flame spread and firebrands. For many mulch experiments, the flame spread was observed to slow as the flame front approached the structure wall. In every Series 1 experiment with zero separation distance, the first ignition of the plywood layer on the shed wall resulted from a firebrand landing in and igniting the mulch at a point much closer to the wall than the fire front. Figure 34 shows a particularly clear example of this phenomenon. The first photo, labelled as time t_{spot}, shows a flame front whose forward movement stalled near the wall of the structure. At this time a firebrand had just landed very close to the wall and ignited the mulch there. From this second point of ignition, flames spread toward the wall and eventually ignited the plywood. In the opposite direction, the flames from this second ignition point rapidly (within 15 s) burned in a line back toward the original flame front, as shown in the top right photograph. This is consistent with the direction of the wind in the vortex near the ground as shown in Fig. 28. The flame front then spread laterally from the burned line, while the original flame front continued to move forward very slowly.

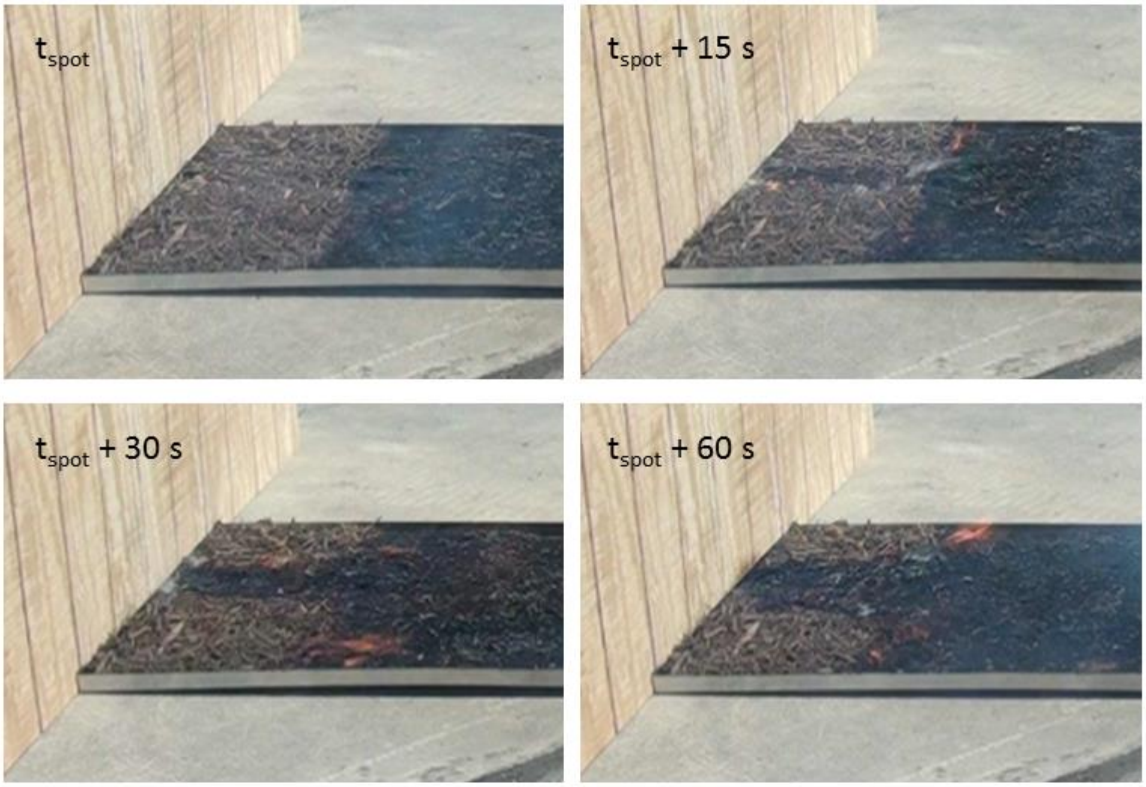

Fig. 34. Time evolution of firebrand spot fire ignited at wall of structure, beginning with first sign of spot fire at t_{spot} [Test A-2].

4.1.2.4. Effects of separation distance

The example in Section 4.1.1 showed the flame spread slowing as the flame front approached the opposing flow caused by the vortex at the base of the shed, which begins at about 1.83 m (6 ft) from the shed, as shown in Fig. 28. This distance depends only on the height of the shed and not on the wind speed. A change in flame spread rate should therefore be observed for mulch experiments in general as the flame front crosses this boundary.

In Fig. 35, the flame front position as a function of time is plotted for several HW mulch experiments by separation distance. In this plot, the black horizontal lines mark only the end of the mulch bed closest to the shed wall for the four separation distances, with the horizontal axis marking a separation distance of 0 m. Ignoring the vertical jumps resulting from the flame front catching up to spot fires, a change in slope is indeed observed when the flame front reaches between 1.5 m and 1.8 m (5 ft to 6 ft) from the shed wall. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

Note that the mulch bed for experiments with a separation distance of 1.83 m (6 ft) is fully located outside of the vortex. For these cases, the flame spread rate does not decrease over the length of the mulch bed.

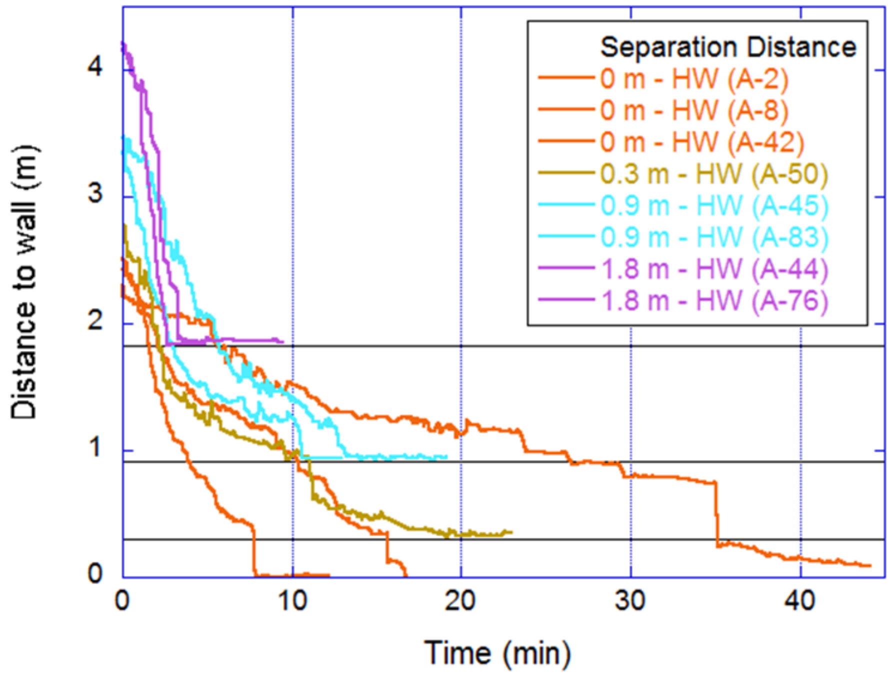

Fig. 35. Effects of separation distance on flame spread for HW mulch at medium wind speed.

4.1.3. Type of Mulch

The fire behavior was studied for four mulch types: shredded hardwood mulch, mini pine bark nuggets, pine straw mulch, and shredded rubber mulch. The effects of halving the thickness for shredded hardwood mulch were observed. Each mulch type was described in Section 2.4.2 and illustrated in Fig. 8.

More data from mulch experiments can be found in Appendix F.

4.1.3.1. Shredded hardwood mulch

Almost half of the mulch experiments (22 out of 45) were performed on shredded hardwood mulch, as can be seen in Table D.1. The previous section showed that the fire spread behavior of hardwood mulch was affected by spotting along the mulch bed, wind speed, and the flow field near the shed. Higher wind speed results in faster flame spread, and the counter-flow on the ground next to the shed slows the flame spread considerably. A firebrand that is lofted can be carried by the flow at the top of the vortex and deposited close to the shed wall, where it can ignite combustible materials and immediately threaten the structure. These wind flow effects were described more fully in Section 3.3.3.

For shredded hardwood mulch, spotting to the target mulch bed occurred in almost every experiment, with spot fires igniting both near the wall and on the outer edge of the target mulch bed. The exception was Test A-97, performed at low wind speed and 0.91 m (3 ft) separation distance, for which no spot fires ignited during the 103 min test duration.

Two experiments were performed at half of the usual mulch thickness. Figure 36 compares plots of flame front location as a function of time for hardwood mulch beds 2.5 cm and 5 cm thick under the same conditions of wind speed and separation distance. The flame spread characteristics are very similar. Note that the flame front for Test A-38 (half thickness) was the farthest back from the shed when the fan was turned on (t = 0), which accounts for some of the difference in the time needed to reach the end of the mulch bed. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

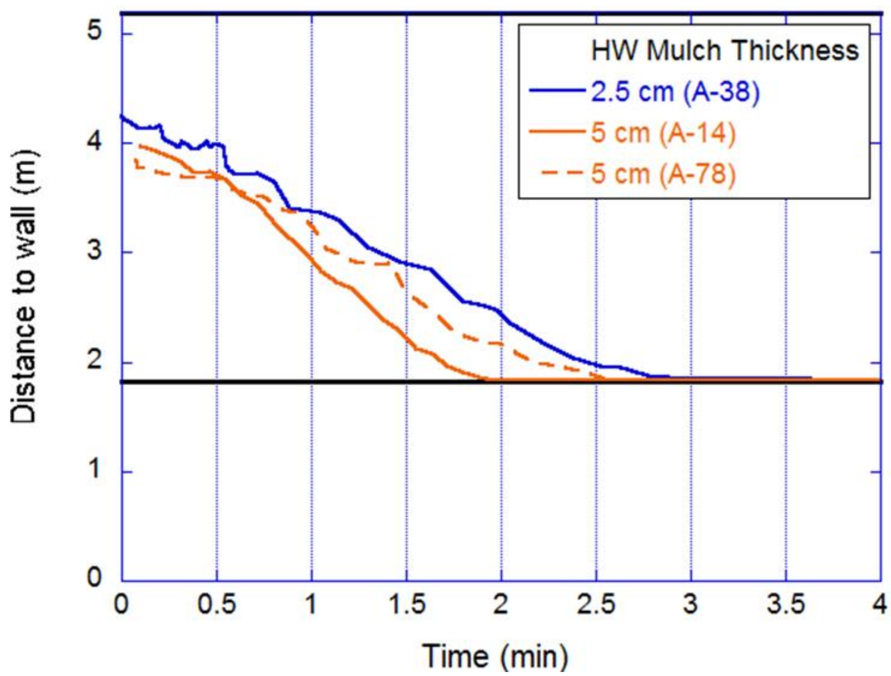

Fig. 36. Effects of HW mulch thickness on flame spread for high wind speed and separation distance of 1.83 m (6 ft). Black lines mark distance of each end of the mulch bed from the shed.

The second experiment performed with the HW mulch bed at half thickness is plotted in Fig. 37 with two full-depth experiments performed under the same conditions. The flame spread for Test A-43 progresses along a nearly identical path to Test A-42, until the former experiment was ended when a spot fire in the target mulch bed reached the wall. The flame fronts for both of these experiments were even across the width of the mulch bed, as compared to Test A-8, which experienced significant spotting as the front progressed. As was discussed in Section 4.1.2.1, spot fires along the length of the mulch bed were found to significantly affect the rate of flame spread. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

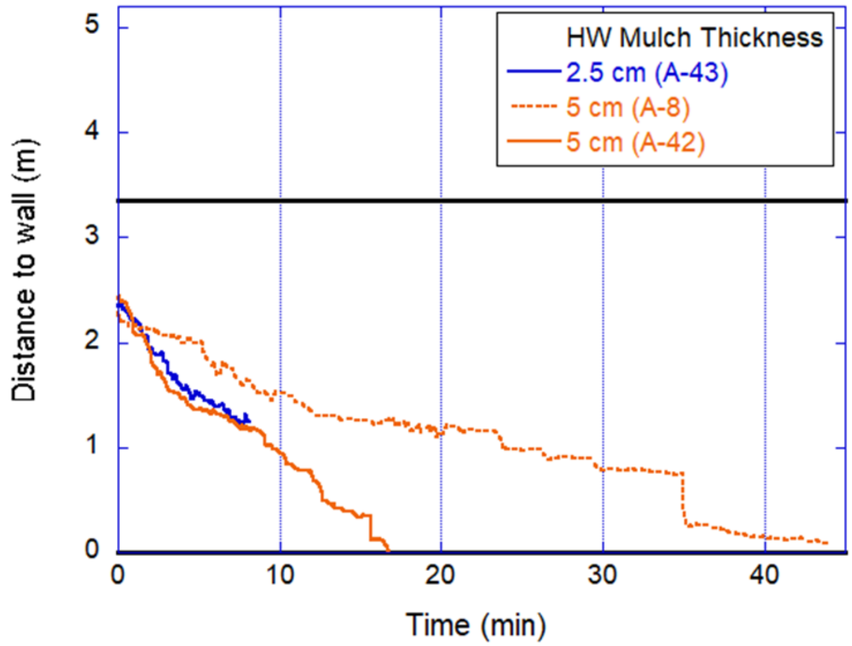

Fig. 37. Effects of HW mulch thickness on flame spread for medium wind speed and zero separation distance from shed.

4.1.3.2. Pine bark mulch

The fire behavior of mini pine bark nugget mulch was similar to that of shredded hardwood mulch, although fire spread occurred somewhat more slowly. Figure 38 shows a time sequence of a typical pine bark mulch experiment. After the fan was started with medium wind speed at time t = 0, the flame front moved toward the shed wall and expanded laterally to the edges of the mulch pan. By t = 8 min, a firebrand had ignited a spot fire farther along the pine bark mulch bed, which grew as a separate fire until it merged with the main flame front at about t = 15 min. A spot fire ignited directly next to the shed wall at about t = 16 min, apparently from a firebrand deposited at the rear of the target mulch bed.

To give an idea of the range of fire behavior observed, Fig. 39 shows examples from four other pine bark mulch experiments. The flame front in some experiments was elongated as in Fig. 39 (a), while for others the fire quickly spread to the walls and the flame front moved forward as a nearly straight line, as in (b) and (c). In the case shown in (d), the burning was somewhat spotty near the flame front.

As seen in Fig. 39 (c), the pine bark mulch left little residue after lightweight firebrands and ash blew away in the wind field. Spotting along the mulch bed was not uncommon; both Fig. 38 and Fig. 39 (a) give examples. Spotting to the target mulch bed occurred in every pine bark experiment, with spot fires igniting both near the wall as in Fig. 39 (b) and on the outer edge of the target mulch bed as in Fig. 39 (d).

Fig. 38. Time sequence of pine bark mulch bed in medium wind speed with zero separation from shed wall [Test A-99].

Fig. 39. Fire behavior examples for pine bark mulch beds with a) medium [Test A-100], b) low [Test C-4], c) medium [Test A-72], and d) high [Test A-86] wind speeds.

Figure 40 shows the flame spread for mini pine bark mulch experiments by separation distance. All three plots demonstrate that flame spread rate increases with wind speed. Comparison with Fig. 33 for shredded hardwood mulch shows that fire spread more slowly over the pine bark mulch, generally doubling or more the time for the fire to reach the end of the mulch bed. This likely results from the difference in texture – as shown in Fig. 8, the shredded hardwood mulch contains long, thin particles that easily ignite and transport fire, as compared to the chunks of mini pine bark mulch. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

The effect of the vortex at the base of the shed on flame spread rate was not as apparent for some of these plots as for the shredded hardwood mulch plots discussed in Section 4.1.2.3. The flame spread rate decreased at about 1.83 m (6 ft) from the wall for some experiments (Tests A-72 and A-55), and the flame front moved more slowly toward the wall after merging with a downwind spot fire for some (Tests A-99 and A-51) However, the plots for other experiments (Tests B-83, C-4, and C-31) did not change significantly in slope as the flame front entered the vortex.

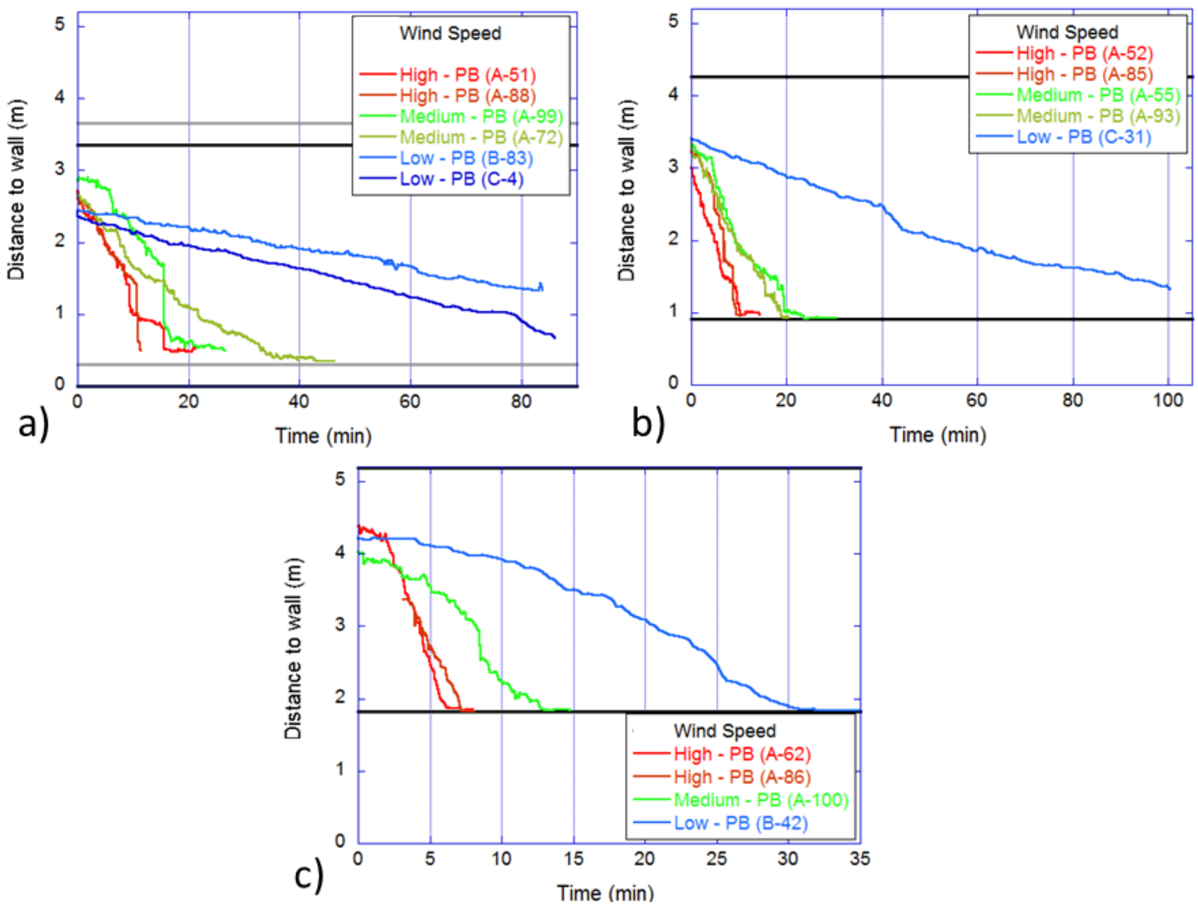

Fig. 40. Effects of wind speed on flame spread for PB mulch at separation distances of a) 0 m and 0.30 m (1 ft), b) 0.91 m (3 ft), and c) 1.83 m (6 ft).

4.1.3.3. Pine straw mulch

Pine straw mulch was found to burn intensely and rapidly. Figure 41 shows the progression of flames over a pine straw mulch bed in contact with the target hardwood mulch bed at the base of the structure. Because of the rapid fire spread, the propane burner was removed after 1 min, 30 s earlier than the normal ignition protocol. The flames reached the target mulch bed 90 s after the fan was turned on at medium wind speed. No ignition took place within the shredded hardwood mulch bed for any pine straw mulch experiment, even though the pine straw mulch was in direct contact with the shredded hardwood mulch. In addition, no spot fires were observed ahead of the flame front along the length of the mulch bed. The firebrands produced by pine straw mulch were apparently too fine and lacking in energy content to ignite spot fires.

Later in this report (in Section 4.3.4.3), experiments on the combination of pine straw mulch and western redcedar privacy fences will be presented. Although pine straw mulch by itself was unable to ignite fuels through lateral contact and firebrands, it was found to be effective in supporting ignition of the fence along its length.

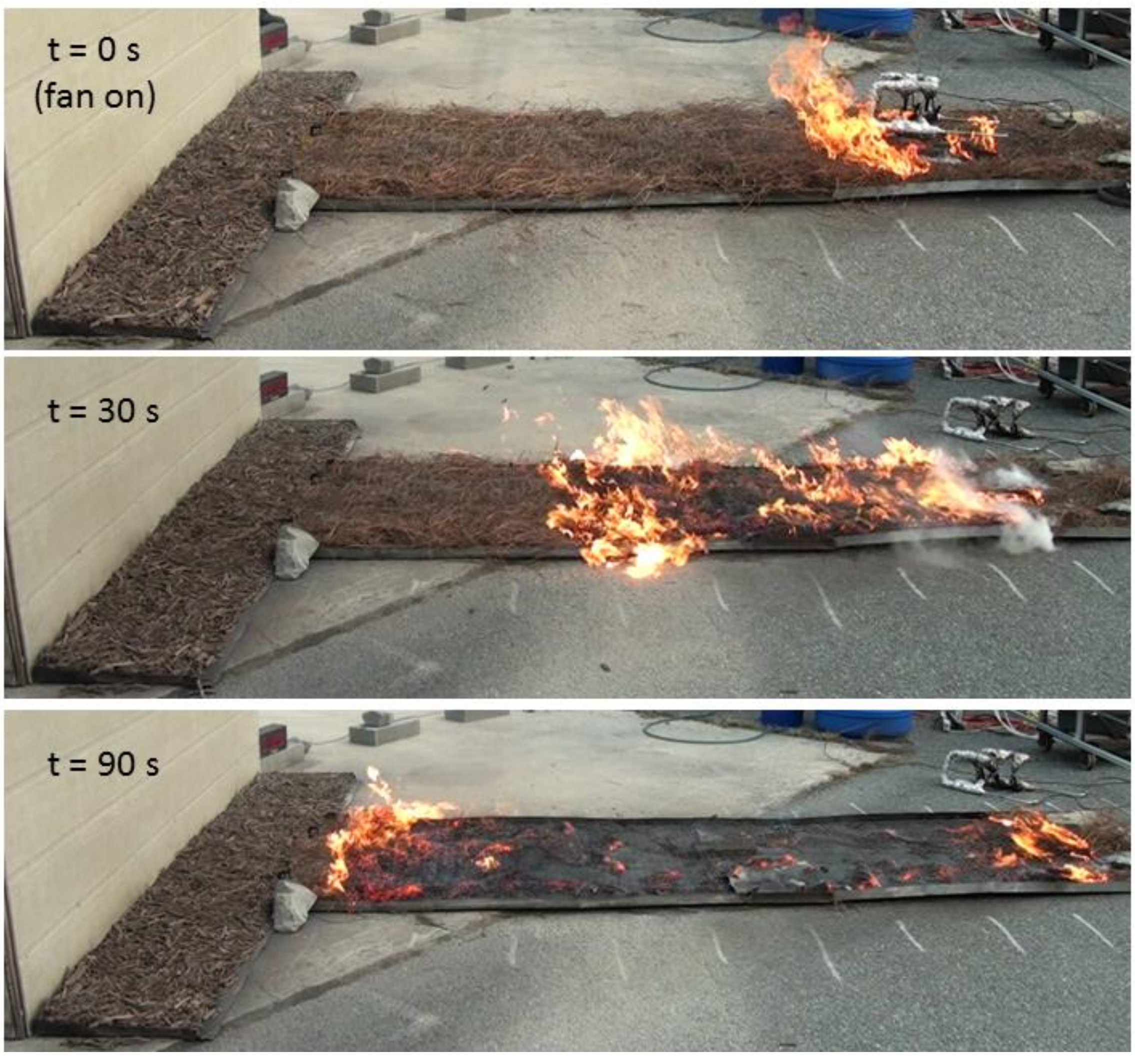

Fig. 41. Time sequence for pine straw mulch bed in medium wind speed [Test A-98].

Figure 42 shows that flame spread over pine straw mulch was rapid for all wind speeds studied in this set of experiments. The flame spread rate did not show a strong relationship with wind speed. Wind is not necessary for a fire to spread rapidly over pine straw mulch, as was demonstrated in experiments by Beyler et al. [27] on a test protocol for flame spread over mulch in the absence of wind. The flame spread does appear to slow in the opposing flow of the wind vortex near the shed wall, as evident in the change in slope for all three wind speeds when the flame front reaches about 1.8 m (6 ft) from the wall. This is similar to the observation for hardwood mulch discussed in Section 4.1.2.4. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

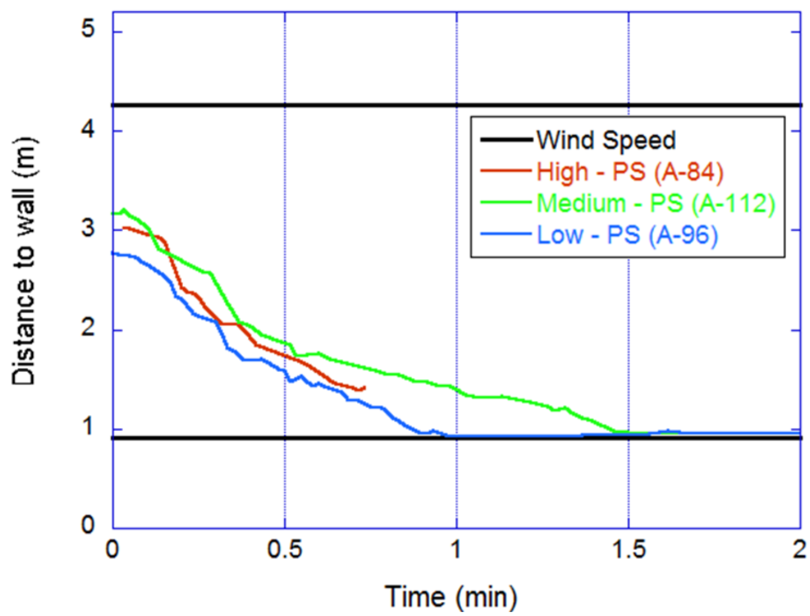

Fig. 42. Effects of wind speed on flame spread for PS mulch at 0.91 m (3 ft) separation distance.

4.1.3.4. Shredded rubber mulch

Synthetic rubber mulch is a product made from recycled tires for use in landscaping. Its fire behavior is illustrated in Fig. 43. The rubber mulch was easy to ignite, and flames spread quickly. Figure 43 (a) shows the conditions at the time that the igniter was removed and the wind machine was turned on. Due to the rapid fire spread, the igniter was removed 15 s before the completion of the 90 s ignition protocol. (In the two other rubber mulch experiments in this study, the single propane torch described in Section 2.6 was used to ignite the mulch rapidly across the full width of the bed.) The flames were considerably higher than with the plant-based mulches tested in this study. The ease of ignition and the high flames and black smoke shown in Fig. 43 (b) are consistent with findings from the University of Nevada Cooperative Extension [56].

Following the initial fire spread over the rubber mulch bed, which lasted less than one minute after the wind machine was turned on (at t = 0 min), the flames subsided as shown in Fig. 43 (c) and (d). The burning pattern of flames interspersed with blackened areas continued until the fire was extinguished with a water spray at t = 6 min. Examination of the mulch bed after the experiment revealed an upper layer of crumbly black residue above a layer of virgin rubber mulch, as shown in Fig. 44. This was consistent with the rapid decrease in height of the intense flames observed as the top layer of mulch burned. The residual noncombustible surface layer interfered with the transport of oxygen to the combustible mulch beneath, slowing the subsequent burning process and resulting in a high temperature area that may expel toxic gases over a long time period. In a low wind speed case, the sporadic burning was observed for over an hour until the fire was extinguished. Disturbing the burning mulch bed can introduce oxygen to unburnt fuel, renewing the flaming in that location.

The rubber mulch ignited spot fires in the target mulch bed next to the shed wall in less than 4 min for medium and high wind speed cases. In the low wind speed case, the rubber mulch was allowed to burn for over 70 min without ignition of a spot fire in the target mulch. Smoke and low flames were observed throughout the experiment. Before turning off the fan, the wind speed was increased to high, and multiple spot fires were ignited within 3 min.

Fig. 43. Time sequence for rubber mulch bed in medium wind speed [Test C-27].

Fig. 44. Shredded rubber mulch extinguished after 6 min, showing upper layer of crumbly residue and lower layer of virgin material.

Although this study did not examine the contents of the smoke emitted by rubber mulch, the toxicity of smoke from tire fires is well-known [57, 58, 59]. Under these test conditions, the fire in this mulch was not found to be more difficult to suppress than in the other mulches tested.

The flame spread plots for the rubber mulch experiments in Fig. 45 show that the flame front reached the end of the mulch pan within about 2 min in each case. Because the medium wind speed experiment used a different ignition source than both low and high wind speed experiments (propane burner and single propane torch respectively), no conclusion can be reached on the relationship of flame spread to wind speed for this mulch type.

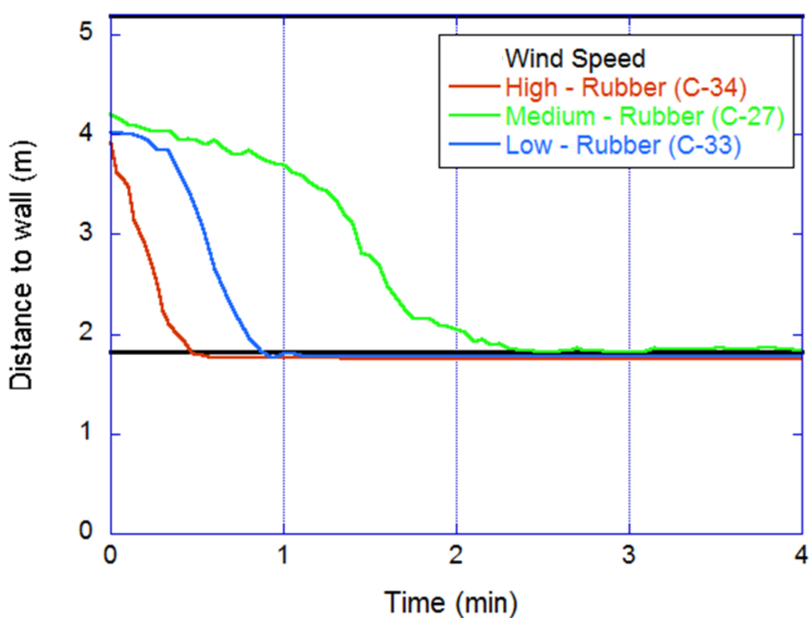

Fig. 45. Effects of wind speed on flame spread for rubber mulch at 1.83 m (6 ft) separation distance.

The uncertainties for the plots in Fig. 45 can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

4.1.3.5. Artificial turf

A single variety of artificial turf was selected for a preliminary comparison of its fire behavior to that of other groundcovers. The selected artificial turf was described in Section 2.4.2, and the cement board substrate was described in Section 2.4.1. Note that there are many formulations of artificial turf comprising different materials and physical designs. The experimental results for this single product should not be considered as representative of fire behavior for artificial turf in general.

The fire behavior of the selected artificial turf sample was observed in two experiments, at low and medium wind speeds. The experiments were performed one after the other, with the fan on an idle setting for a brief period between experiments. Time sequences for Tests D-22 (low wind speed) and D-23 (medium wind speed) are presented in Fig. 46 and Fig. 47, respectively. The shed is to the left of the image, and the wind machine is to the right.

The propane torch described in Section 2.6 ignited the artificial turf in the center far from the shed, as shown in the top image of Fig. 46. The groundcover did not ignite readily – flaming ignition was achieved after three applications of direct flame from the torch. After flaming ignition, the artificial turf continued to burn throughout the two experiments.

Figure 46 shows the progress of the fire in low wind speed. The flames proceeded slowly down the length of the artificial turf for Test D-22, traveling about 0.7 m (2.3 ft) during the 24 min experiment. The fire spread asymmetrically, moving fastest along one edge of the artificial turf bed. The wind machine was then allowed to idle for about 2 min while the instruments were reset.

The fan was brought back up to medium wind speed for Test D-23, which was again allowed to run for about 24 min. Figure 47 shows that the flame front became more linear during the second experiment, with the backing rolling up in lines as the flame spread evened out from side to side. A closeup of the final condition of the artificial turf in Fig. 48 shows (left to right) the charred remains near the ignition area, the rolled-up segments with turquoise backing, the lighter areas where the synthetic fibers had melted, and the unburned artificial turf beyond the final extent of the fire.

The flame spread plots of the two experiments in Fig. 49 show the extent of the melted fibers as a function of time. Because of the asymmetry of the flame spread and the rolling up of the artificial turf as it burned, no conclusion can be drawn from these two experiments regarding the effect of wind speed on the flame spread rate. The uncertainties for these plots can be determined from the uncertainty analysis for mulch in Appendix A.4.1.

No spot fires were observed from burning artificial turf. This study did not examine the contents of the smoke emitted by artificial turf.

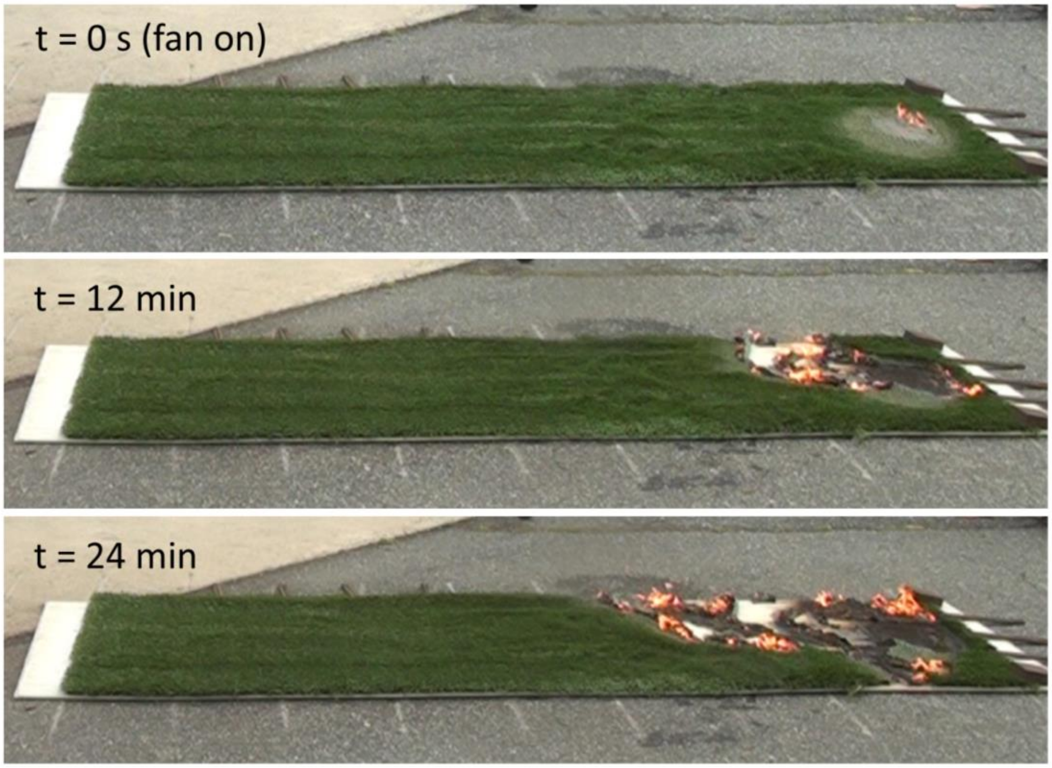

Fig. 46. Time sequence for artificial turf in low wind speed [Test D-22].

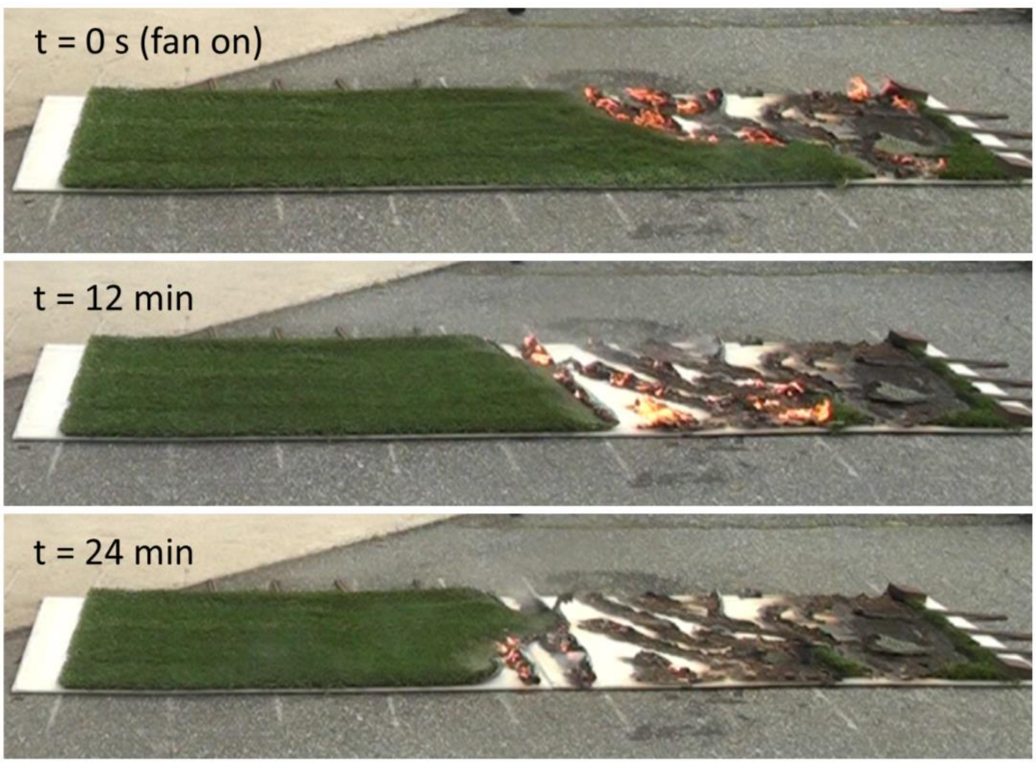

Fig. 47. Time sequence for artificial turf in medium wind speed [Test D-23].

Fig. 48. Curled segments and char residue after burning of artificial turf [Test D-23].

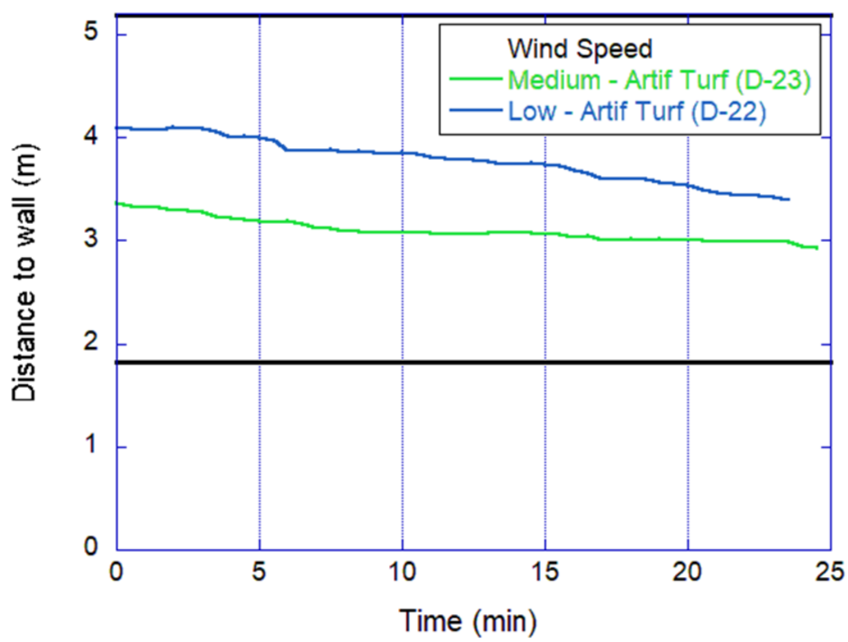

Fig. 49. Effects of wind speed on flame spread for artificial turf at 1.83 m (6 ft) separation distance.

4.1.4. Firebrand Spotting

The target mulch bed positioned along the base of the shed in Series 2 experiments served as a surrogate for building ignition vulnerability, providing a worst case condition of fine combustible material in direct contact with the structure. Ignition of a spot fire that then progressed to the wall demonstrated the ability of the burning mulch bed to generate firebrands capable of threatening the structure. Note that spot fire ignition depends on many factors, including the firebrand (e.g., fuel type, size, shape, glowing or flaming combustion state), the fuel bed (e.g., fuel type, density, porosity, temperature, moisture content), the landing characteristics (e.g., fully or partially embedded, bouncing), and environmental conditions (e.g., temperature, humidity, wind speed) [60]. The firebrands generated by shredded hardwood mulch were captured in water pans in previous field experiments and found to be irregular in shape and less than 10 mm in the largest dimension [23].

Characteristics of the firebrand spotting caused by a burning mulch bed, including the location, timing, and frequency of spot fires, illustrated the hazard to the structure. Some examples of spot fires from experiments on shredded hardwood mulch beds are shown in Fig. 50. In each of these cases, a spot fire ignited in the middle of the target mulch bed or near the shed wall, similar to the experiment shown in Fig. 34. These ignitions were consistent with mulch firebrands that were lofted upward from their initial positions near the ground, carried toward the shed by the wind vortex, and deposited somewhere within the target mulch bed.

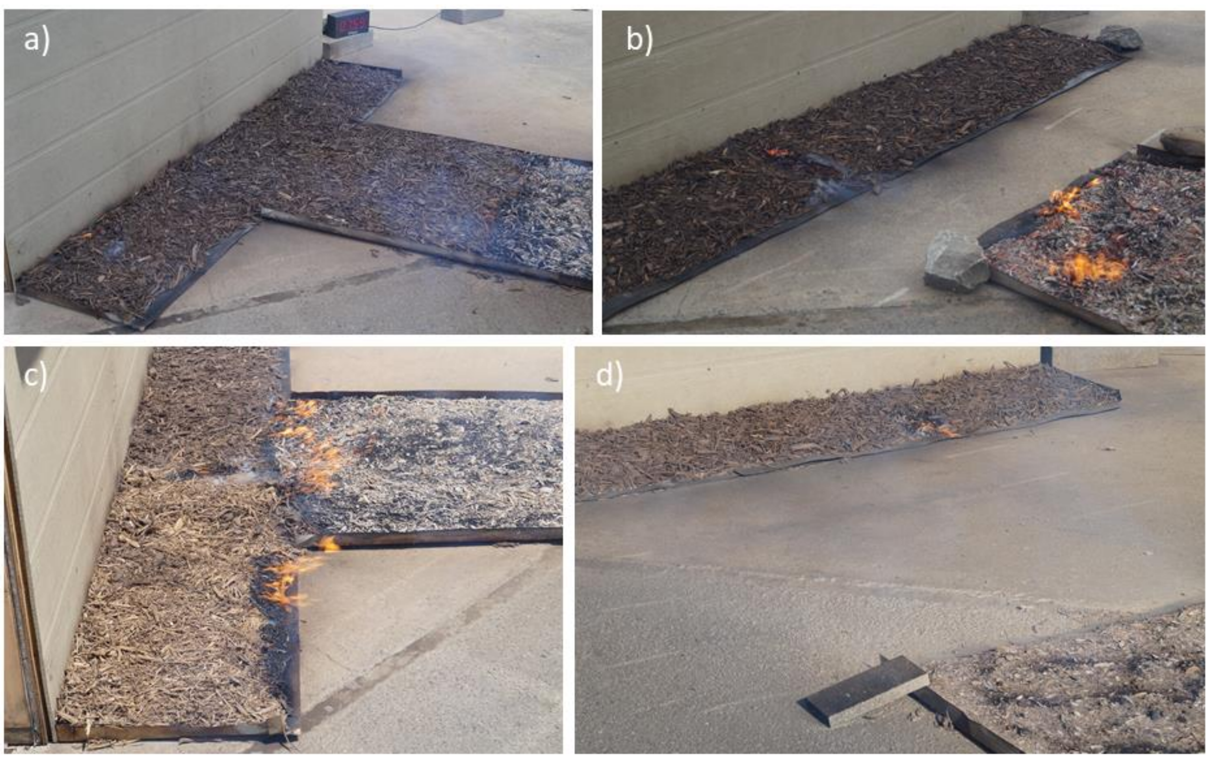

Fig. 50. Spot fires in target mulch bed resulting from mulch experiments a) HW mulch at half thickness in medium wind [Test A-43], b) HW mulch in high wind [Test A-80], c) HW mulch in medium wind [Test A-42], d) HW mulch in low wind [Test A-104].

Ignitions were also observed along the outer edge of the target mulch bed, as in Fig. 50 (c). The firebrands creating these spot fires may have been transported on the ground before being caught in the mulch. These fires progressed slowly toward the wall, with smoke and flame patterns extending away from the wall as visual indicators of the flow field. The flame spread toward the wall was clearly in opposed flow mode.

In most cases, the fire that first reached the structure was a spot fire ignited close to the shed wall by a lofted firebrand, even for mulch beds in intimate contact with the target mulch bed.

The experiments did not provide insight into the size or energy content of firebrands that were capable of igniting spot fires in the target mulch bed. Individual firebrands in flight were small and difficult to observe directly under the daylight conditions of the field experiments. Firebrands large enough for visual tracking usually traveled on the ground and seldom reached the target bed. The first sign of an ignition was smoke; it was not possible to distinguish the firebrand responsible for the spot fire from the target mulch bed. The roughness of the target mulch bed prevented firebrands from moving after they had landed, so that firebrand accumulation was possible only by chance. Spot fires occurred infrequently. For the 156 experiments in this study using a target mulch bed (Series 2), only 11 resulted in more than ten spot fires before the experiment was ended. The largest number of spot fires for the Mulch Only experiments discussed in this section was seven. Some spot fires, but not all, transitioned from smoldering to flaming combustion during the experiment.

Spot fire ignitions often occurred after the flame front had reached the end of the mulch bed, as in the cases shown in Fig. 50 (b) and (d). The times to ignition of the first spot fire are plotted as a function of wind speed in Fig. 51 and as a function of separation distance in Fig. 52. As mentioned in Section 2.7.1 and discussed in Appendix C.2, the wind speed value was the average of the velocities measured by the lower four bidirectional probes along the centerline of the probe array.

The data indicates that the time to ignition of the first spot fire was related to wind speed. Spot fires ignited in less than 20 min in all medium wind speed cases and in less than 10 min in all high wind speed cases. For shredded hardwood mulch and pine bark mulch in low wind conditions, spot fires that threatened the structure took up to an hour to ignite. Figure 52 shows that ignition times did not depend on separation distance.

Timing data was also collected for the ignition of the first spot fire to put flames against the wall (Fig. 53) and the first observation of flames on the wall (Fig. 54). The first spot fire to reach the wall was influenced by the location at which the spot fire ignited within the mulch bed. Firebrands that were lofted by the wind vortex and deposited close to the wall were more likely to reach the wall quickly. Transition from smoldering to flaming had to occur before flames could be observed on the wall.

With the exception of one experiment on pine bark mulch (Test C-31), for which early spot fires that ignited at the front of the target mulch bed failed to reach the shed wall, Fig. 53 and Fig. 51 are very similar. In many cases, the first spot fire to ignite was also the first to reach the wall. Comparing Fig. 54 with Fig. 53 demonstrates that the time between spot fire ignition and flames on the wall was generally a few minutes or less.

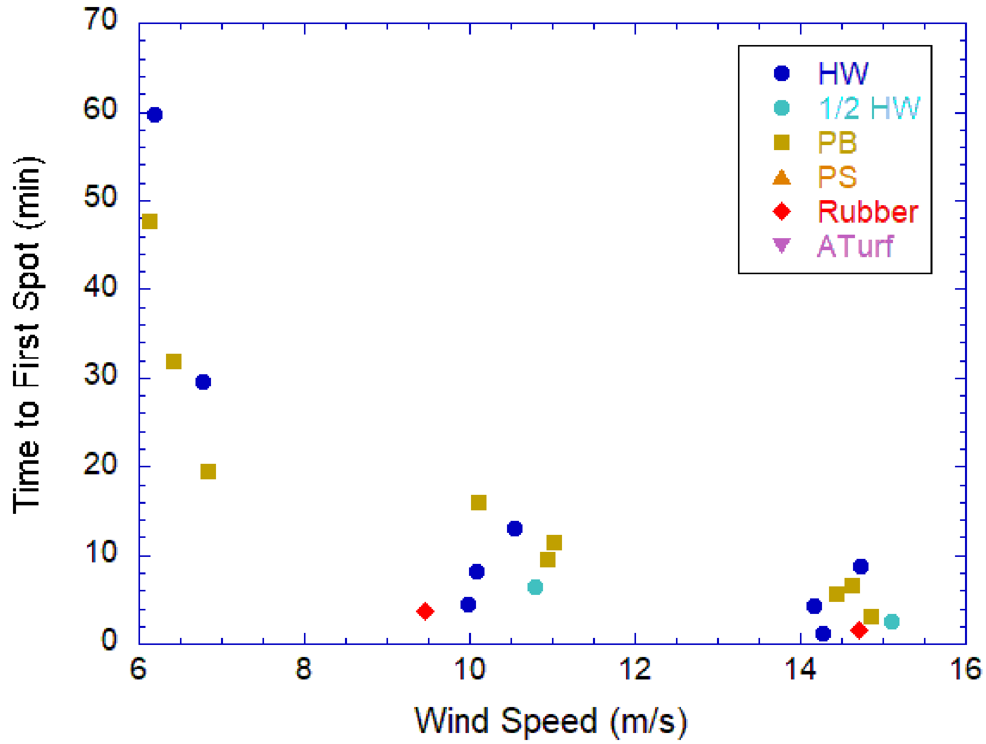

Fig. 51. Time to ignition of first spot fire vs. wind speed for mulch experiments.

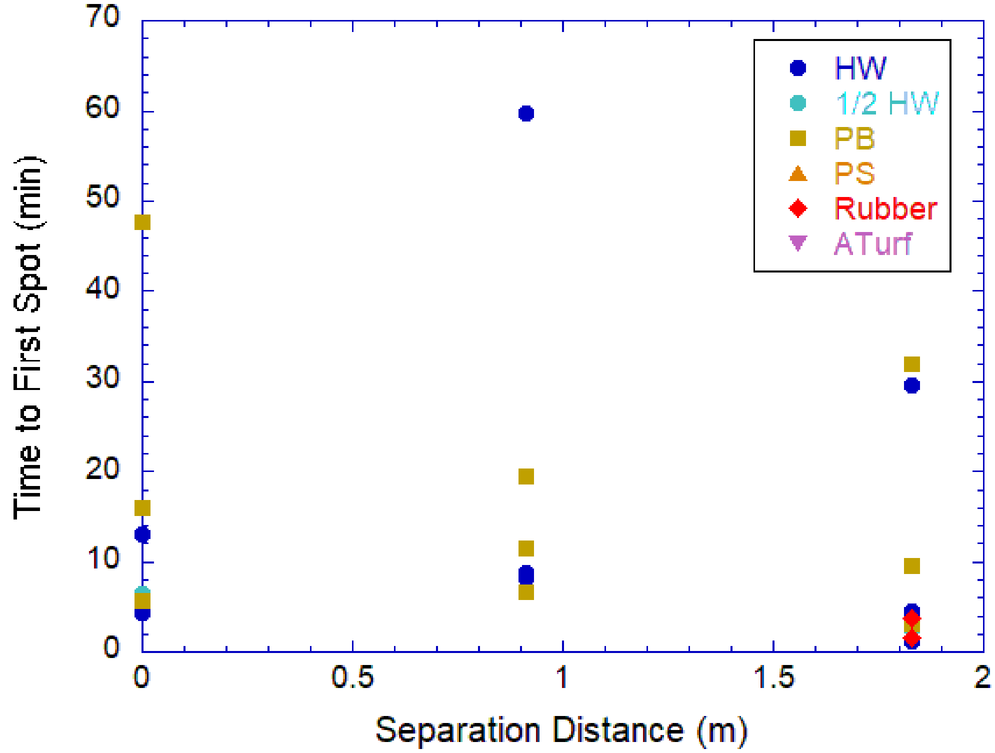

Fig. 52. Time to ignition of first spot fire vs. separation distance for mulch experiments.

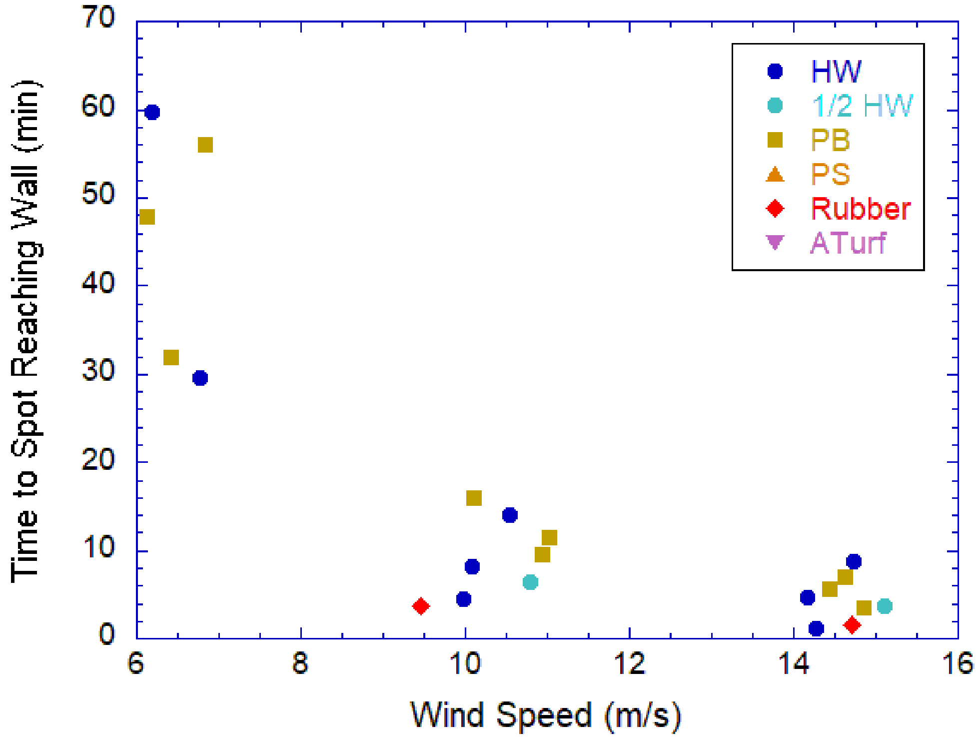

Fig. 53. Time to ignition of first spot fire to put flames against the wall vs. wind speed for mulch experiments.

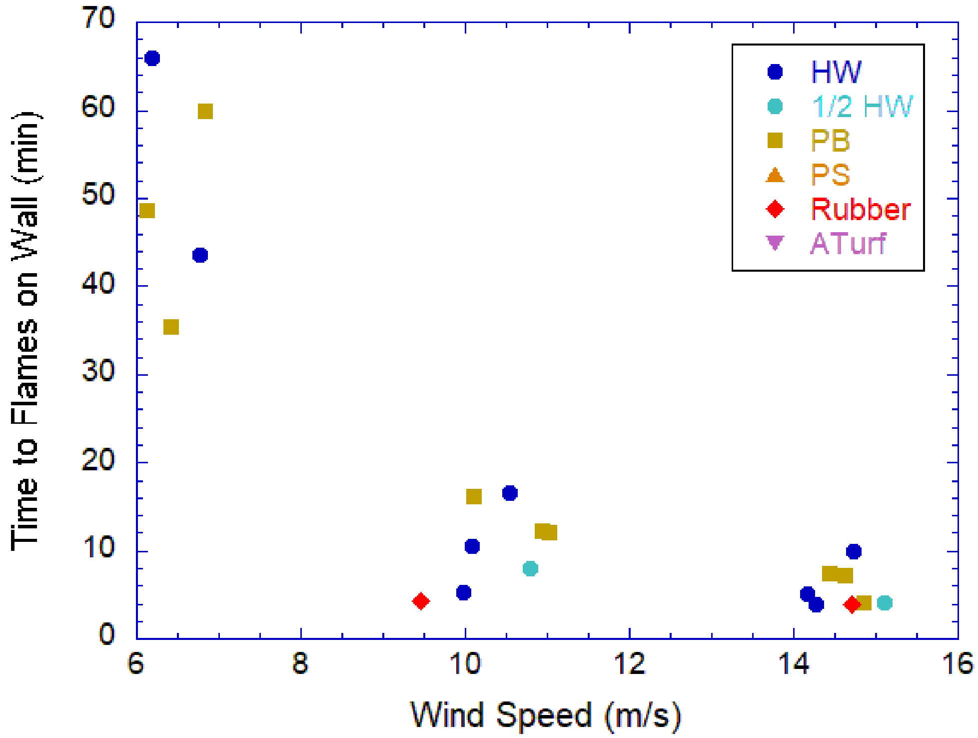

Fig. 54. Time to flames reaching the wall vs. wind speed for mulch experiments.

Table 1 lists the number of Series 2 experiments of each mulch type by whether or not spot fires were ignited in the target mulch bed. This table summarizes the data from Table D.1, where the color key identifies experiments in which the fire spread to the shed through spotting (in green) and experiments in which the fire did not reach the shed (in pink). The three shredded hardwood mulch and rubber mulch experiments that did not produce spot fires were at low wind speeds. Neither the bed of pine straw mulch nor artificial turf generated spot fires in any experiment.

Table 1. Number of experiments producing spot fires for each mulch type.

Type of Mulch	Number of Experiments With Spot Fires	Number of Experiments Without Spot Fires
Shredded hardwood (HW)	10	2
Pine Bark (PB)	10	0
Pine Straw (PS)	0	5
Rubber	2	1
Artificial Turf (AT)	0	2

4.1.5. Summary

The mulch experiments demonstrated the dependence of fire behavior on the wind field, type of mulch, and firebrand spotting. Key findings from this set of experiments include the following.

Fire spread behavior. The fire spread behavior in a mulch bed is affected by the flow field, ignition of spot fires downwind, and the geometry of the mulch bed and structure.

- Flame spread is strongly affected by the wind flow field. The flame front progresses faster as wind speed increases.
- The flow field is highly turbulent and is modified by obstacles.
- A vortex is generated when the wind flow is perpendicular to the wall of a structure. The vortex slows the flame spread over a mulch bed as it approaches the structure due to the change in flow direction. On a smooth ground surface, the surface winds tend to move firebrands toward a line parallel to the wall where the vortex meets the flow from the fan and to the sides of the structure. Firebrands that are lofted may be carried close to the wall by the vortex and deposited at the base. Such spot fires threaten the structure immediately and also spread rapidly outward from the wall.
- Spot fires along the mulch bed allow the fire to jump in the direction of the wind. This makes the flame spread more unpredictable, even as it slows the progress of the flame front.

Type of mulch. Fire behavior is a strong function of the type of mulch. The material properties and physical characteristics of the mulch influence the ease of ignition, fire intensity, rate of fire spread, production and size of firebrands, and smoke toxicity.

- Shredded hardwood mulch and pine bark mulch can burn and emit firebrands for longer than an hour.
- Pine straw mulch burns rapidly with high intensity. The fire did not spread laterally into an adjacent bed of shredded hardwood mulch. Firebrands did not ignite spot fires in the target mulch bed.
- Rubber mulch burns with high initial intensity and significant smoke output. Formation of a crumbly residue layer reduces the flame height and allows the fire to burn for a long time as virgin material beneath is ignited. Larger flames can break through when the residue layer is disturbed.
- The single type of artificial turf tested in this study was difficult to ignite and exhibited slow flame spread.
- Reducing the mulch thickness for shredded hardwood mulch from 5 cm to 2.5 cm does not have a large effect.

Firebrand spotting. Firebrands are generated by all mulch types tested.

- Spot fires often ignite close to the wall of the structure, due to the deposition of lofted firebrands by the vortex at the base of the wall.
- Deposition of firebrands is unpredictable due to variety in shapes and sizes and the turbulence in the wind field.
- The time to spot fire ignition decreases as wind speed increases. Spot fires ignited in less than 20 min in all medium wind speed cases and less than 10 min in all high wind speed cases.
- Spot fires may occur after the flame front has reached the end of the mulch bed and the initial flaming combustion has subsided.
- Firebrands from pine straw mulch did not ignite spot fires in the target mulch bed.

4.2. Fence Only Experiments

The experiments in this section investigate the fire behavior for a fence in the absence of mulch at its base. This represents the best-case fire scenario for combustible fences, in which the area underneath and along the sides of the fence is completely clear of fine fuels, including grass or accumulated leaves. This condition was explored for western redcedar privacy fences and redwood lattice fences at a variety of wind speeds and separation distances from the nearby structure. A vinyl fence was tested under high wind speed conditions, and a wood-plastic composite fence was tested at low wind speeds.

The test matrix for Fence Only experiments is shown in Table D.2 in Appendix D. The details of each experiment, including parameter values, images, flame spread data, wind plots, and summary values, can be found in Appendix G. In each case, timing was measured from the point after ignition when the wind machine was turned on.

4.2.1. Example

The slow progress of fire over a combustible fence in the absence of fine fuels is shown in Fig. 55. In this experiment (Test A-26), a western redcedar privacy fence was separated from the shed by 1.83 m (6 ft) and exposed to high wind speeds averaging 12.7 m/s (28.4 mi/h) along the centerline. Figure 55 (a) shows the ignition of the end of the fence farthest from the shed using the propane burner. Image (b) shows the glowing combustion of the area around the ignition at about 2.5 min after the fan had been turned on, including the stringer, post, and the first two boards near the ground. At about t = 4.5 min, image (c) shows that a piece of the first board had fallen to the ground. In image (d), at about t = 7.5 min, the wind had blown this firebrand along the ground and back into contact with the fence, where it caused glowing combustion in a new location. Image (e) shows that the combustion has not progressed beyond the first two boards by t = 11.5 min. This is about one minute after the fan was turned off, marking the end of the experiment.

A smaller, more easily transported firebrand was deposited in the target mulch bed at the base of the shed at about 8 min after the fan was turned on. Figure 56 shows the resulting spot fire at approximately one minute after it was ignited. The firebrand ignited the mulch bed at its intersection with the shed wall. This indicates that the firebrand was likely to have been lofted, striking the wall of the structure and falling into the mulch bed or following the path of the vortex adjacent to the wall that was discussed in Section 3.3.2.

Fig. 55. Progression of glowing combustion over western redcedar privacy fence in high wind speed [Test A-26], showing a) ignition, b) erosion of board at t = 2.5 min, c) large firebrand at t = 4.5 min, d) secondary ignition by firebrand at t = 7.5 min, and e) burn pattern at t = 11.5 min.

Fig. 56. Firebrand spotting at 9 min after fan on for Test A-26.

4.2.2. Fire Spread Behavior

In the absence of fine fuels adjacent to and beneath a combustible fence, the fire spread from a single point of ignition was found to be slow. Glowing combustion was the primary mode observed during the burning process, with the occasional appearance of small flames. The gap between boards delayed horizontal flame spread for privacy fences, although it was not wide enough to arrest the fire. For diagonal lattice fences, the lack of alignment between slats and wind slowed the flame spread. For both fence types, the stringer near the ground made of pressure treated pine contributed to flame spread by providing a continuous path aligned with the wind. Its thickness may have deterred rapid burning in some cases, although in other cases a transition to flaming combustion allowed the stringer to accelerate fire spread.

As the combustion progressed over the fence boards, it was typical for pieces of board to break off. If ignited, these pieces became large firebrands that were capable of spreading the fire to other combustibles, depending on their aerodynamic properties and the wind. Under the conditions in this study, large pieces usually remained near where they fell.

Only two experiments, both with WRC privacy fences, showed the fire spreading a significant distance downwind, beyond the immediate region of ignition. In these cases, the stringer transitioned to flaming combustion for an extended period of time, providing a continuous pathway for carrying the fire downwind at a more rapid pace than glowing combustion. The separation distance between the end of the fence and the wall of the structure in these experiments was 1.83 m (6 ft). Both experiments were over an hour in duration. In Test A-101, shown in Fig. 57, a fire ignited at the base of the fence farthest from the shed took over an hour to progress from the ignition point to a point halfway down the length of the panel. As can be observed in the bottom two images, pieces of the fence boards broke off as the fire on the stringer progressed. In this case, no spot fire was observed over the entire test duration. In the other case (Test A-91) a spot fire ignited in the target mulch bed after 35 min. The wind speed level was medium for Test A-101 and high for Test A-91.

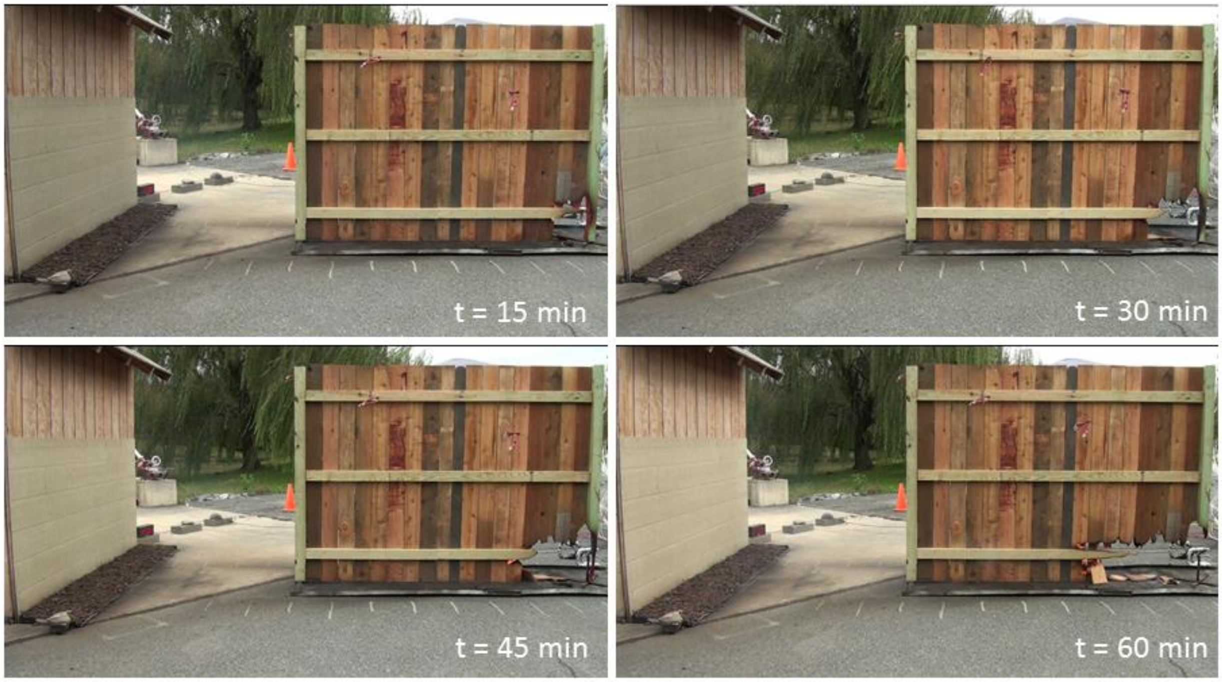

Fig. 57. Time sequence for Test A-101, western redcedar privacy fence only (no mulch), with medium wind speed at 1.83 m (6 ft) separation from shed.

In Fig. 58 the location of the flame front is plotted as a function of time for all fence-only experiments performed on western redcedar privacy fences and redwood lattice fences. The initial location of the flame front reflects the separation distance of the fence from the shed wall, which was found to affect the rate of spreading of the fire toward the structure. The flame front progressed toward the wall for experiments with 1.83 m (6 ft) separation but remained near the point of ignition for smaller separation distances. This is consistent with the effects of wind near the ground, as discussed in Section 3.3.2. Near the ground, the vortex generated near the wall of the structure creates a stagnation point at about 1.83 m (6 ft) from the wall, as illustrated in the contours of the average wind field in Fig. 28. In these fence-only experiments, the burning remained close to the ground, and none of the flame fronts approached within 2 m of the wall of the structure, even when the experiment ran for over an hour. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2 and listed in Table A.6.

Similar fire behavior was observed in fence experiments performed by IBHS [21, 22]. In the IBHS experiments, firebrands were expelled from a firebrand generator into a wind field that was oriented perpendicular to the fence panels. Some of these firebrands lodged in cracks and interstices in the fence, igniting the fence and resulting in holes that expanded slowly through glowing combustion.

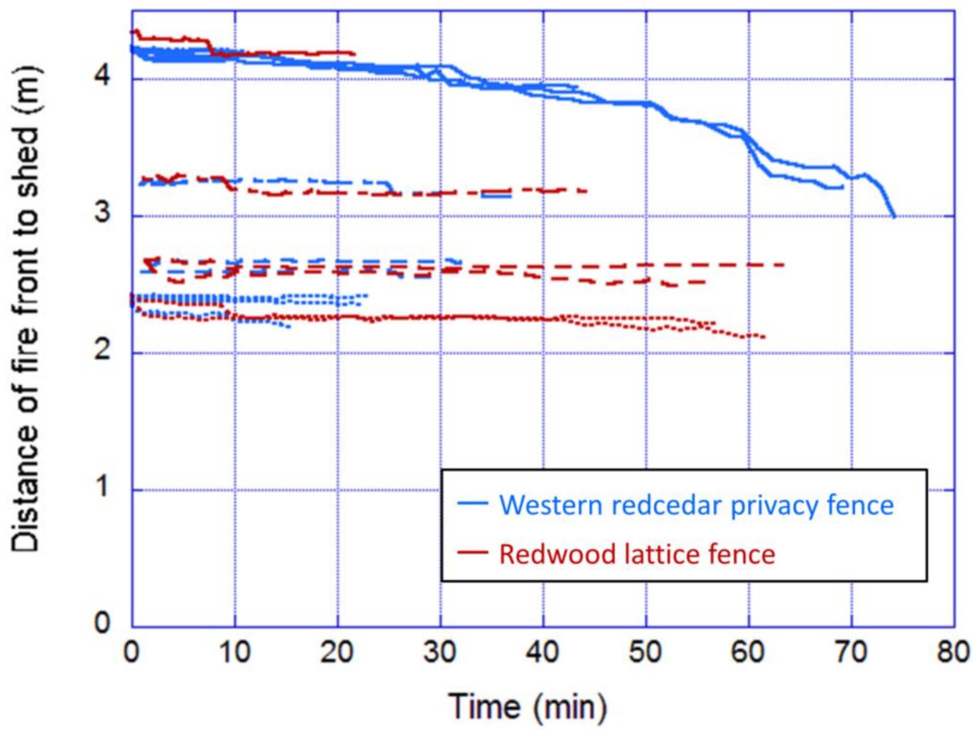

Fig. 58. Location of the flame front on the fence as a function of time. Blue lines indicate experiments on western redcedar privacy fences, and red lines are from redwood lattice fence experiments. Line style indicates separation distance between the fence and the shed: 0 m (dotted), 0.30 m (1 ft) (dashed), 0.91 m (3 ft) (dot-dash), and 1.83 m (6 ft) (solid).

4.2.3. Type of Fence

The fire behavior of four fence types (western redcedar privacy, redwood lattice, and vinyl and wood-plastic composite privacy fences) was studied without fine fuels beneath. Each fence type was described in Section 2.5 and illustrated in Fig. 11.

More data from experiments with fences only (without mulch) can be found in Appendix G.

4.2.3.1. Western redcedar privacy fence

Figure 59 shows photos from experiments with western redcedar privacy fences at medium wind speeds, for the four separation distances studied. Slow fire spread through glowing combustion and occasional flaming were observed in all cases. Figure 59 (a) shows a fence board shortly before a piece broke off during combustion, and in images (c) and (d) pieces of fence boards are lying on the ground. Results from experiments performed at high wind speeds were very similar, as shown in Fig. 60.

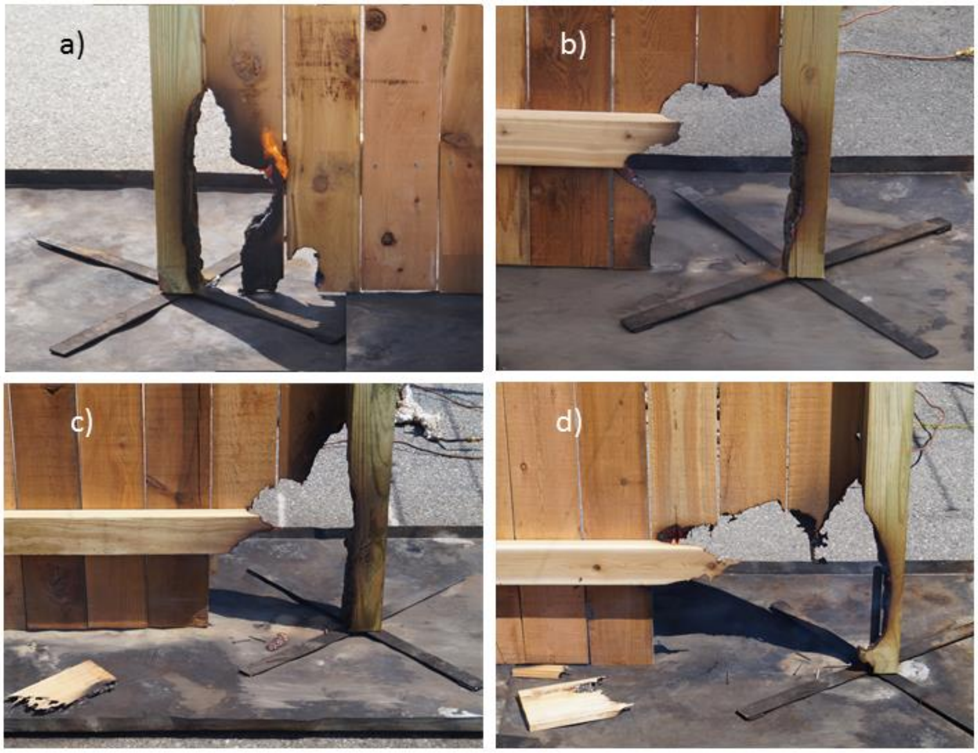

Fig. 59. WRC privacy fence without mulch, in medium wind speed at separation distances of a) 0 m [Test A-18], b) 0.30 m (1 ft) [Test A-21], c) 0.91 m (3 ft) [Test A-65], and d) 1.83 m (6 ft) [Test A-30].

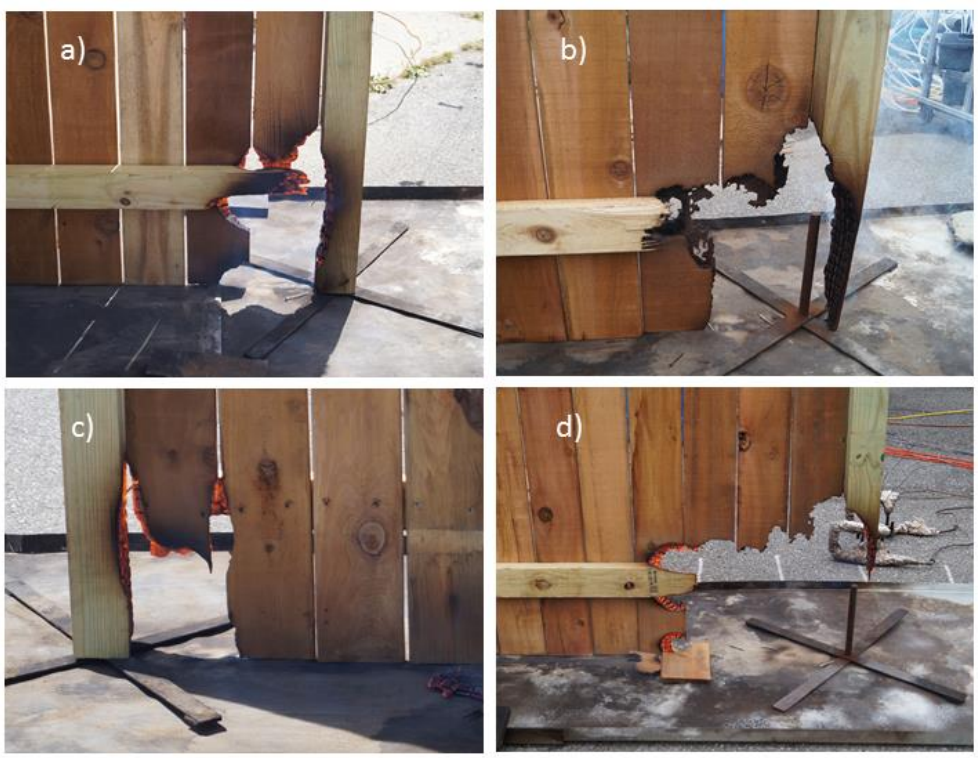

Fig. 60. WRC privacy fence without mulch, in high wind speed at separation distances of a) 0 m [Test A-28], b) 0.30 m (1 ft) [Test A-32], c) 0.91 m (3 ft) [Test A-25], and d) 1.83 m (6 ft) [Test A-91].

4.2.3.2. Redwood lattice fence

Burn patterns resulting from the combustion of redwood lattice fences are shown in Fig. 61 for medium wind speeds and various separation distances. All lattice fences in this study had a diagonal grid. The wood slats were therefore at an angle to the wind, so that flame spread along the slats was not aligned with the wind. The horizontal stringer provided a path for the fire aligned with the wind but was much thicker than the slats, and progress along the stringer was also slow. As was observed for WRC privacy fences, pieces of the fence occasionally broke off. If the pieces continued to smolder, they became firebrands that could spread the fire farther if transported by sufficiently high winds.

Fig. 61. Redwood lattice fence only, in medium wind speed at separation distances of a) 0 m [Test A-82], b) 0.30 m (1ft) [Test A-113], c) 0.91 m (3 ft) [Test A-77], and d) 1.83 m (6 ft) [Test A-75].

4.2.3.3. Vinyl privacy fence

A single test was performed on a vinyl privacy fence without mulch. It was difficult to ignite the fence using the propane burner, and little change had been observed in the char pattern when the experiment was ended after 4 min. The final condition of the fence is shown in Fig. 62.

Fig. 62. Vinyl privacy fence in high wind conditions at 0 m separation distance [Test A-34].

4.2.3.4. Wood-plastic composite fence

A wood-plastic composite fence (WPC1) was studied both with and without mulch. In the absence of more data, the following is considered limited preliminary data. More experiments to study the fire behavior of this category of fence are planned.

Very different fire behavior was observed for the wood-plastic composite #1 (WPC1) fence in the absence of mulch. As shown in Fig. 63, a fire ignited at the upwind base of the fence under low wind conditions developed into a large fire with flames extending well above the fence and licking the shed from 1.83 m (6 ft) away. The fire was expanded by the boards falling out of the top and bottom frames as the composite material softened; boards 1.83 m (6 ft) in length fell to either side of the fence and created a fire zone up to 3.6 m (12 ft) wide. Some softened boards near the post leaned forward as they fell and increased the fire exposure of the shed. The final configuration of the boards after extinguishment is shown in Fig. 64.

Fires in the target mulch bed next to the shed can be seen in the final frame of the sequence in Fig. 63, at t = 14.1 min. Fires ignited along a large part of the front edge of the mulch bed in the final 10 s before the fire was extinguished, likely due to direct flame contact rather than firebrands.

Fig. 63. Time sequence for Test E-2, wood-plastic composite fence WPC1 alone (without mulch), with low wind speed at 1.83 m (6 ft) separation from shed.

Fig. 64. Final configuration of wood-plastic composite boards after Test E-2.

As occurred for many of the cases in which the fence was fully involved, there was evidence that the shed might have been in danger of igniting if the fire had been allowed to continue. Figure 65 shows water being applied to the underside of the eaves of the shed as part of the extinguishment of the fire after the experiment. Smoke can be seen rising from the shed roof in this image – water was also applied to cool the roof. It was clear from this and other experiments with large flames that 1.83 m (6 ft) separation distance was insufficient to prevent the structure from ignition.

Fig. 65. Water being applied to the eaves of the shed after Test E-2. Smoke rising from the roof is visible.

Flame spread over the WPC1 fence as a function of time will be discussed with the other wood-plastic composite fence experiments in Section 4.3.3.7.

4.2.4. Firebrand Spotting

Firebrand spotting to the target mulch bed was an uncommon occurrence in the experiments carried out on fences in the absence of fine fuels. This is illustrated in Table D.2, where the color key identifies experiments in which the fire spread to the shed through spotting (in green) and other cases in which little spread occurred (in red) and summarized in Table 2. Out of 18 bare fence experiments with a target mulch bed present, 16 of which were with wood fences, spotting occurred in only six cases. The four cases for WRC privacy fences all occurred under high wind conditions.

The large pieces of wood that broke off the fence boards primarily stayed on the ground near where they fell. None of these large firebrands were observed igniting spot fires in the target mulch bed at the base of the shed.

Table 2. Number of experiments producing spot fires for each fence type.

Type of Fence (No Mulch)	Number of Experiments With Spot Fires	Number of Experiments Without Spot Fires
Western redcedar privacy (WRC)	4	6
Redwood lattice (RWL)	1	5
Vinyl privacy (Vinyl)	0	1
Wood-plastic composite (WPC1)	1	0

For those fence-only experiments in which firebrand spotting occurred, the times to ignition of the first spot fire are plotted as a function of wind speed in Fig. 66. Data was too sparse to detect a relationship with either wind speed or separation distance (not plotted). Under high wind speed conditions, spot fire ignition occurred as early as 3 min after the wind machine was turned on.

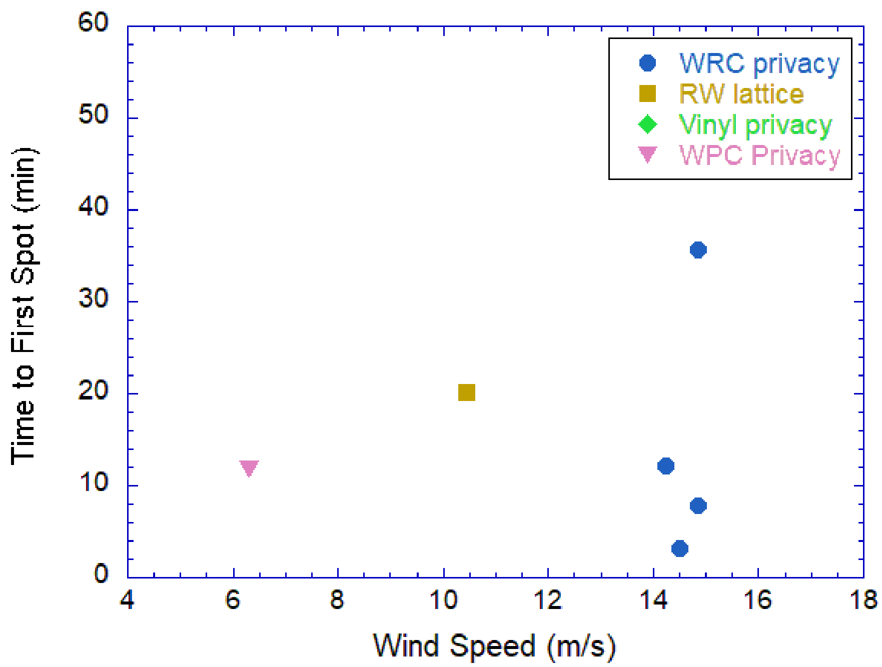

Fig. 66. Time to ignition of first spot fire vs. wind speed for experiments with fence only.

Figure 67 and Fig. 68 plot the time to ignition for the first spot fire to put flames against the wall and the time to flames on the wall for fence experiments without mulch. The spot fires produced by wood fences all reached the wall. One spot fire took almost 20 min to put flames against the wall after ignition, while the others reached the wall within 3 min. The burning wood-plastic composite fence resulted in flames along the entire front of the target mulch bed, possibly resulting from direct flame contact rather than from firebrands. None of these fires reached the wall, but in this case that was of secondary concern to the large flames from the burning fence itself.

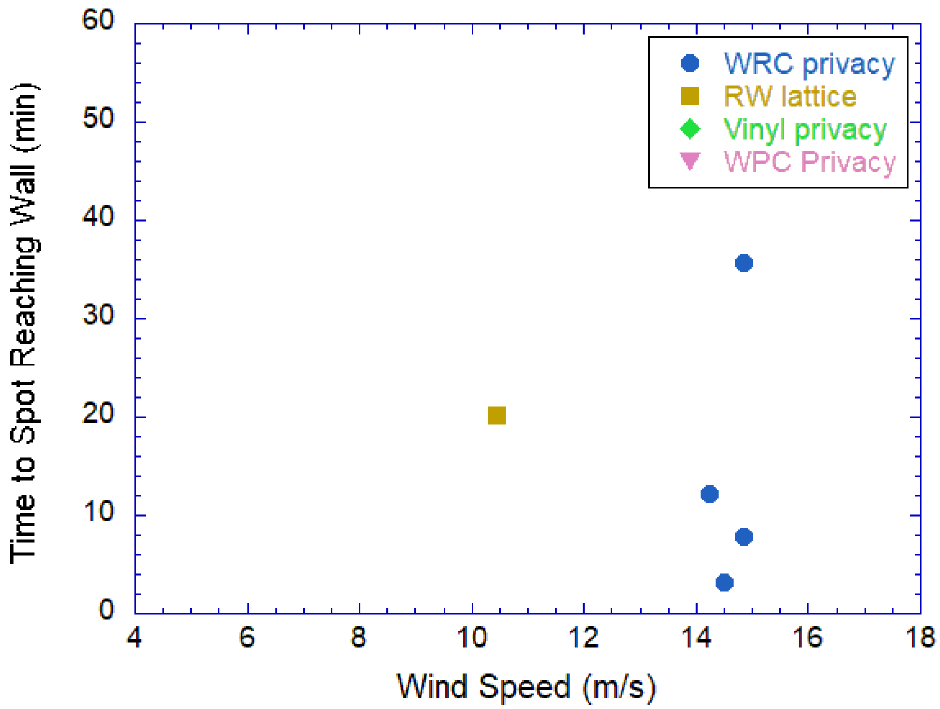

Fig. 67. Time to ignition of first spot fire to put flames against the wall vs. wind speed for experiments with fence only.

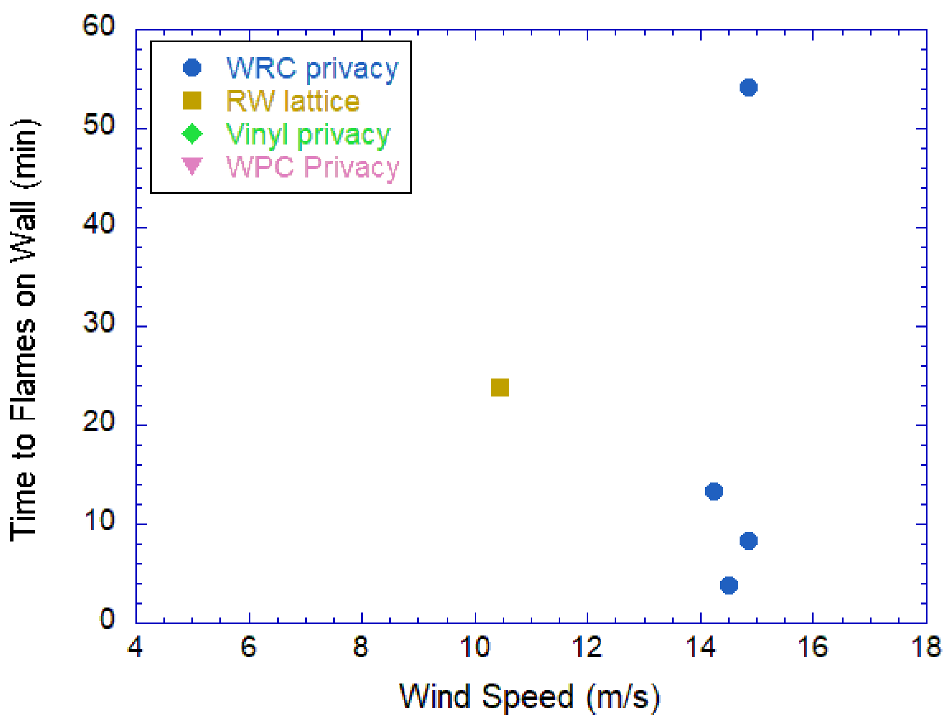

Fig. 68. Time to flames reaching the wall vs. wind speed for experiments with fence only.

4.2.5. Summary

Because the fire behavior is so different, this summary will discuss wood/vinyl fences and wood-plastic composite fences separately.

It may be difficult to keep a wood fence sufficiently clear of fine combustible materials to achieve the slow-growth fire behavior described in this section. Even without mulch, windblown debris such as leaves and pine needles may accumulate during a WUI event.

For the set of experiments performed in this study, the absence of fine combustibles resulted in the following findings for wood fences:

Fire spread behavior. The fire spread over wood fences in the absence of fine combustibles is generally slow.

- The fence combusts slowly from the point of ignition.
- The burning process is characterized by glowing combustion and occasional brief flaming.
- The stringer provides a continuous path for the fire aligned with the wind. If the stringer transitions to flaming combustion, fire spread along the fence is accelerated.
- The fire spread behavior does not depend on the wind flow field or on separation distance from the shed.

Type of fence. The glowing combustion typical of wood fences without mulch is affected by physical connection and gaps.

- Western redcedar privacy fences burn slowly with glowing combustion and occasional small flames near the point of ignition. The gap between boards may slow but not arrest horizontal flame spread. Stringers provide a continuous pathway for the fire.
- Redwood lattice fences burn slowly with glowing combustion and occasional small flames near the point of ignition. Diagonal slats direct the flame spread. Stringers provide a continuous pathway for the fire in the direction of wind flow.
- Vinyl privacy fences result in limited fire exposures and low or no fire spread under the tested wind conditions.

Firebrand spotting. Wood fences produce large firebrands (up to 14 cm × 20 cm) from pieces of the fence breaking off and small firebrands (on the order of millimeters) from glowing combustion.

- Large firebrands may be generated by detachment of pieces of the fence. Under the conditions of these experiments, the large firebrands remained on the ground close to where they fell. They were able to ignite other combustible objects that contacted them.
- Although uncommon, spot fires ignited by small firebrands from wood fences can occur, especially in high winds. A spot fire was seen to ignite close to the structure in as little as 3 min after the wind machine was turned on.

Wood-plastic composite fences. Even in the absence of fine combustibles, limited preliminary data indicates that ignition of wood-plastic composite fences can result in high intensity fire behavior. The fire behavior of this category of fence needs to be studied further; upcoming experiments are planned at NIST.

- The entire fence can become engulfed in flames.
- The top and bottom frames can distort and release burning boards, which fall and can extend the flaming region 1.83 m (6 ft) to each side of the fence. Softened boards can fall forward in the wind, extending the flaming region beyond the fence as well. This is a life safety hazard for people attempting to egress near the fence.
- Fires in the target mulch bed next to the shed appear to have been ignited by radiation and direct flame contact rather than by firebrands.
- Smoke coming from the roof of the shed after the experiment indicates that a separation distance of 1.83 m (6 ft) between a fence and a structure is inadequate to prevent ignition. A long fence will increase the fire exposure by adding to the available fuel and linear extent, and other factors such as sloping terrain will also add to the hazard.

4.3. Fence and Mulch Experiments

A fence is not typically isolated from fine combustible materials. At its base there may be grass, mulch, vegetative plantings, or accumulated leaves or needles. Dry leaves and other lightweight materials may be moved around by the wind. Accumulated debris can become compressed by the action of wind and rain, fixing the potential fuel in place as a target for ignition. When a fence is in close contact with the ground, it can be difficult to keep the area near the bottom of the fence clear of combustible materials.

In this set of experiments, fences were erected over a bed of mulch in a variety of combinations. The results not only demonstrate the fire behavior under the specific conditions tested but also provide an understanding of the general case in which fine combustible materials lie along the base of a combustible fence. As listed in Table D.3, Table D.4, and Table D.5 of Appendix D, a variety of fences, including western redcedar privacy and good neighbor fences, redwood and pine lattice fences, and vinyl privacy fences were tested in combination with shredded hardwood mulch. Western redcedar privacy fences were combined with other mulches as well, including pine bark mulch and pine straw mulch. Some experiments were performed with shredded hardwood mulch at half the usual thickness (2.5 cm compared to the usual 5 cm) to observe the effects of mulch thickness on fire behavior.

The details of each experiment, including parameter values, images, flame spread data, wind plots, and summary values, are presented in Appendix H. The data analysis focuses on the fire spread along the fence, which was assisted by the progress of the fire along the mulch bed.

4.3.1. Example

Figure 69 shows a sequence of video images from an experiment (Test A-29) in which a western redcedar fence was erected above a bed of shredded hardwood mulch. In this experiment, the wind speed was in the medium range, averaging 9.6 m/s (21.5 mi/h) along the centerline, and the separation distance between the end of the fence and the shed was 1.83 m (6 ft). After the fan was turned on, marking the start of the experiment at t = 0 min, the fire rapidly (within 1 min) reached the end of the fence closest to the shed. The burn pattern on the fence downwind from the ignition area at t = 1 min shows that the initial progress of the fire remained below the bottom stringer. At later times, the charred area extended above the bottom stringer in the part of the fence panel closest to the shed, reaching a maximum height a few boards away from the end of the fence. This pattern will be related to the wind field in Section 4.3.2.2. The fire remained well below the middle stringer until the spot fires reached the wall, ending the experiment.

On a smaller scale, the upward fire spread was fastest in the narrow gaps between boards, as indicated by the char marks and by the increasing gap widths in the images at t = 3 min and t = 5 min. Within the gaps, the progression of the fire was aided by radiative and convective heat transfer between the edges of the boards. The fire was also shielded from the horizontal winds, which otherwise interfere with upward fire spread.

The first sign of smoke in the target mulch bed next to the shed occurred shortly after t = 2 min. By t = 3 min, four spot fires were visible along the outer edge of the target mulch bed. By t = 4 min, at least two more spot fires had ignited closer to the shed wall, including the spot fire that was the first to reach the wall at about t = 4 min 45 s. The final image in Fig. 69 shows the spot fires at t = 5 min, shortly before the experiment ended and the fan was turned off.

This experiment may be compared with the experiment with the same fence in the absence of mulch in Fig. 57, which was performed under similar conditions. The most obvious change in the fire behavior when mulch has been added to the base of the fence is the much faster progress of the fire. Contributing factors to this result include the continuous pathway provided by the mulch and the high temperatures of the fire at the base of the fence.

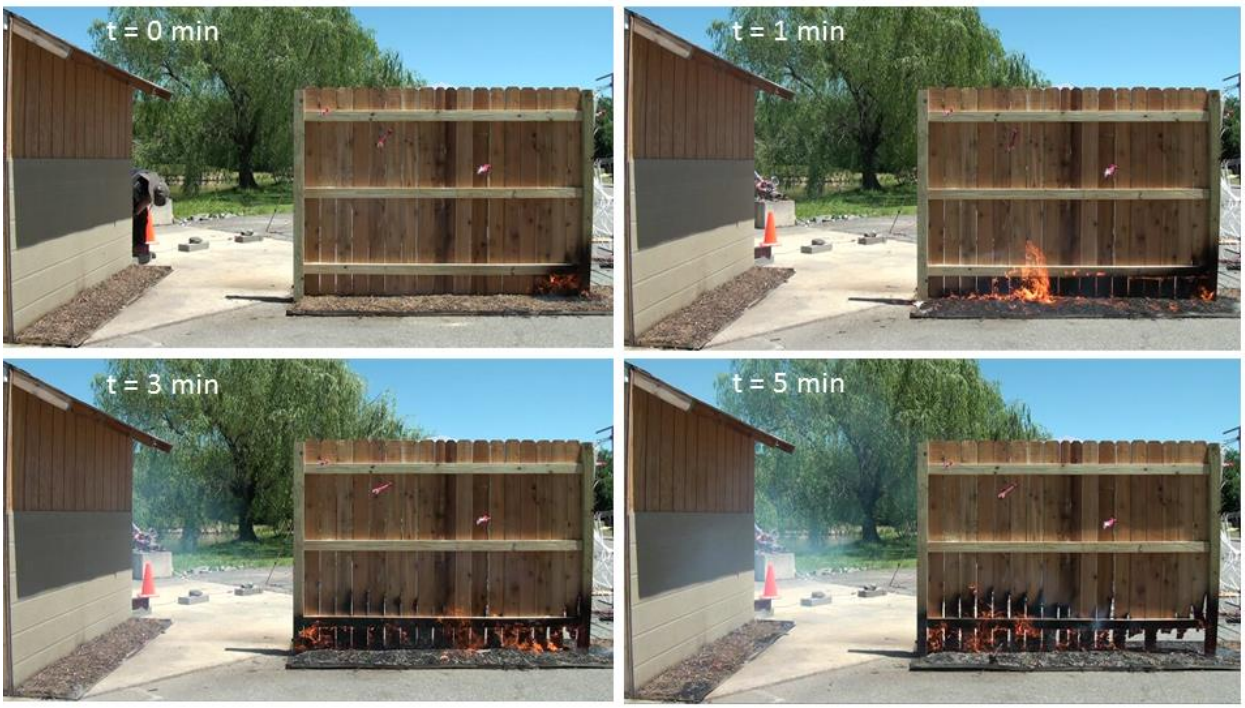

Fig. 69. Image sequence from video of western redcedar fence combined with shredded hardwood mulch, at medium wind speed and 1.83 m (6 ft) separation distance from structure [Test A-29].

Figure 70 plots the location of the charred point on the fence that is closest to the shed wall as a function of time. As an aid to orientation, the horizontal lines mark the inner and outer edges of the posts at each end of the fence. This plot shows a rapid progress of the flame front during the first minute of the experiment, with a maximum flame spread rate of 3.6 m/min ± 0.2 m/min.

The plot can be compared with medium wind speed plots in Fig. 33 (b), which show experiments under the same conditions with shredded hardwood mulch alone. The interaction with the fence more than halved the time for the fire to reach the end of the mulch bed. Combining a fence with mulch led to a fire that is more intense and moves more rapidly than for either fuel on its own.

The black error bars in Fig. 70 show the expanded uncertainty (95 % confidence level) for each of these points. As shown in the uncertainty analysis for fences in Appendix A.4.2 and listed in Table A.6, the expanded uncertainty for horizontal flame front location was ±4.8 cm.

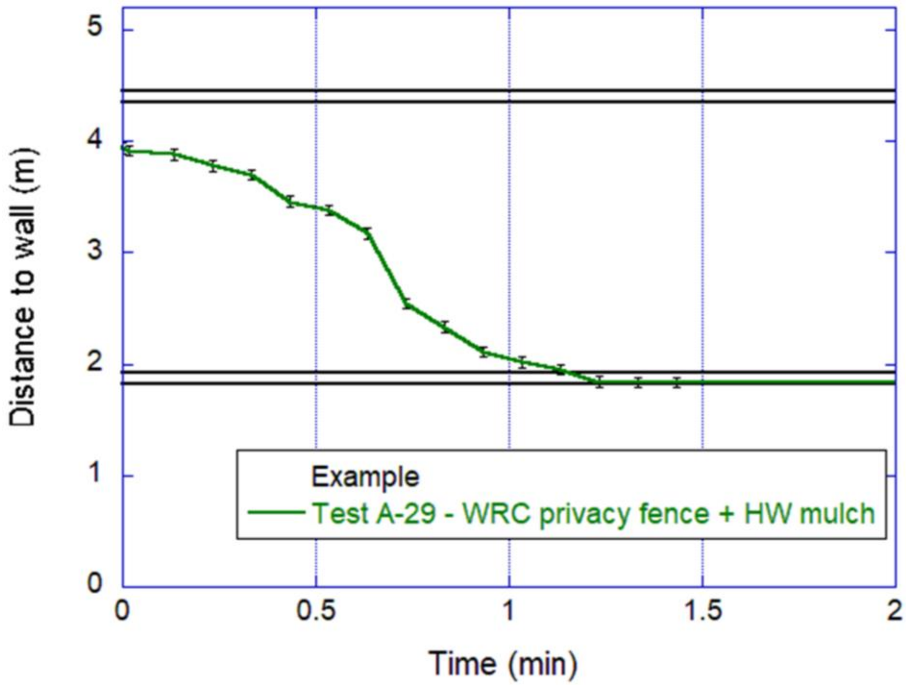

Fig. 70. Flame front location vs. time for Test A-29, showing expanded uncertainty.

The time progression of the burning privacy fence is shown in Fig. 71, where the outlines of charred regions on the fence are plotted at five equal time intervals after the fan was turned on and ending at the end of the test. The light brown lines on this plot outline the posts on both ends of the fence and the three stringers. This plot shows the rapid progress of the flames from the ignition area on the lower right to the end of the fence closest to the shed. It also shows how the lower and middle stringer slowed the upward spread of the fire. Similar profiles are given in Appendix H for all experiments involving fences.

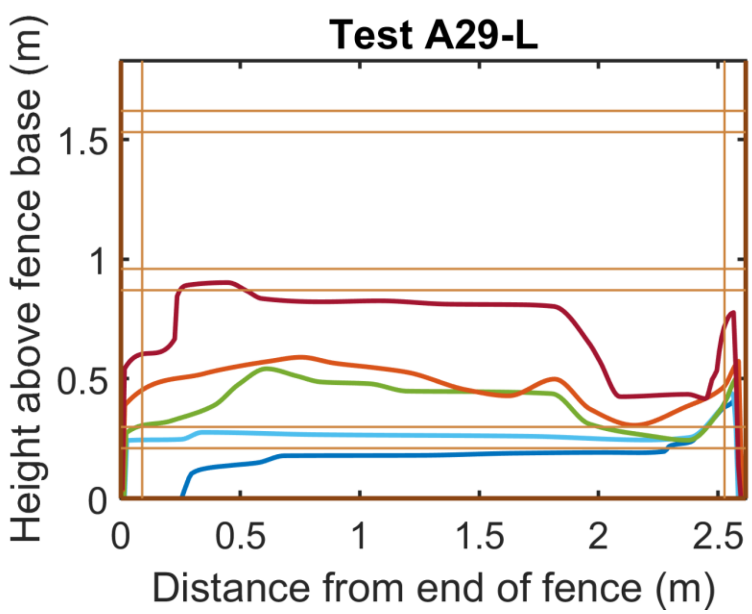

Fig. 71. Char patterns on western redcedar privacy fence during Test A-29, from the left camera view (ignition at the lower right).

The uncertainties for the plots in Fig. 71 are described in the uncertainty analysis for fences in Appendix A.4.2 and listed in Table A.6.

4.3.2. Fire Spread Behavior

This section describes the observed effects of wind speed and separation distance on fire behavior for the combinations of fence and mulch. In other experiments, raising the height of a privacy fence over the mulch bed was studied as a possible way to mitigate the fire spread. Experiments that added a second fence panel to the end of the fence setup were conducted to determine whether a longer fence would make a difference in the results.

4.3.2.1. Effects of wind speed

Experiments at all three wind speed levels (low, medium, and high) and all four separation distances (0 m, 0.30 m, 0.91 m, and 1.83 m) were performed on western redcedar privacy fences and on redwood lattice fences, with shredded hardwood mulch at the base of the fence in each case. Characteristic fire behaviors were sought by looking for common features of fences and mulch under similar conditions and trends with changes in key variables.

Figure 72 compares images at the three wind speed levels from experiments performed on privacy and lattice fences at 1.83 m (6 ft) separation distance from the shed. Similarities in the progress of the charred area on the fence were apparent between the two fence types. In every case, the fire burned rapidly to the end of the mulch bed and fence. The char pattern near the end of the experiment was highest for the lowest wind speed, reflecting both the tendency of higher wind speeds to keep flames closer to the ground and the longer time duration for the experiment. As will be discussed in Section 4.3.5, ignition of spot fires was a function of wind speed, so that a spot fire under low wind speed conditions generally required more time to reach the wall and end the experiment.

In these experiments, the stringers tended to slow the upward progress of the char by limiting the flame height on one side of the fence. The fence often burned below the lowest stringer for a while before the fire continued to spread upwards. In an actual WUI fire, stringers may also enhance the fire spread, since they provide locations for firebrands to lodge and ignite new fires on the fence.

For this study, none of the experiments were performed in the presence of vegetation. Lattice fences in particular are typically used in a garden setting, with plants nearby or growing on them. This vegetation would provide another source of fuel to ignite the fence and encourage flame spread.

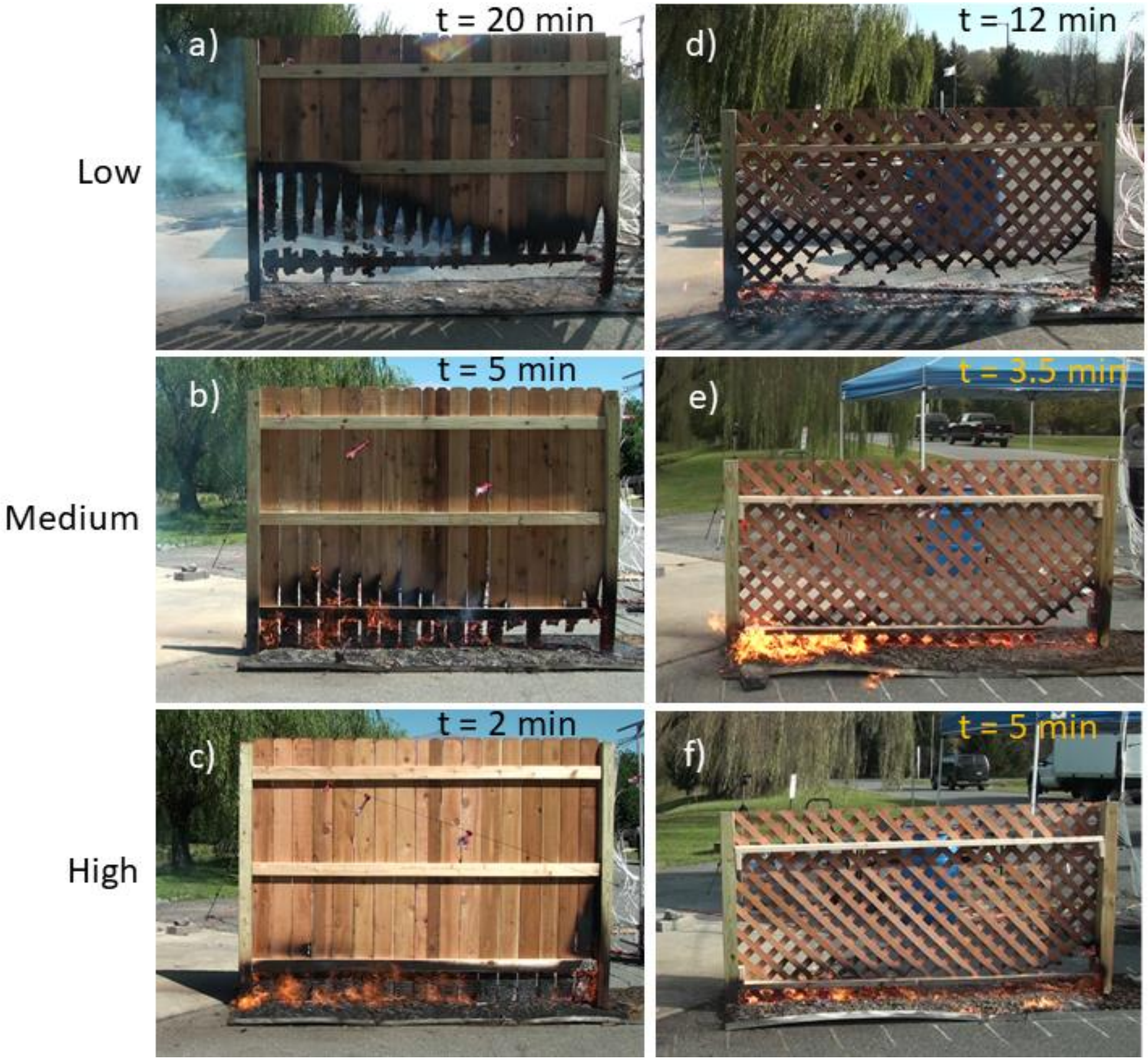

Fig. 72. Burn patterns for low, medium and high wind levels for WRC privacy fences: a) Test A-102, b) Test A-29, and c) Test A-31 and RW lattice fences: d) Test A-107, e) Test B-79, and f) Test B-85.

The positions of the char front on the fence closest to the shed wall for these experiments are plotted as a function of time in Fig. 73. The plots show a general trend of faster flame spread with increasing wind speed, with the flame front taking considerably longer to reach the end of the fence and mulch bed for low wind speeds. For medium and high wind speeds, the relationship is less clear, with little distinction between these plots for privacy fences and flame spread slightly faster for medium than high wind for the lattice fence experiments.

Figure 73 also indicates that for each wind speed the flame front proceeded more rapidly along the western redcedar privacy fence than the redwood lattice fence, at least for a separation distance of 1.83 m (6 ft). This was not generally the case, however, as will be shown in the next section. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

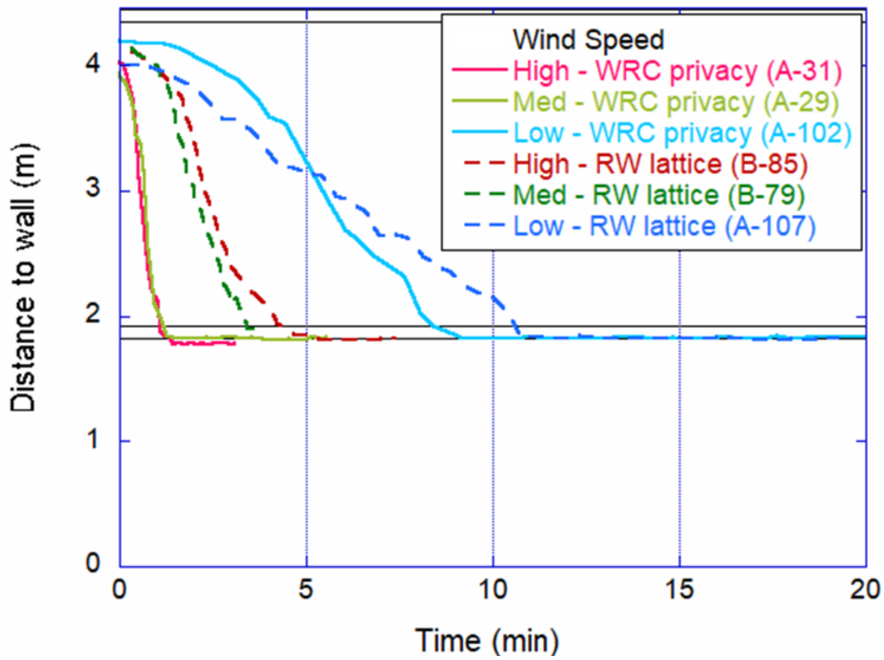

Fig. 73. Effects of wind speed on flame front location vs. time for WRC privacy fences and RW lattice fences shown in Fig. 72.

More detailed information for each of these experiments, including char distance, height, and profiles vs. time, can be found in Appendix H.

4.3.2.2. Effects of separation distance

Assembling images from experiments performed under similar wind conditions but different separation distances can provide insights on how a fence with mulch beneath behaves in fire as a function of distance from a nearby structure. In Fig. 74, the burn patterns at four separation distances are shown for western redcedar privacy and redwood lattice fences combined with shredded hardwood mulch. All experiments in this figure were carried out under low wind conditions. The wind flow is directed at the structure – note that the results will be different for other orientations of the structure with respect to the wind.

The effects of the vortex at the base of the shed that was described in Section 3.3.2 are apparent in the burn patterns for both privacy and lattice fences in Fig. 74. The fences that abut the shed wall, with zero separation distance, are char-free within about 0.5 m (1.6 ft) of the wall. Just upwind from the unburned region, the char is at its maximum height away from the ignition area. This shows the effects of the wind profile, with the flow from the fan rising as it approaches the shed wall and then separating into winds that form the vortex at the base of the shed and winds that go over the roof.

As the fence was positioned farther from the shed wall, the char pattern demonstrating the influence of the wind field moved downwind along the fence. At separation distances of 0.91 m and 1.83 m (3 ft and 6 ft respectively), the effects of the vortex were no longer seen, but the shape of the char continued to reflect the upward tilt of the flow. Similar effects from the vortex and local wind direction were seen for medium and high wind speeds (not shown), although the maximum height on the fence was lower under these conditions.

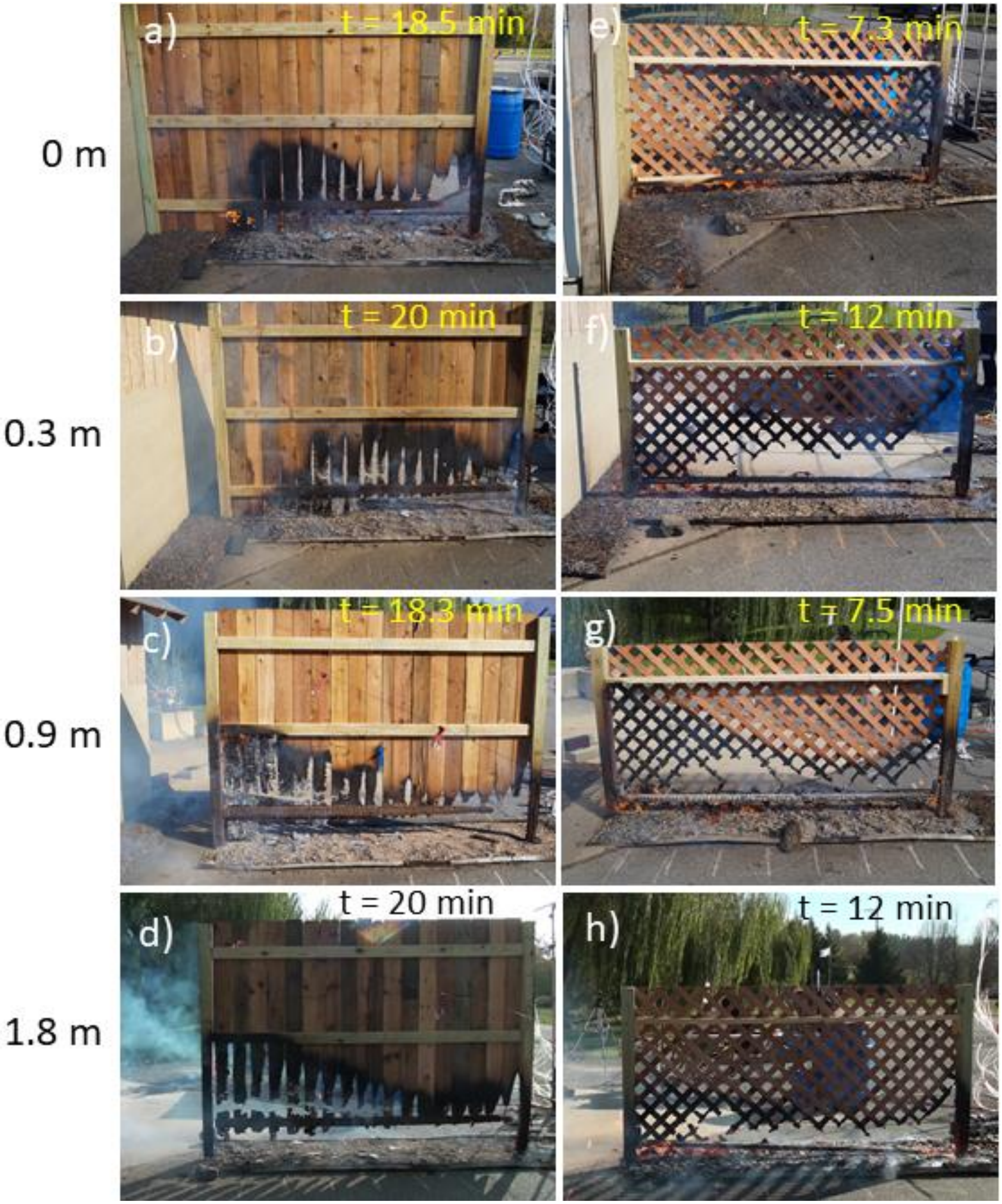

Fig. 74. Burn patterns at low wind speed for separation distances of 0 m, 0.30 m (1 ft), 0.91 m (3 ft), and 1.83 m (6 ft) for WRC privacy fences: a) Test A-106, b) Test A-105, c) Test A-95, and d) Test A-102 and RW lattice fences: e) Test B-66, f) Test B-74, g) Test B-59, and h) Test A-107.

Figure 75 compares the plots of char progress as a function of time for all experiments shown in Fig. 74. The horizontal lines in this plot mark the end of the fence and mulch bed closest to the shed wall for the four separation distances (the line for zero separation is the x-axis). Looking at the privacy fence (solid lines) and lattice fence (dashed lines) results separately, flame spread down the fence was generally faster for larger separation distances and slower for separation distances of 0 m and 0.30 m (1 ft). The lattice fence experiment at 1.83 m (6 ft) separation was an exception to this, with a flame spread rate comparable to that for small separation distances. Part of the increase in flame spread rate over the fence with increasing separation distance may be related to the distance from the wind machine; wind profiles are discussed in Appendix C. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

For separation distances of 0.91 m (3 ft) and smaller, the flame spread over the lattice fence was faster than that over the privacy fence. This is the opposite trend from that found in Fig. 73, showing the difficulty of reaching conclusions based on a small number of experiments in the presence of variables that could not be controlled in the test environment (including ambient winds, temperature, and humidity). In all cases, placing mulch under the fence panel resulted in steady progression of the fire along the fence, reaching the end of the panel in minutes.

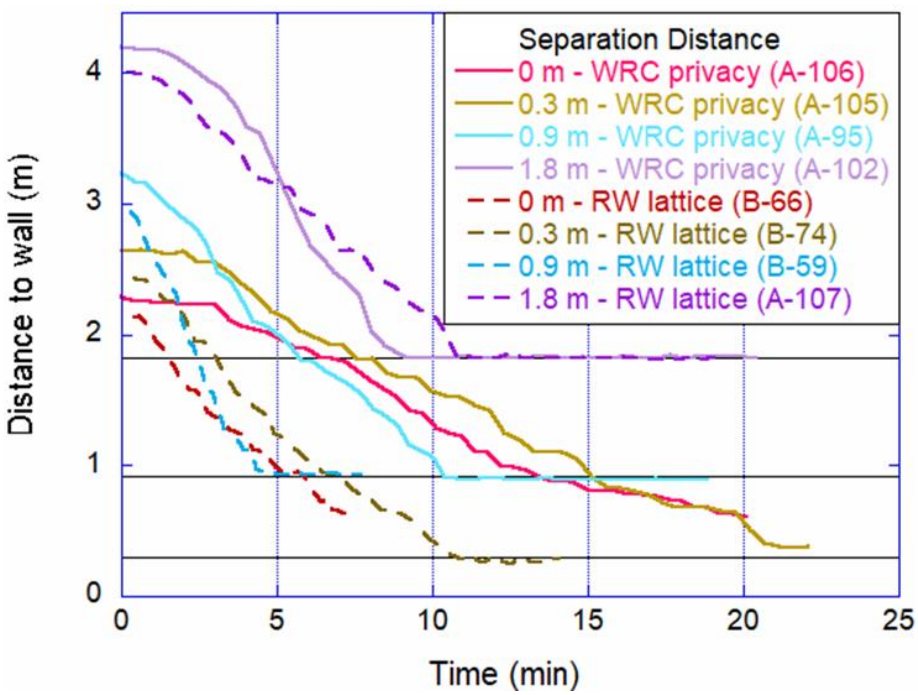

Fig. 75. Effects of separation distance on flame front location vs. time for WRC privacy fences and RW lattice fences at low wind speed.

Note that the wind pattern will change for a different wind direction or geometry of the fence with relationship to the structure. The pattern of charring is likely to be different under different conditions.

More detailed information for each of these experiments, including char distance, height, and profiles vs. time, can be found in Appendix H.

4.3.2.3. Effects of fence length

The standard fence arrangement for this study involved a single fence panel between two posts. To determine how fence length affects the fire behavior, two experiments were carried out with a set of two western redcedar privacy fence panels placed end-to-end, with shredded hardwood mulch at the base. The first experiment, Test C-19, was arranged in the usual manner, with a 1.83 m (6 ft) separation distance from the shed downwind. In the second experiment, Test D-3, the shed was removed completely. Figure 76 shows the two configurations. Both experiments were performed at low wind speeds.

Fig. 76. Set-up for two-panel length western redcedar fence combined with shredded hardwood mulch a) with and b) without a structure downwind [Tests C-19 and D-3, respectively].

Figure 77 shows a video image of Test C-19 at 45 min after the fan was turned on, shortly before the experiment was ended. From the viewpoint of this camera, the wind machine was to the right of the fence and the shed was to the left. The fence was ignited at the lower right corner. This image can be compared to Fig. 78, which shows a single panel length experiment under the same conditions. Note that the latter fence also appeared in the previous section in Fig. 74 (d), where it was used to illustrate char patterns at different separation distances. The progress of the char front toward the shed for these two experiments is plotted as a function of time in Fig. 79.

The char pattern for the downwind panel of the two-panel length fence was consistent with that in the single panel experiment, indicating that a single fence panel was sufficient for learning about fire behavior close to the structure. As seen in Fig. 77, the fire stayed below the lowest stringer as it progressed along the first panel of the double panel fence from the point of ignition. Comparing Fig. 77 and Fig. 78, the flame spread over the panel closest to the shed is similar for single and double panel lengths. The char pattern rises as it approaches the post to the left, reflecting the rise in the air flow approaching the shed. The char never exceeds the lowest stringer on the upwind panel and remains below the center stringer on the downwind panel, although singe marks are observed along the length of this stringer. The upward spread of fire between boards is especially noticeable on the lee side of the center post of the double panel fence, where the height of the char pattern exceeds that at any other point along the fence.

Fig. 77. Two-panel length western redcedar fence combined with shredded hardwood mulch, at low wind speed and 1.83 m (6 ft) separation distance [Test C-19], at t = 45 min.

Fig. 78. Single panel western redcedar fence combined with shredded hardwood mulch, at low wind speed and 1.83 m (6 ft) separation distance [Test A-102], at t = 20 min.

Figure 79 shows that it took about 25 min after the fan was turned on for the flame front to reach the center post. The fire slowed as it approached this point. After passing the center post, the fire took about 12 min to reach the post closest to the shed. This compares to about 9 min for the fire on the single panel fence to move from the point of ignition to the same post. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

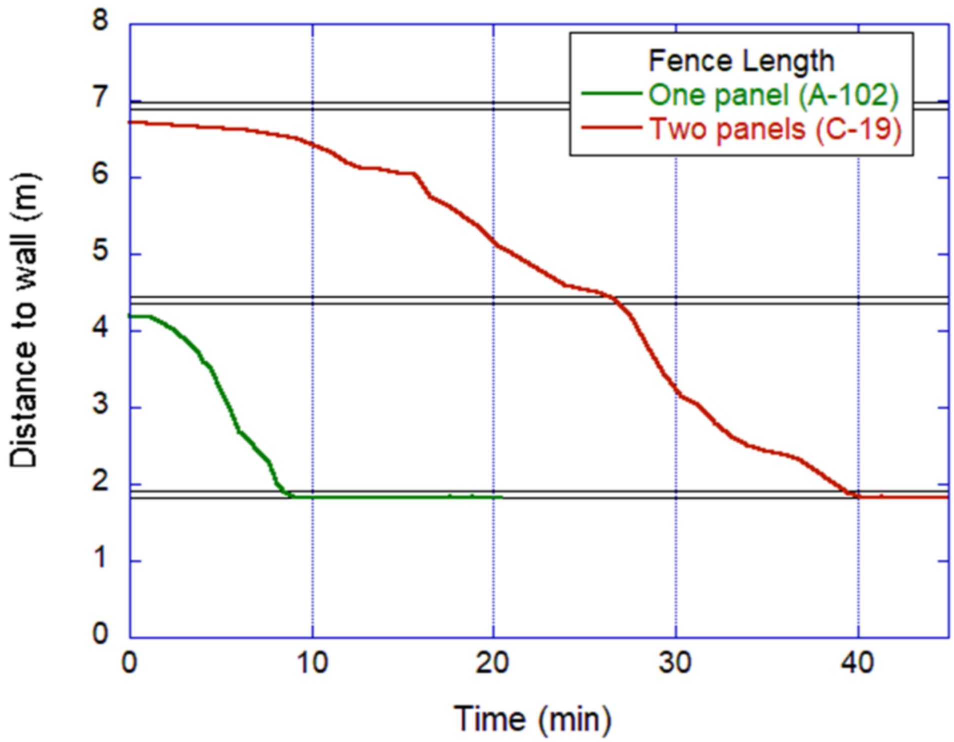

Fig. 79. Effects of fence length on flame front location vs. time at low wind speed.

An image from Test D-3, in which the shed was removed, is shown in Fig. 80. Compared to Fig. 77 showing the case with the shed in place, the char pattern is generally higher along the length of the two panels, although it remains below the center stringer. The char reaches its highest point at the same place for both experiments – on the lee side of the center post.

Figure 81 compares the progress of the flame front downwind as a function of time for both two-panel length experiments. The flame front progressed considerably slower down the fence when a structure was present downwind, possibly due to local recirculation effects. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

Fig. 80. Two-panel length western redcedar fence combined with shredded hardwood mulch without a structure downwind, at about t = 12 min [Test D-3].

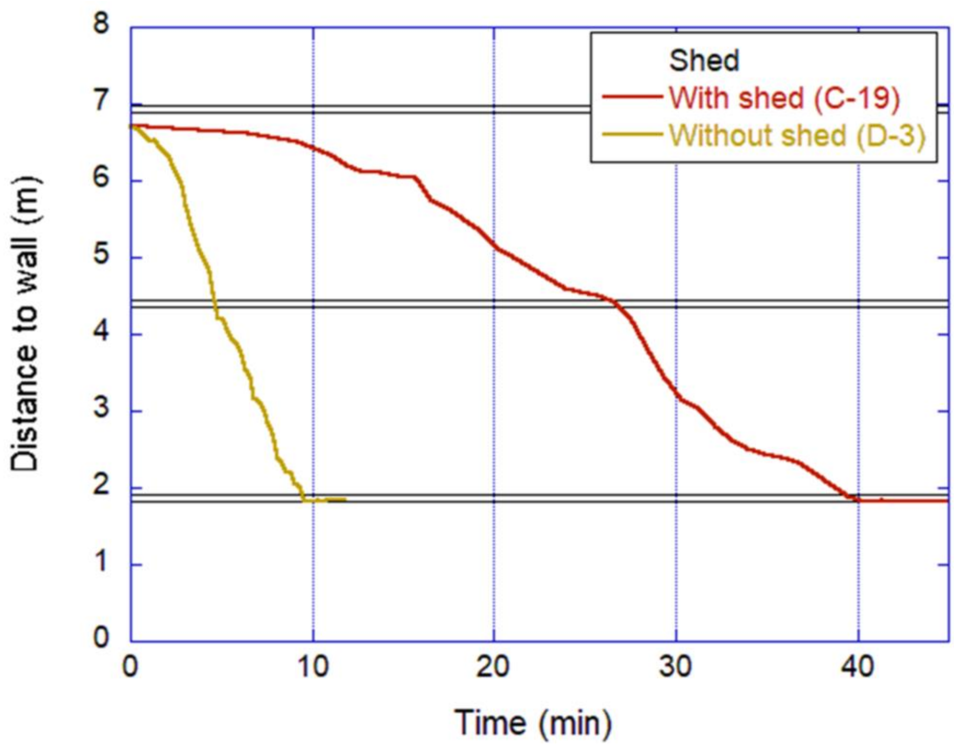

Fig. 81. Comparison of two-panel length fences with and without a structure downwind.

4.3.2.4. Effects of height above mulch bed

Mulch beneath the fence significantly changes the fire behavior. Without a fine combustible fuel at the base, fences burn very slowly beyond the point of ignition, as discussed in Section 4.2. With a mulch bed below, the fire progresses from one end of a fence panel to the other in minutes. This suggests that one potential mitigation technique might be raising the fence panel to a height that allows the fire on the mulch bed to decouple from the fence.

A series of experiments was carried out to look at this option. Photographs in Fig. 82 show the configurations before ignition, in which western redcedar privacy fence panels were attached to the end posts with clearances from the shredded hardwood mulch bed ranging from 0 cm to 15.2 cm. The fence/mulch combinations in cases (a) through (d) were ignited using gas burners on each side of the fence. In case (e), a ring burner (described in Section 2.6) was positioned on its side to the left of the post. This method placed more fire directly on the fence panel during ignition. Experiments were performed under low wind speeds (5 m/s to 9 m/s) at a separation distance of 1.83 m (6 ft) from the shed wall.

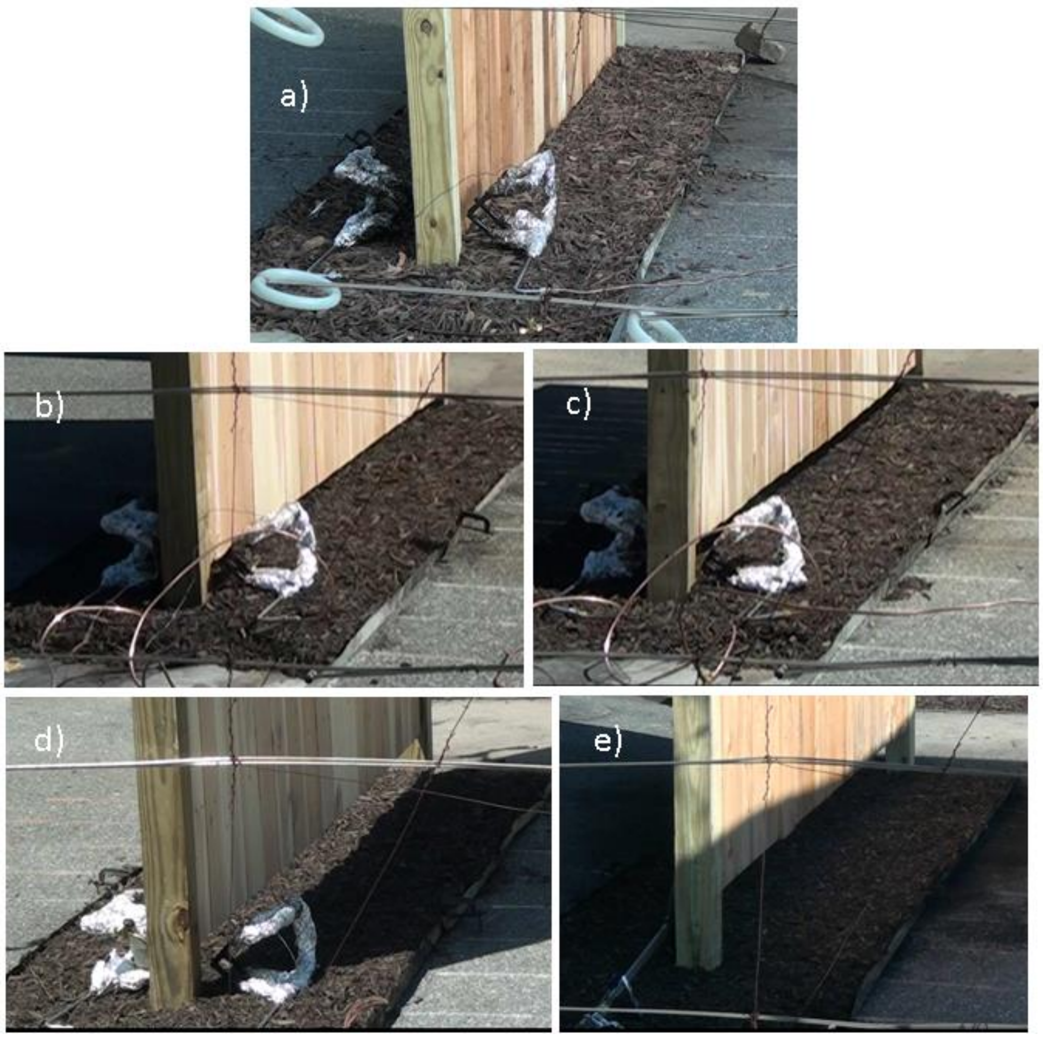

Fig. 82. Setups for western redcedar privacy fence panels at a height above the shredded hardwood mulch pan of a) 0 cm [Test A-102], b) 5.1 cm (2 in) [Test C-10], c) 7.6 cm (3 in) [Test C-11], d) 10.2 cm (4 in) [Test C-14], and e) 15.2 cm (6 in) [Test C-28].

Figure 83 shows the char pattern late in each experiment, and Fig. 84 plots the location of the flame front with time. With the privacy fence in direct contact with the top of the mulch bed in case (a), the mulch and fence interacted to generate a burn pattern typical of this combination. (Images from Test A-102 were previously displayed in Fig. 74 (d) and Fig. 78.)

As shown in Fig. 84, raising the fence panel more than 5.1 cm (2 in) above the mulch bed slowed the involvement of the fence in the fire. For cases (b) and (c), the fire did not rise significantly above the lowest stringer during the experiment. In case (d), with the privacy fence lifted by 10.2 cm (4 in) above the mulch, only the bottom surfaces of the panel boards and the area around the burner ignition were observed to char until 24 min into the test. At this time the bottom stringer ignited, followed by the board segments below the stringer. In case (e) the fence burned only slowly away from the point of ignition, duplicating the fire behavior that was observed in Section 4.2 in the absence of mulch. This indicated that the fence panel was indeed decoupled from the mulch along its length when it was raised 15.2 cm (6 in) above the mulch bed.

Fig. 83. Comparison of results from privacy fences raised above the hardwood mulch pan by a) 0 cm [Test A-102], b) 5.1 cm (2 in) [Test C-10], c) 7.6 cm (3 in) [Test C-11], d) 10.2 cm (4 in) [Test C-14], and e) 15.2 cm (6 in) [Test C-28].

The uncertainties for the plots in Fig. 84 are described in the uncertainty analysis for fences in Appendix A.4.2 and listed in Table A.6.

These results demonstrate a trend of fire behavior with fence height above a mulch bed under specific conditions of wind and ignition and are not intended to recommend a specific fence height. Different types of fence and mulch may behave differently. It should also be noted that attaching a wire screen below a raised fence to deter animals from going in or out of the yard would reduce the value of this approach, since leaves and other combustible materials could then collect at the base of the fence.

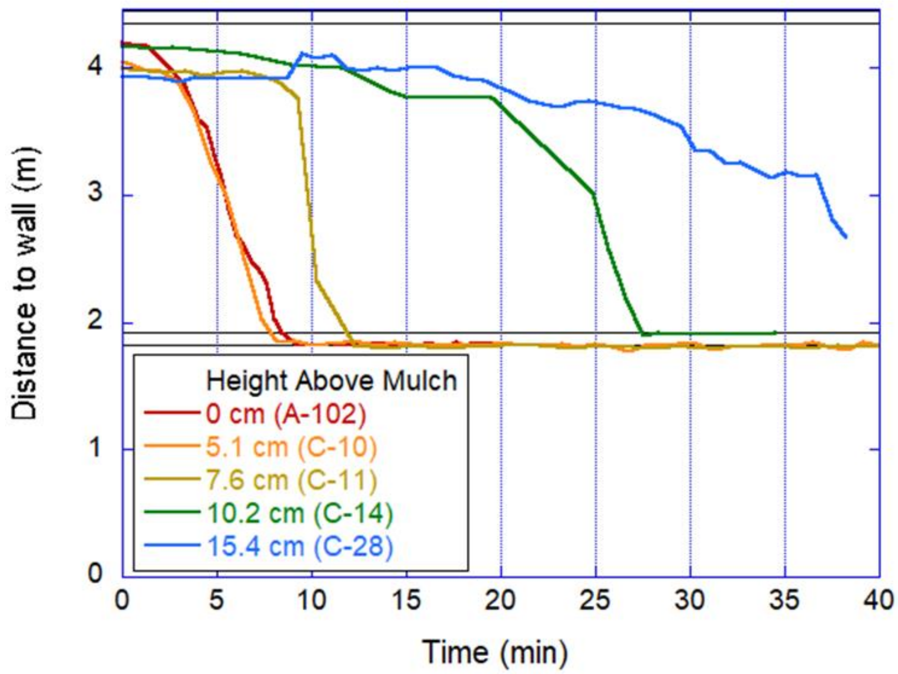

Fig. 84. Effects of height above hardwood mulch bed on flame front location vs. time for WRC privacy fences shown in Fig. 83.

4.3.3. Type of Fence, combined with HW Mulch

This section compares the fire behavior for three types of privacy fences (new and aged western redcedar and vinyl), two types of lattice fences (redwood and pine), western redcedar good neighbor fences, and a wood-plastic composite fence. All were combined with shredded hardwood mulch beneath the fence. Comparison with the fence experiments without mulch from Section 4.2 shows the impact of having fine combustible materials beneath the fence.

4.3.3.1. Western redcedar privacy fence

The fire behavior of western redcedar privacy fences combined with shredded hardwood mulch was studied under a variety of conditions. A number of these experiments have been presented already. A video image from the same experiment used as an example in Section 4.3.1 is shown in Fig. 85. At this time, 4.5 min after the fan was turned on, the flames have covered the full length of the fence panel and several spot fires have ignited in the mulch bed next to the shed. This image shows the typical char pattern shape at a 1.83 m (6 ft) separation distance, with increasing height toward the end of the fence near the shed that likely reflects the wind field, as discussed in Section 4.3.2.1. The charred area remains below the center stringer. Char marks and increased gap widths show that fire spreads upwards between the boards as well as over their surfaces. The stringers provide a continuous connection from board to board, and the bottom of the lowest stringer is subjected to the heat from the fire in the mulch bed.

Fig. 85. WRC privacy fence with HW mulch at medium wind speed, at about t = 4 ½ min [Test A-29].

In Fig. 86, plots (a) through (d) show the flame spread as a function of time for experiments at the four separation distances studied. As described previously, the flame front position was measured as the closest distance to the shed of the char pattern on the fence. Comparing the experiments performed under the same nominal conditions (same wind speed and separation distance), it's clear that there was considerable variation among experiments. However, two trends can be observed. First, increasing the wind speed generally resulted in faster flame spread along the fence. This was most apparent for low wind speed conditions, under which the flame front could take twice as long to reach the end of the fence as under medium wind speed conditions. Second, the flame spread was generally faster (shorter time to reach the end of the fence) at longer separation distances from the shed. These two trends have been discussed at greater length in Sections 4.3.2.1 and 4.3.2.2, respectively. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

The addition of a western redcedar privacy fence to a shredded hardwood mulch bed significantly increased the flame spread rate, as can be seen by comparing Fig. 86 to the plots for hardwood mulch alone in Fig. 32 and Fig. 33. In many of the experiments for fence plus mulch at separation distances of 0 m and 0.91 m (3 ft), the fire reached the end of the mulch bed in half the time taken for the mulch alone. With the fence present, the fire did not slow as much as it approached the wall of the structure.

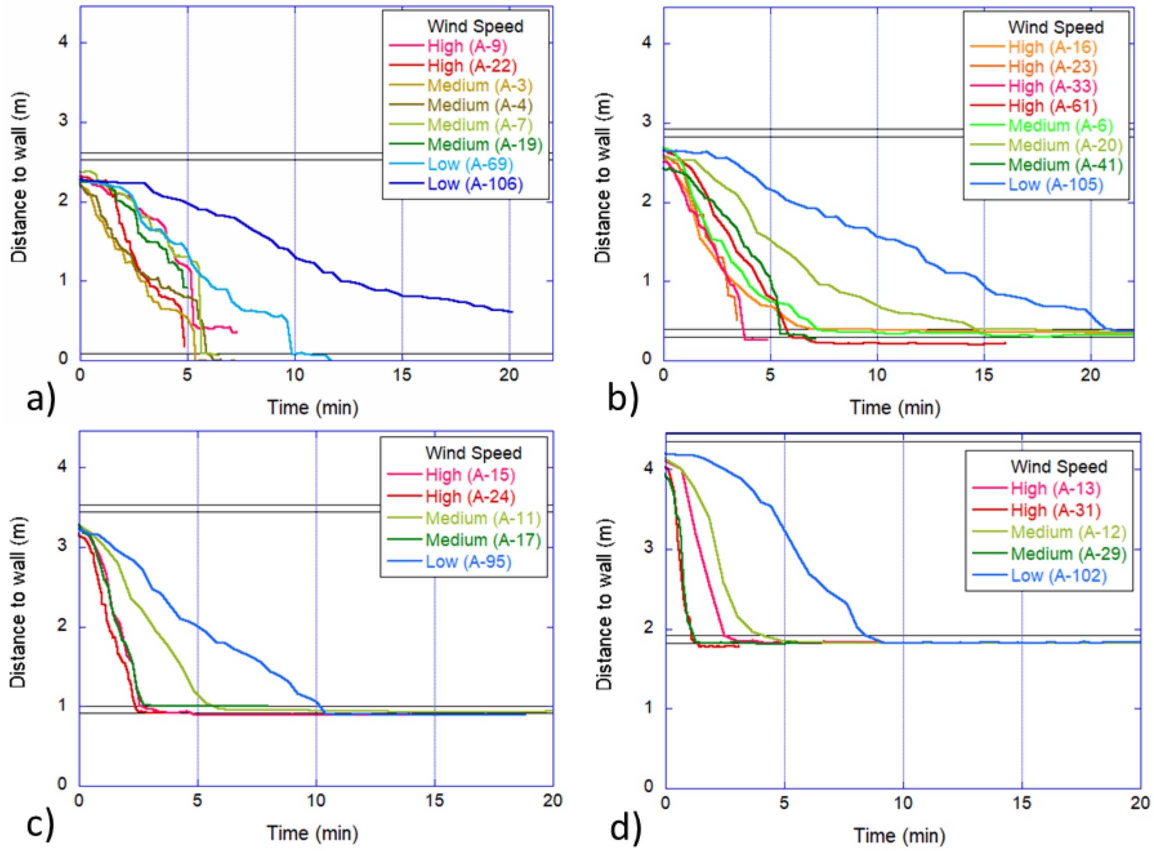

Fig. 86. Effects of wind speed on flame spread for WRC privacy fence combined with HW mulch at separation distances of a) 0 m, b) 0.30 m (1 ft), c) 0.91 m (3 ft), d) 1.83 m (6 ft).

4.3.3.2. Aged privacy fence

Experiments with mulch at all three wind speeds were performed on the aged western redcedar (presumed) privacy fences described in Section 2.5.1, at a separation distance of 1.83 m (6 ft). The results were similar to those for new western redcedar privacy fences, as can be seen by comparing Fig. 87 to Fig. 85. The fires on both new and aged WRC fences remained well below the center stringer. By the time of this photo just after t = 5 min, all of the fence boards had burned below the first stringer, releasing large and small firebrands in addition to firebrands from the mulch. One of the large broken-off pieces of fence can be seen on the ground between the fence and the target mulch bed. Several spot fires ignited in the target mulch bed between t = 4 min and t = 5 min, as can be observed from the smoke.

Flame spread over the aged privacy fences is plotted in Fig. 88. For these three experiments, the flame spread rate increases with increasing wind speed. At a separation distance of 1.83 m (6 ft) from the shed, the time for the fire to travel from the ignition point to the far end of the fence panel is 2 min for high wind speeds and less than 8 min for low wind speeds. This agrees well with the results for new WRC privacy fences plotted in Fig. 86 (d). The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

Fig. 87. Aged privacy fence, at medium wind speed, at t = 5.2 min [Test C-25].

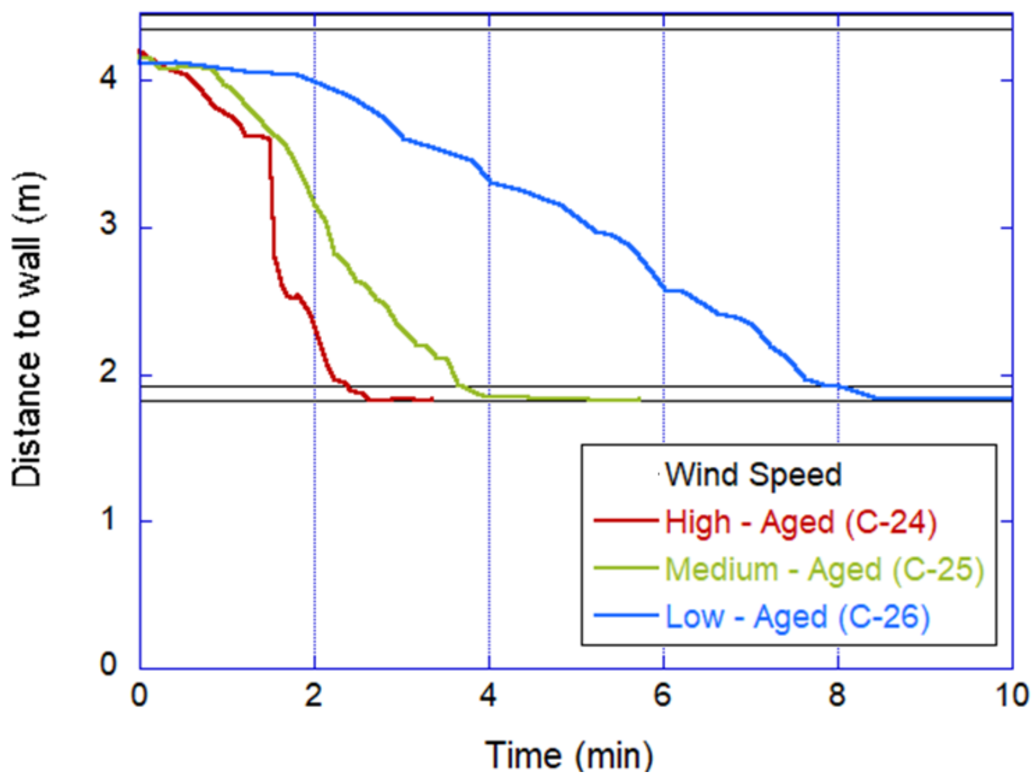

Fig. 88. Effects of wind speed on flame spread for aged privacy fence/HW mulch at separation distance of 1.83 m (6 ft).

4.3.3.3. Vinyl privacy fence

The fire behavior of a vinyl privacy fence with shredded hardwood mulch at its base differed strongly from that of the same fence without mulch. With mulch, the fire reached the shed wall within minutes.

Figure 89 provides a sequence of images showing phenomena observed during this experiment, in which there was zero separation distance between the fence and the shed. The gas burner ignited the vinyl fence/mulch combination readily at the base of the fence far from the shed, and at t = 1 min the fire was well-established. The image at t = 1.5 min shows the fire engaging the vinyl post, which resulted in intensification of the flames, a significant amount of black smoke, and thin blackened pieces of the fence skittering over the ground or lofted in the air. In this image a large fragment can be seen in mid-air and two smaller pieces are on the ground. By t = 3.5 min, spot fires had ignited both along the fence downwind of the main flame front and in the target mulch bed close to the wall. The vinyl fence post, panel, and bottom frame were blackened and distorted. The final image at t = 6.2 min shows the conditions just before water was applied. By this time, the bottom frame was no longer confining the fence panel, which swung back and forth in the wind. The mulch had burned from the point of ignition to the shed, and several vinyl fence fragments can be seen on the ground next to the mulch bed.

This fire behavior can be compared to that of the vinyl fence in the absence of mulch, which was difficult to ignite and supported little fire spread, as described in Section 4.2.3.3.

Note that the charring in the upper right corner of the vinyl fence in Fig. 89 resulted from Test A-34 without mulch, in which so little damage took place that the same fence was turned upside down and reused.

Fig. 89. Image sequence for vinyl privacy fence attached to wall with medium wind speed [Test A-35].

4.3.3.4. Redwood lattice fence

Experiments on a redwood lattice fence combined with shredded hardwood mulch were performed at all wind speeds and separation distances. An image from an experiment at 1.83 m (6 ft) separation distance and medium wind speed is shown in Fig. 90. The fire behavior trends with wind speed and separation distance were previously discussed in Sections 4.3.2.1 and 4.3.2.2, respectively. As a summary, in all cases the fire burned rapidly (within 12 min) from the point of ignition to the end of the fence and mulch bed close to the shed. The char pattern on the fence was highest for the lowest wind speed but did not exceed the half-height of the fence during the experiment. The burning was most intense below the lower stringer, with chunks of the fence occasionally breaking off. These large firebrands added to the flux of smaller firebrands from the fence and mulch. The shape of the char pattern on the fence reflected the wind vortex near the shed. The target mulch bed ignited in every case, and spot fires generally reached the shed wall more quickly at higher wind speeds.

These fire behavior trends for fences combined with shredded hardwood mulch were the same for redwood lattice fences and for western redcedar privacy fences.

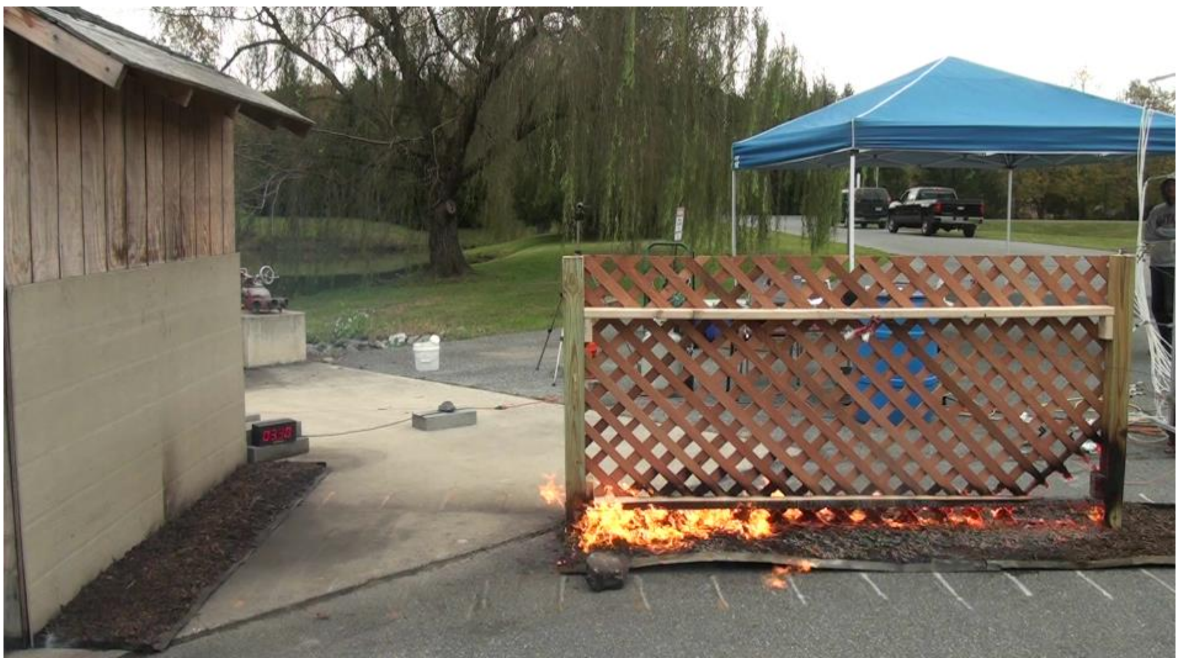

Fig. 90. Redwood lattice fence combined with shredded hardwood mulch, 3½ min after fan on, at medium wind speed [Test B-79].

The four plots in Fig. 91 show flame front location as a function of time for redwood lattice fence/HW mulch experiments at the four separation distances. Although the highest wind speed generally resulted in the fastest flame spread for these experiments, the relationship between flame spread rate and wind speed was inconsistent. A relationship between flame spread rate and separation distance was not clear. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

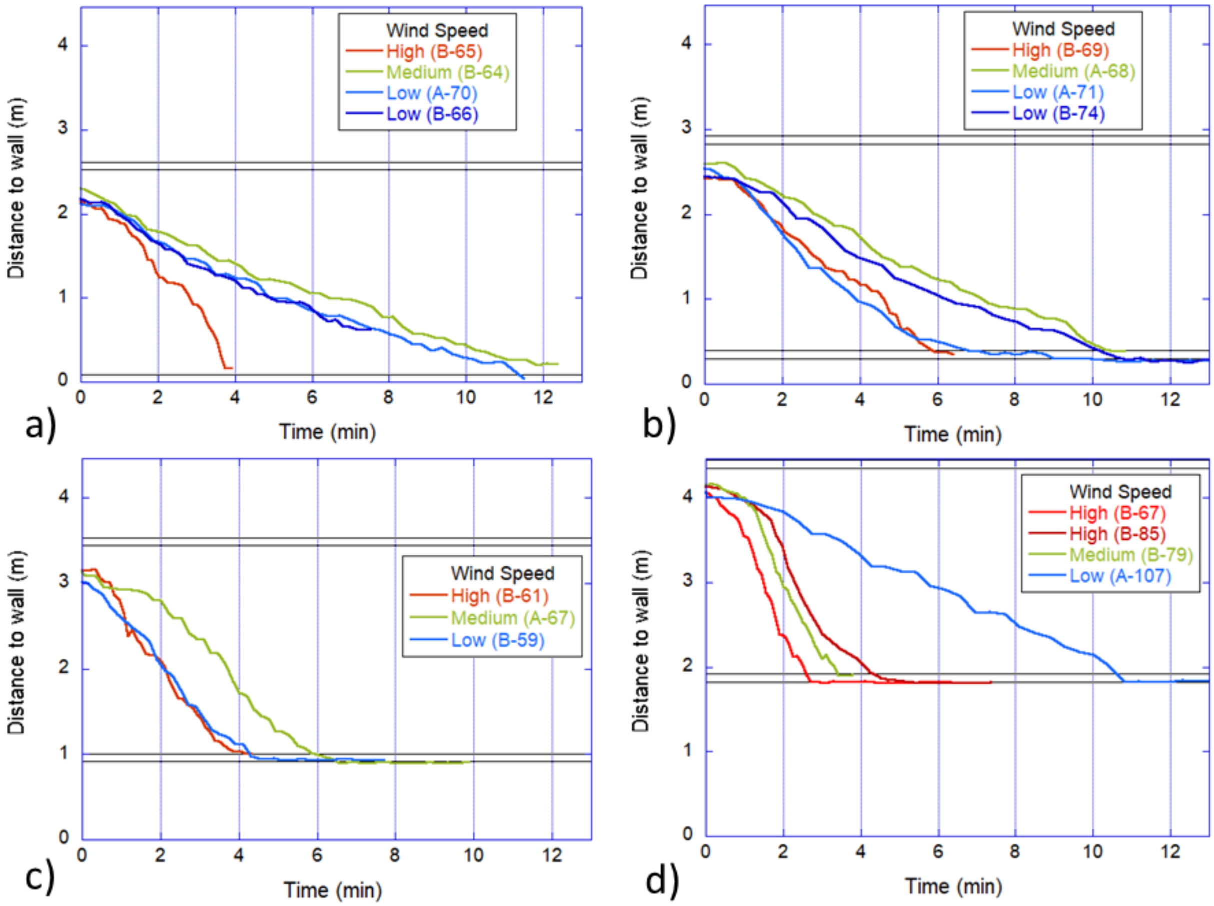

Fig. 91. Effects of wind speed on flame spread for RW lattice fence/HW mulch at separation distances of a) 0 m, b) 0.30 m (1 ft), c) 0.91 m (3 ft), d) 1.83 m (6 ft).

4.3.3.5. Pine lattice fence

Experiments at the three wind speed levels were performed on pine lattice fences with shredded hardwood mulch at the base. All used a separation distance of 1.83 m (6 ft) from the shed. Fig. 92, an image from a pine lattice fence experiment at medium wind speed captured 3.5 min after the fan was turned on, can be compared directly to Fig. 90, which shows a redwood lattice fence experiment under the same conditions and at the same time.

The plot of flame front location as a function of time in Fig. 93 confirms the similarity in fire behavior between pine and redwood lattice fences combined with shredded hardwood mulch. At low wind speeds, the charring took about 11 min to reach the end of the fence closest to the shed, while at medium and high wind speeds the time to reach the end was less than 5 min. The flame front reached the end of the fence sooner for the medium wind speed case (green solid line) than for the high (red solid line). This is partially because the initial location of the flame front for the medium wind speed case was closer to the far end of the fence. The maximum flame spread rates for these two cases were not appreciably different. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

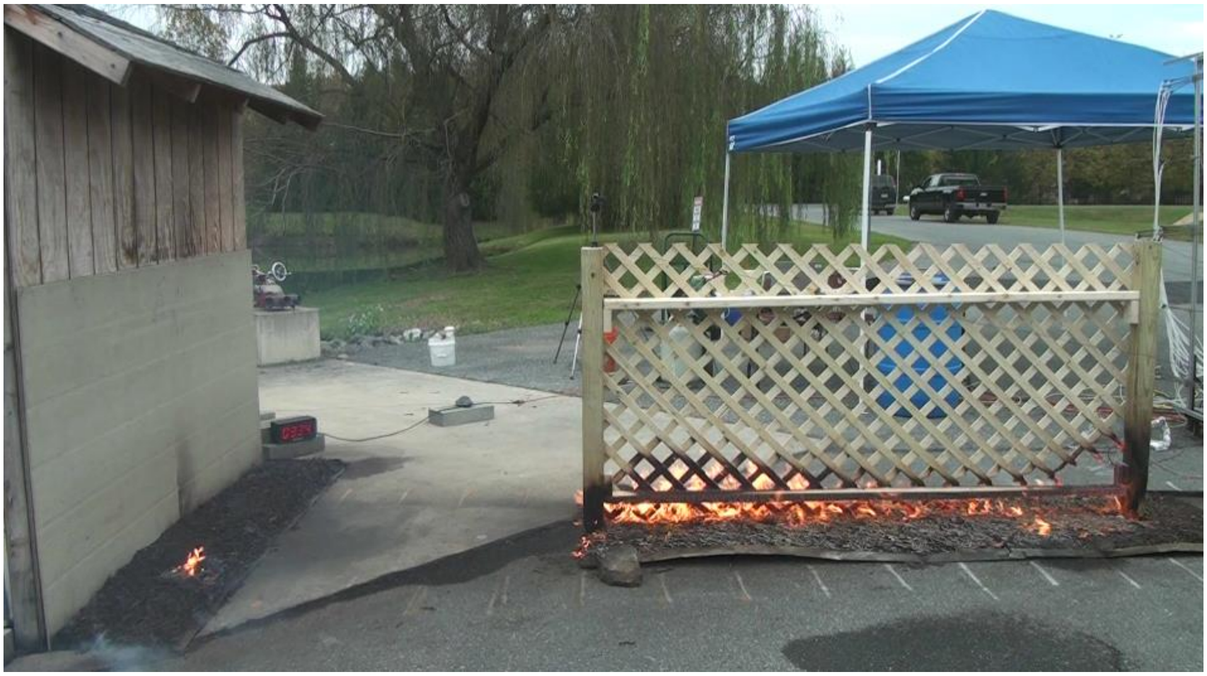

Fig. 92. Pine lattice fence combined with shredded hardwood mulch, 3 ½ min after fan on, at medium wind speed [Test B-81].

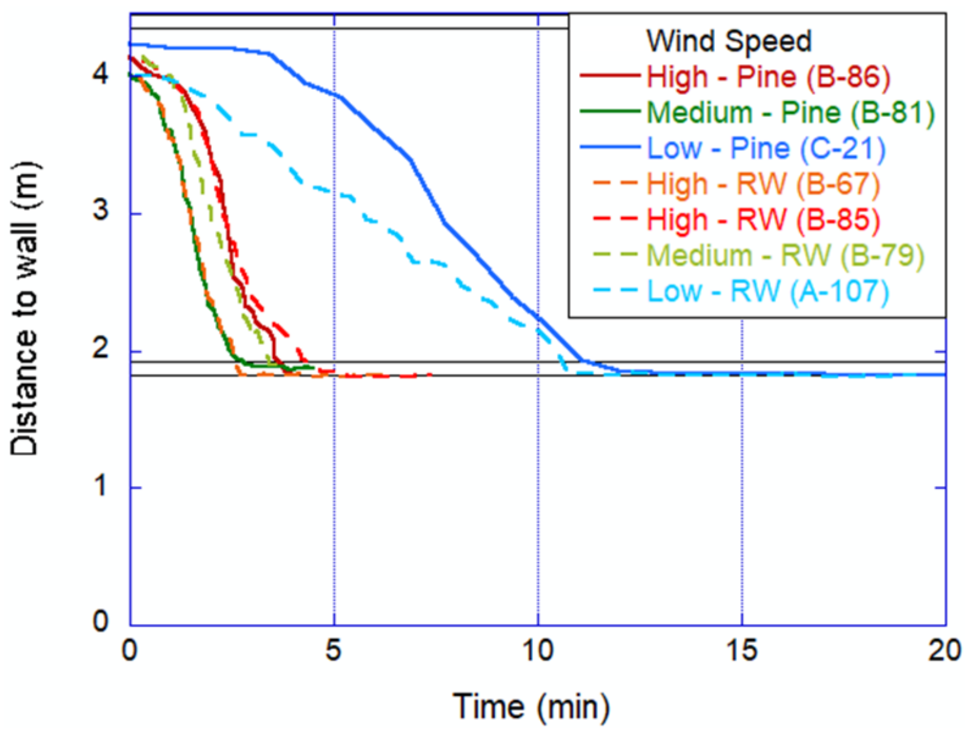

Fig. 93. Effects of wind speed on flame spread comparing pine lattice and redwood lattice fences at 1.83 m (6 ft) separation distance. Shredded hardware mulch was arranged at the base of both fences.

4.3.3.6. Good neighbor fence

The fire behavior of a good neighbor fence differed qualitatively from that for the privacy fences and lattice fences observed in this study. The time sequence in Fig. 94 shows the progress of fire over a good neighbor fence under low wind speed conditions at 1.83 m (6 ft) separation distance. For the first 6 min of the experiment, the fire remained below the first stringer. By t = 8 min, flames extended upward to the center stringer along the inner surfaces of the boards, on the side facing the stringers. The fire above the first stringer then moved downwind and attacked the second stringer. By t = 10 min, the fire extended into the space above the second stringer. The fire exceeded the height of the third stringer at t = 12 min, and by the time the fire was extinguished at t = 13.7 min the fence was in flames along its entire height. The stepping-stone nature of the upward fire growth downwind is illustrated clearly in the final frame of the sequence.

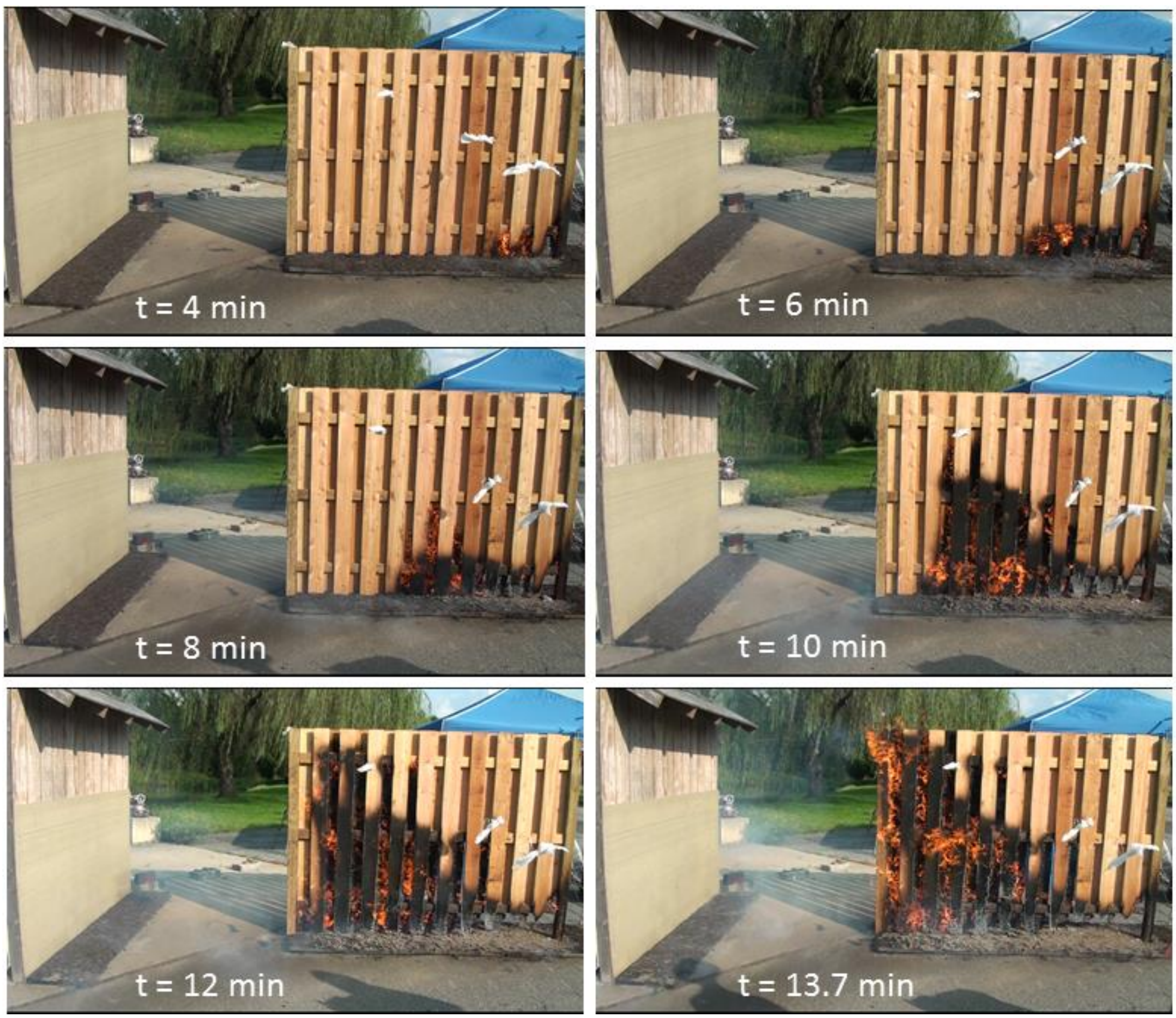

Fig. 94. Time sequence for good neighbor fence at low wind speed [Test C-18].

This fire behavior can be compared with the discussion and images in Section 4.3.2 for privacy and lattice fences, which show fire spread (from a single ignition near the ground) remaining below the center stringer and manifesting as charring rather than flaming.

The reasons behind the differences in fire behavior can be found in the alternating board (board on board) construction of the good neighbor fence. Attachment of the boards to alternate sides of the stringers places combustible material on two vertical planes separated by the 3.8 cm (1.5 in) stringer thickness. This creates corridors between the stringers for convection of heat and combustible gases. In addition, heat is transferred between inner board surfaces through thermal radiation, even if the boards are not overlapping. The importance of these physical phenomena will become even more apparent in Section 4.4 on parallel fences.

Figure 95 shows the fire behavior of the good neighbor fence at higher wind speeds. Both video images are just prior to water application that ended each experiment after spot fires reached the shed wall. These images show the higher intensity of the fire over the good neighbor fence as compared to the privacy and lattice fences shown in Section 4.3.2. They also show the same relationship between wind speed and the height of the fire on the fence shown in Fig. 72. These experiments don't answer the question of how the fire would evolve over the fence at later times or downwind over multiple panels.

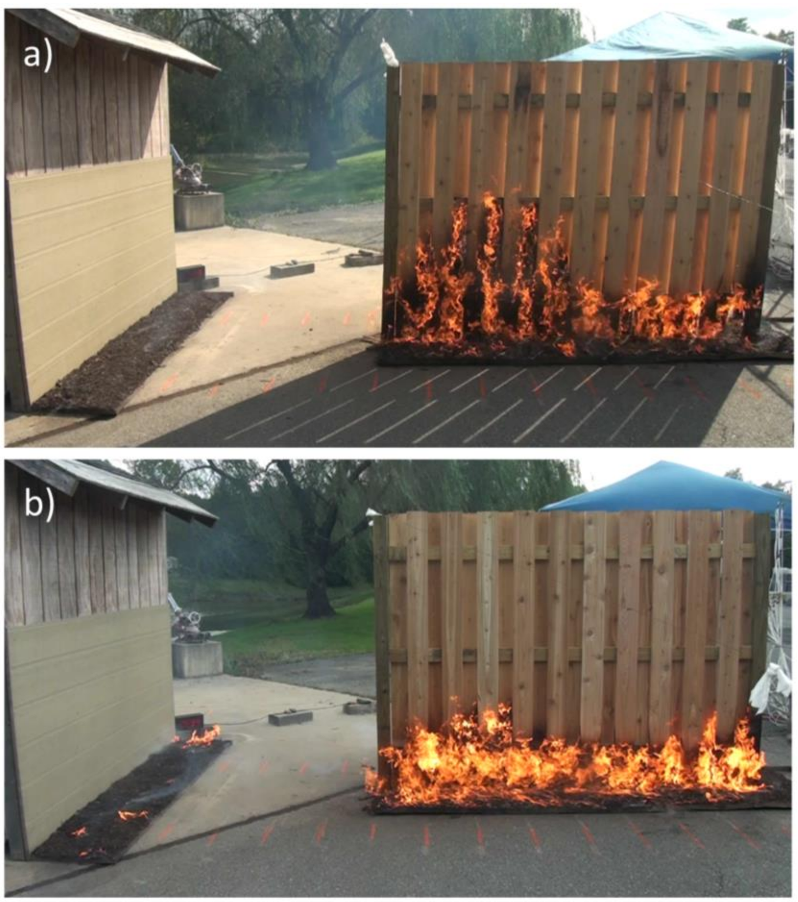

Fig. 95. Good neighbor fence experiments at a) t = 4.5 min for medium wind speed [Test C-22] and b) t = 2.6 min for high wind speed [Test C-23].

The downwind progress of the flame front for good neighbor fences combined with shredded hardwood mulch is plotted in Fig. 96 for the three wind speeds. The flame spread rate increases with increasing wind speed, and the time to reach the end of the fence near the shed is similar to that found for the other combinations of wood fence and shredded hardwood mulch in this section. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

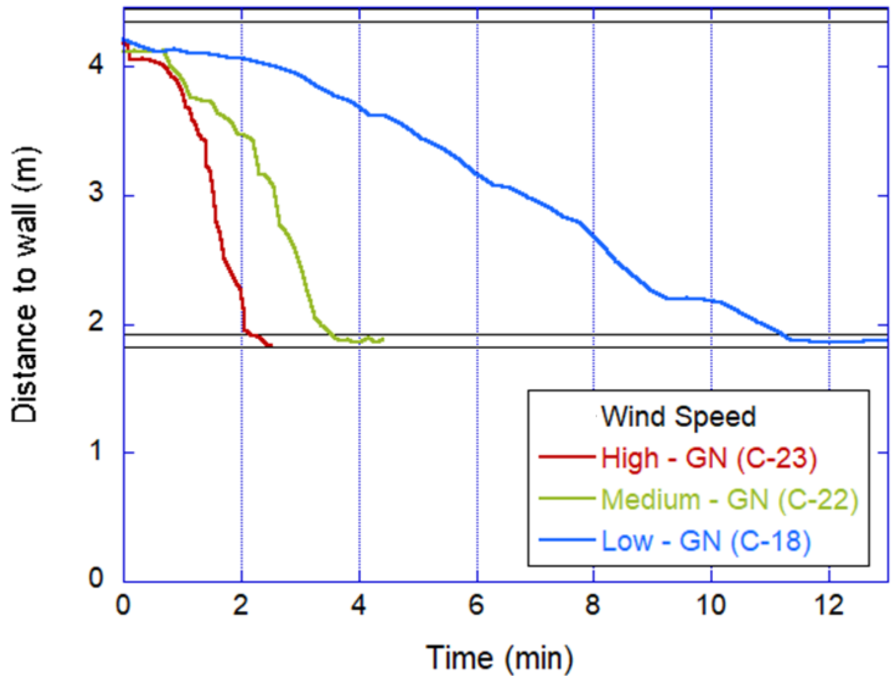

Fig. 96. Effects of wind speed on flame spread for good neighbor fence/HW mulch at separation distance of 1.83 m (6 ft).

4.3.3.7. Wood-plastic composite fence

In this study, limited testing was carried out on two types of wood-plastic composite fences. The two experiments performed on wood-plastic composite fences with shredded hardwood mulch illustrated the effects of both fence design and material formulation. Both were privacy fences, with interlocking vertical boards for WPC1 and horizontally-oriented boards held in place by a frame for WPC2. Material properties for both fences are discussed in Appendix B, and an experiment on the WPC1 without mulch has already been discussed in Section 4.2.3.4. Both experiments were carried out at low wind speed and 1.8 m (6 ft) separation distance.

Because only three experiments were performed on WPC fences, the following is considered limited preliminary data. More experiments with different designs and materials under various conditions are needed to fully understand the fire behavior of this category of fence.

The fire behavior for the WPC1 fence with shredded hardwood mulch beneath was similar to that observed in Section 4.2.3.4 for the same fence in the absence of mulch. Figure 97 shows a fire ignited at the upwind base of the fence developing into a large fire with flames extending well above the fence within 6 min of turning on the fan. As before, the boards fell to the sides as the top and bottom frames softened and distorted, expanding the fire on both sides and toward the downwind side of the fence and creating a fire zone up to 3.6 m (12 ft) wide. The final configuration of the boards after extinguishment is shown in Fig. 98, with the final positions of boards to either side and downwind of the fence panel highlighted with arrows.

As in the case without mulch in Section 4.2.3.4, fires ignited in the target mulch bed next to the shed only after the flames had become intense. The first fire in the target mulch bed next to the shed ignited just before t = 7 min. Because it ignited immediately adjacent to the shed wall, this may have been a spot fire, possibly ignited by a firebrand originating in the mulch bed beneath the fence. The set of fires in the target mulch bed just before extinguishment can be seen in the final frame of the sequence in Fig. 97, at t = 7.8 min.

Fig. 97. Time sequence for wood-plastic composite fence #1 at low wind speed and 1.83 m (6 ft) separation distance [Test E-1].

Fig. 98. Final configuration of wood-plastic composite boards after Test E-1. Yellow arrows highlight the final positions of fallen fence boards.

The fire behavior for the WPC2 fence with shredded hardwood mulch beneath is quite different, as shown in the sequence in Fig. 99. As the fire consumed each horizontal board in turn, the boards above it slipped downward, still confined within the black aluminum frame defining the panel. Fig. 100 gives an example of the boards collapsing downward over a period of one second as the support from the bottommost two boards gave way. As the remaining segment of each board fell flat against the ground, it tended to disrupt the flames, slowing the burning process until the flames reestablished themselves on the edges of the board. The flame height never reached above the halfway point on the fence, and the fire diminished on its own as it ran low on fuel. With the frame holding the boards in line with the fence during the fire, the fuel stayed within a couple of feet from the centerline. The final configuration of the boards shortly before extinguishment is shown in Fig. 101.

A spot fire ignited at t = 19 min near the wall. It can be seen in the final frame of Fig. 99 as a dark spot with smoke at the far end of the wall near the clock.

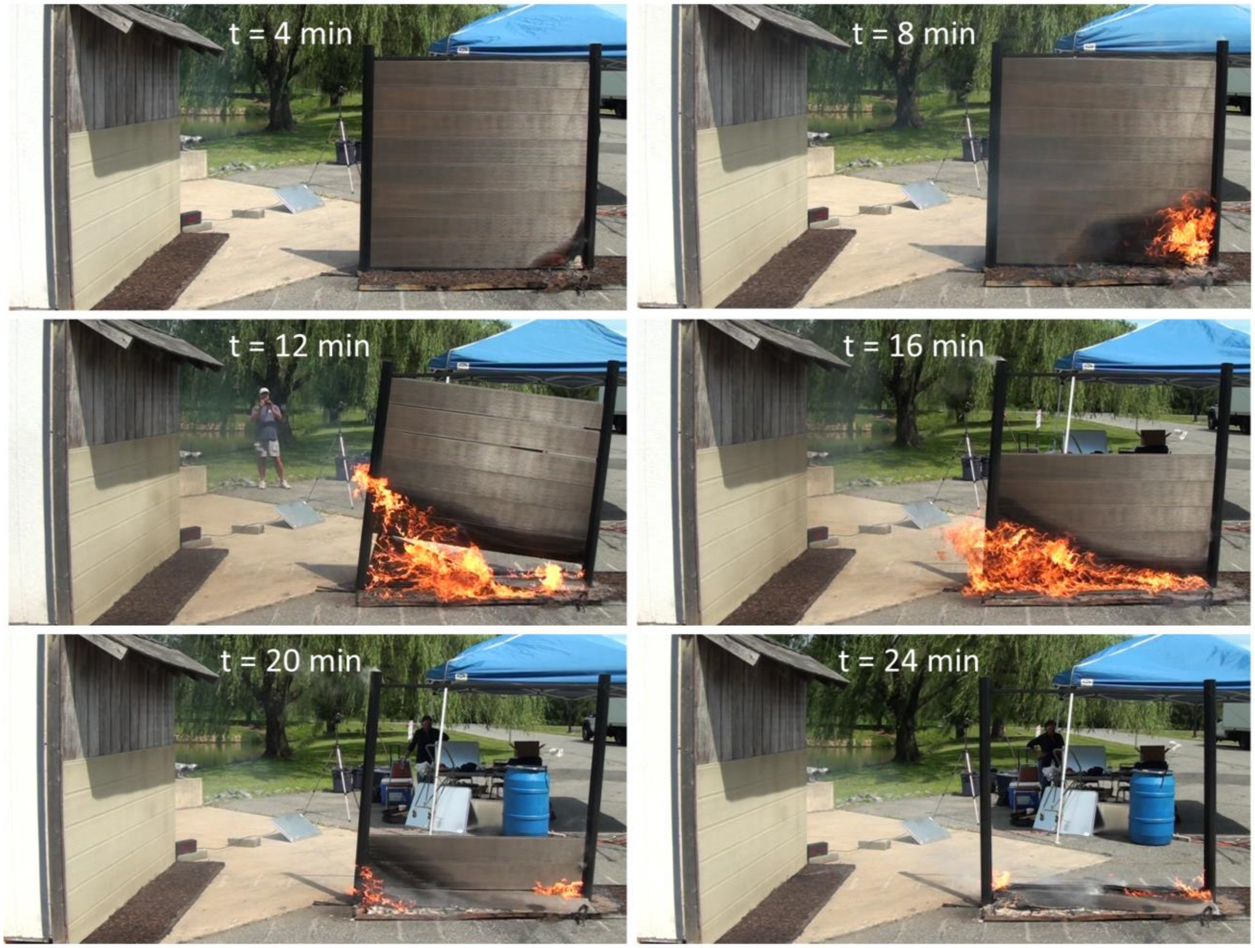

Fig. 99. Time sequence for wood-plastic composite fence #2 at low wind speed and 1.83 m (6 ft) separation distance [Test F-1].

Fig. 100. Collapse of horizontal planks shortly after t = 12 min [Test F-1].

Fig. 101. Final configuration of wood-plastic composite boards after Test F-1.

The location of the flame front as a function of time for the wood-plastic composite fences tested in this study is plotted in Fig. 102. This includes WPC1 without mulch (discussed in Section 4.2.3.4) in addition to the two fence types WPC1 and WPC2 in combination with shredded hardwood mulch from this section. All three experiments were performed at low wind speed and at 1.83 m (6 ft) separation distance from the shed. Note that the lines denoting the fence posts are in different locations because WPC2 fence panels are shorter than WPC1. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

Experiments on WPC1 with and without HW mulch (Tests E-1 and E-2, respectively) indicated that the presence of mulch below the fence acted to accelerate the progress of the flame down the fence. Comparing WPC2 with WPC1 under the same conditions (Tests F-1 and E-1, respectively), the flame front for WPC2 is considerably slower, reaching the end of the fence in almost twice the time of WPC1 despite being ignited closer to the shed. At 6 min from the point of ignition to the end of the panel, the flame front progresses faster over the WPC1 fence/HW mulch combination than for any other fence-mulch combination in this study.

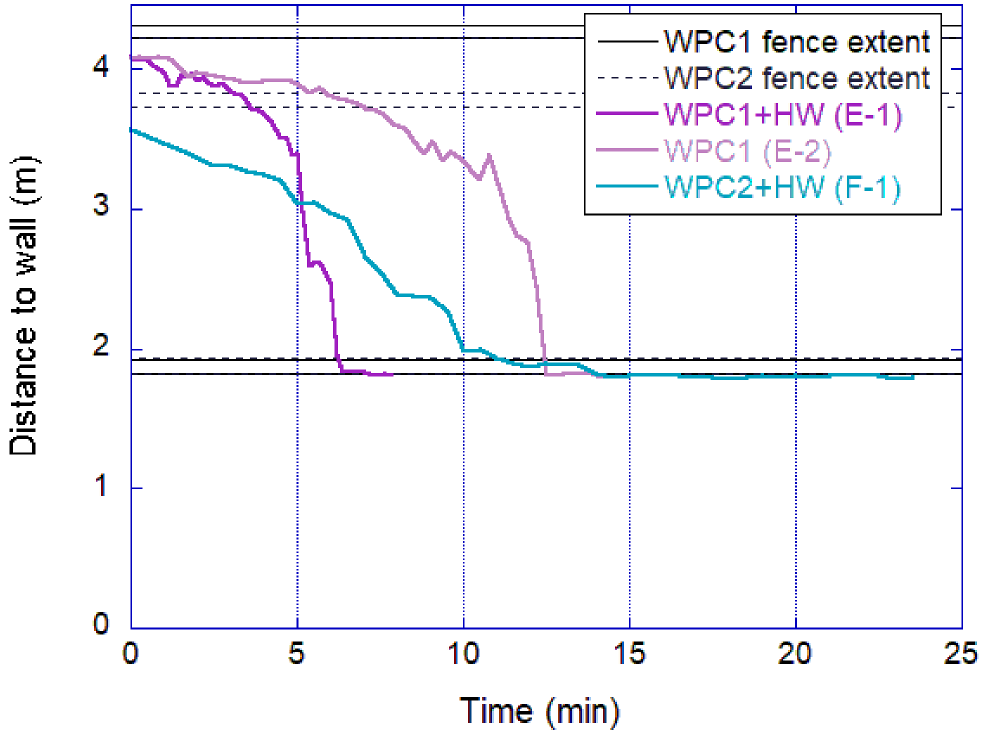

Fig. 102. Flame spread as a function of time for wood-plastic composite fence experiments.

4.3.4. Type of Mulch, combined with WRC Privacy Fence

This section compares the fire behavior for western redcedar privacy fences in combination with different types of mulch, including shredded hardwood mulch at two thicknesses, pine bark mulch, and pine straw mulch. Comparison with the experiments of mulch alone from Section 4.1 illustrates how combustible objects can interact to intensify fire behavior, including flame spread and firebrand generation.

4.3.4.1. Shredded hardwood mulch with half thickness

A series of experiments to investigate the effects of mulch thickness on fire behavior was performed on a western redcedar privacy fence combined with shredded hardwood mulch. For these experiments, the thickness of the mulch bed was reduced by half to 2.5 cm. Experiments were performed at all three wind speed levels and four separation distances.

Mulch thickness was not found to have a large effect on fire behavior. Figure 103 compares snapshots at t = 5 min from experiments with full and half mulch thickness (images (a) and (b) respectively) that were carried out under the same conditions – medium wind speed and 1.83 m (6 ft) separation distance. Both show similar char pattern shapes, reflecting the wind field near the structure as described in Section 4.3.2.1. Multiple spot fires are visible in the target mulch beds in both images.

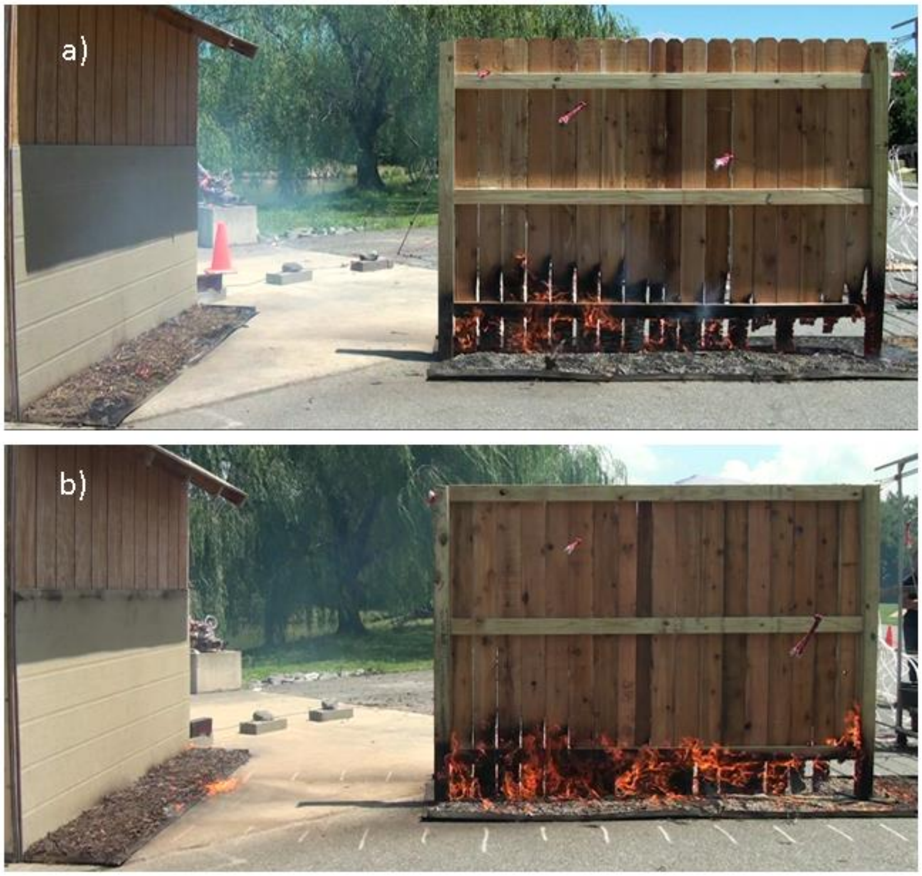

Fig. 103. WRC fence with HW mulch in medium wind speed with mulch thickness equal to a) 5 cm [Test A-29] and b) 2.5 cm [Test A-64], at t = 5 min.

Figure 104 shows the location of the flame front on the fence as a function of time for experiments with half mulch thickness. The general trend of increasing flame spread rate with increasing wind speed is demonstrated in these plots. Comparing these plots with matching plots in Fig. 86 from experiments with full mulch thickness, mulch thickness did not appear to significantly affect flame spread rate. A possible exception was found in low wind speed experiments, for which the flame front was generally observed to reach the end of the fence 2 min to 5 min faster for the thinner mulch bed. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

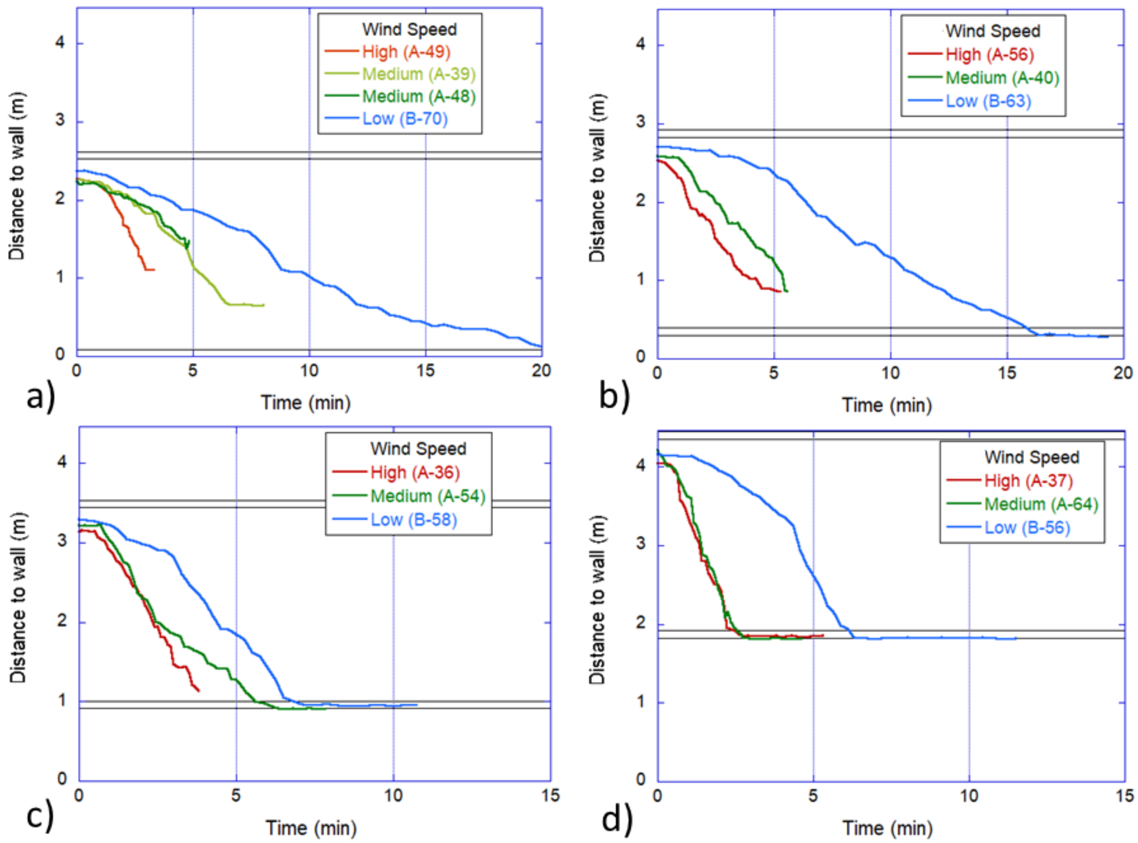

Fig. 104. Effects of wind speed on flame spread for WRC privacy fence combined with half thickness (2.5 cm thick) HW mulch at separation distances of a) 0 m, b) 0.30 m (1 ft), c) 0.91 m (3 ft), d) 1.83 m (6 ft).

4.3.4.2. Pine bark mulch

A full set of experiments, at all wind speeds and separation distances, was performed with a bed of mini pine bark mulch at the foot of a western redcedar privacy fence.

Figure 105 and Fig. 106 show sequences for experiments performed under the same conditions (medium wind speed and 1.83 m (6 ft) separation distance). The flame spread progressed at about the same rate for both experiments, although the char pattern was higher for Test A-74 than for Test A-90. The charring over the single panel did not reach higher than the center stringer, consistent with the results for other privacy fences (and lattice fences) with hardwood mulch discussed in Section 4.3.2.1.

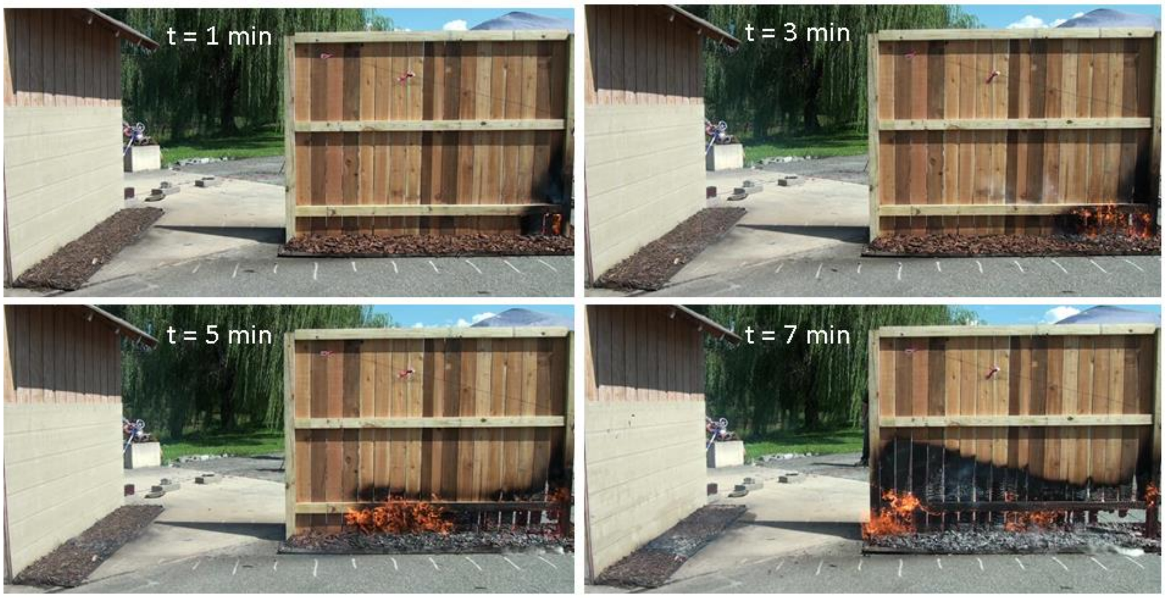

Fig. 105. Time sequence for WRC privacy fence and PB mulch in medium wind speed [Test A-74].

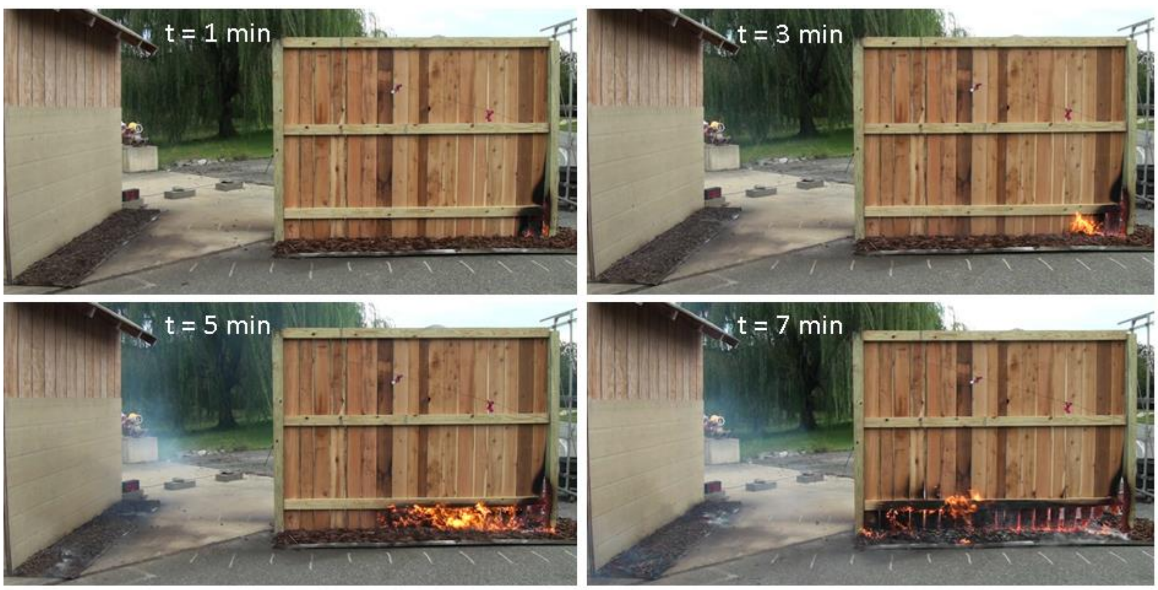

Fig. 106. Time sequence for WRC privacy fence and PB mulch in medium wind speed [Test A-90].

The plots of flame spread as a function of time for the four separation distances are given in Fig. 107. Experiments with pine bark mulch generally progressed somewhat more slowly than those with shredded hardwood mulch, as can be seen by comparing these plots to Fig. 86. However, the difference in time for the fire to reach the end of the fence panel was usually 5 min or less.

The key finding that combining combustible objects increases the hazard disproportionately is illustrated by comparing Fig. 107 to Fig. 40, showing fire spread plots for a mini pine bark mulch bed. Adding a privacy fence to the pine bark mulch bed resulted in flames reaching the end of the mulch pan two to four times faster. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

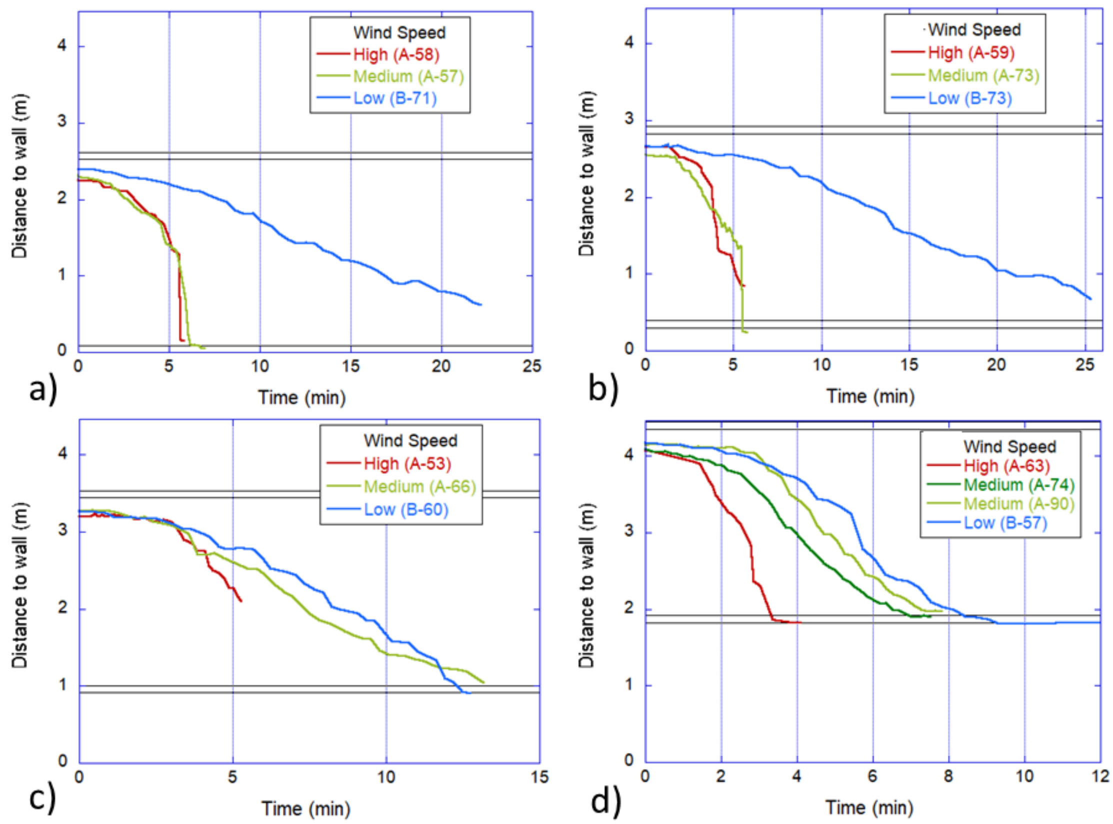

Fig. 107. Effects of wind speed on flame spread for WRC privacy fence combined with PB mulch at separation distances of a) 0 m, b) 0.30 m (1 ft), c) 0.91 m (3 ft), d) 1.83 m (6 ft).

4.3.4.3. Pine straw mulch

In Section 4.1.3.3, a bed of pine straw mulch was found to burn intensely and quickly, but without igniting the target hardwood mulch bed through flames or firebrands, even when in direct contact. The addition of a western redcedar privacy fence was found to make the situation more hazardous. As can be seen in Fig. 108, the pine straw mulch ignited the fence panel along its entire length within 30 s as the fire rapidly spread downwind. The fence then generated firebrands, which ignited the target mulch bed at t = 4 min. A flaming section of the target mulch bed is visible in the image at t = 5 min, with more spot fires visible at t = 10 min.

After the pine straw mulch was consumed, the privacy fence continued to undergo glowing combustion and occasional flaming, which slowly consumed the boards near the ground. This is evident in the differences between images at t = 5 min and t = 10 min. The difference between the fence burning in this case and in the experiments without mulch discussed in Section 4.2.3.1 is that here the pine straw mulch rapidly ignited the entire fence at its base, allowing the fence to become a source of firebrands along its entire length. This fire behavior can also be expected if fine combustible debris such as needles or leaves are allowed to accumulate along the fence.

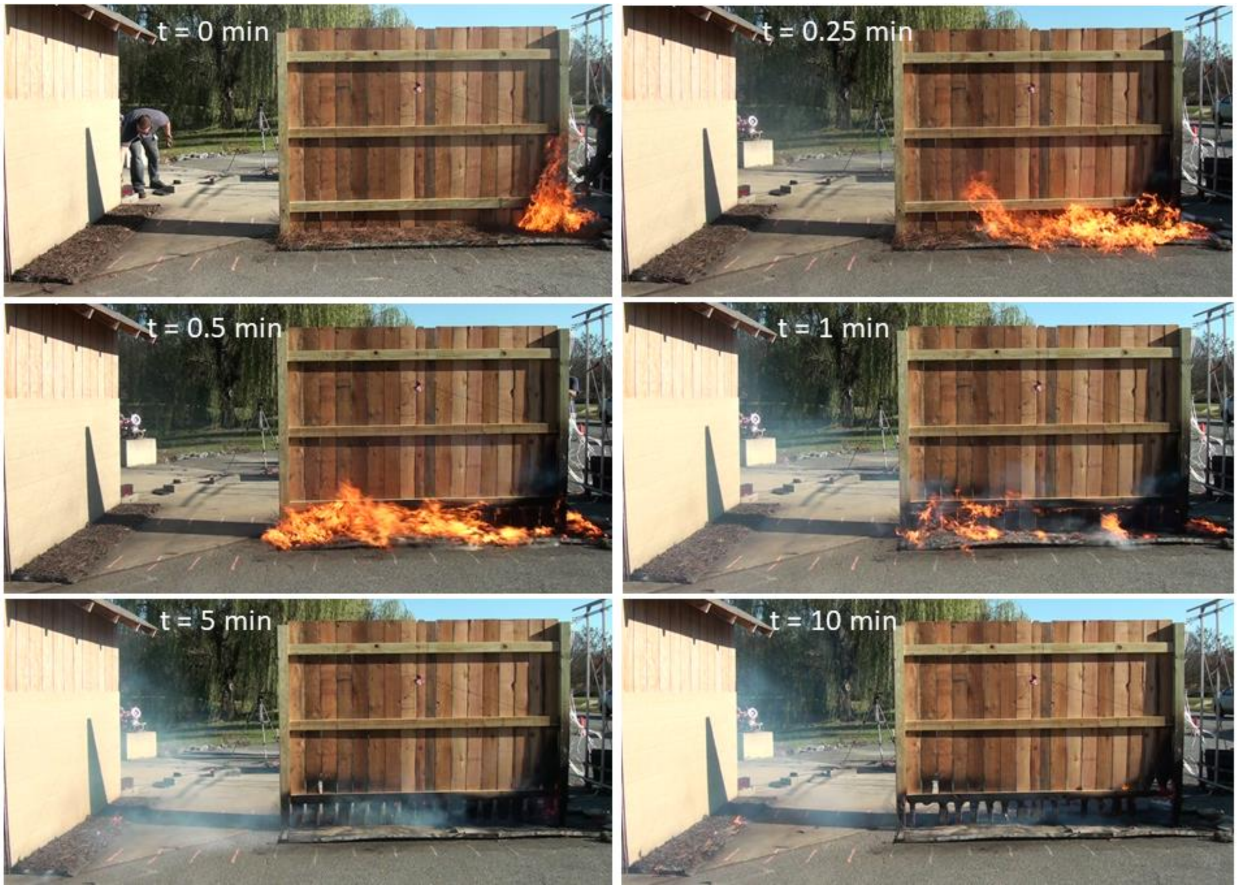

Fig. 108. Time sequence for WRC privacy fence in PS mulch at medium wind speed [Test A-109].

Seven experiments were performed on western redcedar privacy fences combined with pine straw mulch, at medium and low wind speeds as listed in Table B.3. In all cases, this combination resulted in the ignition of spot fires in the target mulch bed by firebrands, presumably from the fence.

Plots of flame front location as a function of time in Fig. 109 show the rapid spread of fire as the pine straw mulch burned and ignited the privacy fence. The fastest flame spread was for a separation distance of 1.83 m (6 ft), shown in plot (c), for which the fence panel was away from the flow effects of the shed. In these experiments, the flame front reached the end of the fence/mulch bed in less than a minute. At 0.91 m (3 ft) separation, shown in plot (b), the fire crossed the length of the panel in 1.5 min or less. This matched the spread rate over pine straw mulch in the absence of the fence, which was plotted in Fig. 42. For a separation distance of 0 m, the pine straw mulch bed abutted the target hardwood mulch bed at a distance of 0.46 m (18 in) from the shed wall. In plot (a), the flames on the fence reached the target mulch bed at about t = 3 min, after which the final approach to the wall was slow, with spot fires reaching the wall first. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

In all cases, the fire spread much faster on the western redcedar privacy fence for pine straw mulch than for shredded hardwood mulch, as can be seen by comparison of Fig. 109 with Fig. 86. Unlike the latter, flame spread with pine straw mulch did not vary with wind speed.

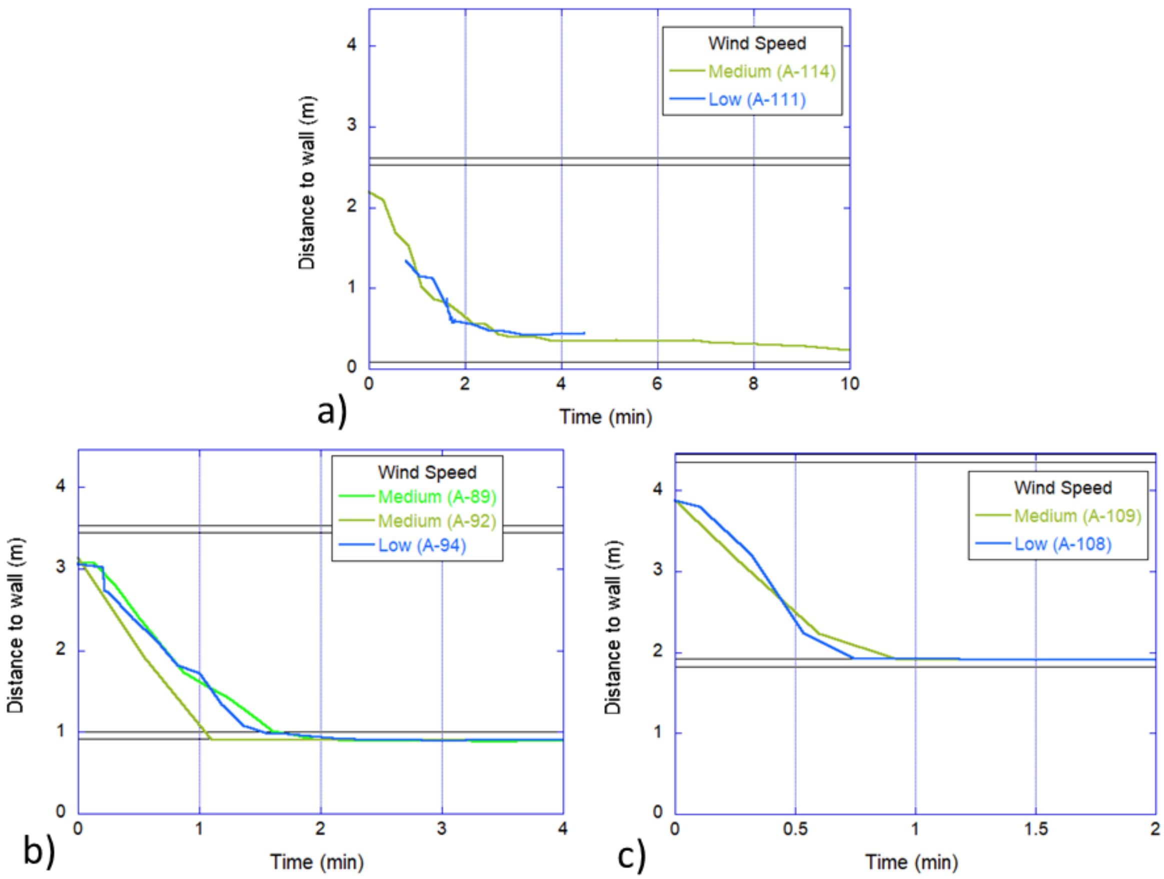

Fig. 109. Effects of wind speed on flame spread for WRC privacy fence combined with PS mulch at separation distances of (a) 0 m, (b) 0.91 m (3 ft), and (c) 1.83 m (6 ft).

As pointed out in Section 4.1.3.3, a study by Beyler et al. [27] showed that fire spreads quickly over pine straw mulch even with no wind, suggesting that wind is not a dominant factor.

4.3.5. Firebrand Spotting

All combinations of fence and mulch tested in this study ignited spot fires in the target mulch bed next to the shed, as shown in Table 3. The presence of both fence and mulch generated firebrands, even when one of the elements had not demonstrated the capacity to ignite spot fires on its own (e.g., vinyl fence or pine straw mulch). Table 3 summarizes the data from Table D.3, Table D.4, and Table D.5, where the color key identifies in green those experiments in which the fire spread to the shed. The only fence plus mulch experiments in which the fire did not reach the shed (in pink) were Series 1 experiments, which did not include a target mulch bed at the base of the shed wall. Only Series 2 experiments were included in Table 3.

Table 3. Number of experiments producing spot fires for each fence plus mulch type.

Fence and Mulch Combination	Number of Experiments With Spot Fires	Number of Experiments Without Spot Fires
Western redcedar privacy fence (WRC) / Shredded hardwood mulch (HWM)	22	0
Aged western redcedar privacy fence (aged WRC) / Shredded hardwood mulch (HWM)	3	0
Vinyl privacy fence (Vinyl) / Shredded hardwood mulch (HWM)	1	0
Redwood lattice fence (RWL) / Shredded hardwood mulch (HWM)	12	0
Pine lattice fence (PL) / Shredded hardwood mulch (HWM)	3	0
Good neighbor fence (GN) / Shredded hardwood mulch (HWM)	3	0
Wood-plastic composite fence (WPC) / Shredded hardwood mulch (HWM)	2	0
Western redcedar privacy fence (WRC) / Shredded hardwood mulch at half thickness (half HWM)	13	0
Western redcedar privacy fence (WRC) / Pine bark mulch (PBM)	13	0
Redwood lattice fence (RWL) / Pine bark mulch (PBM)	1	0
Western redcedar privacy fence (WRC / Pine straw mulch (PSM)	7	0

The times to ignition of the first spot fire as a function of average wind speed of the bottom four probes along the centerline are displayed in Fig. 110 for the combinations of fence and mulch listed above. In general, the time to ignition decreased with increasing wind speed. The longest times to spot fire ignition occurred for western redcedar privacy fences with shredded hardwood mulch, although some experiments with this combination spotted very quickly. Spot fires ignited in less than 15 min for all medium wind speed cases and in less than 6 min at high wind speeds, with one exception. The scatter was widest at low wind speeds, with ignition times ranging from 2 min to 34 min.

Figure 111 shows that spot fire ignition times did not depend on separation distance.

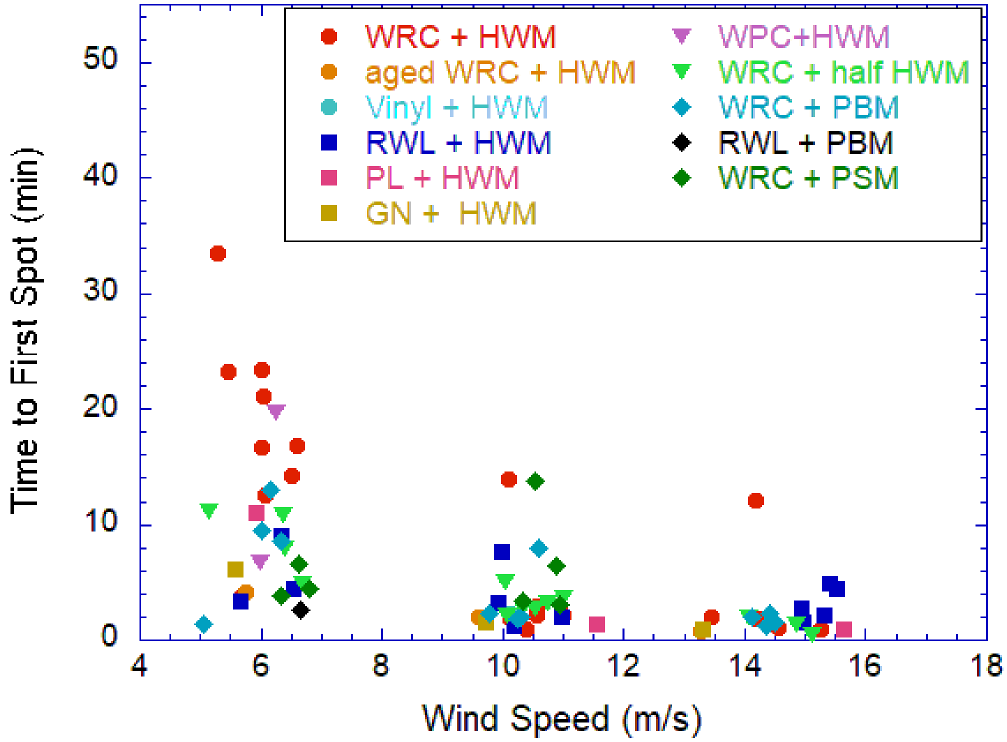

Fig. 110. Time to ignition of first spot fire vs. wind speed for fence plus mulch experiments.

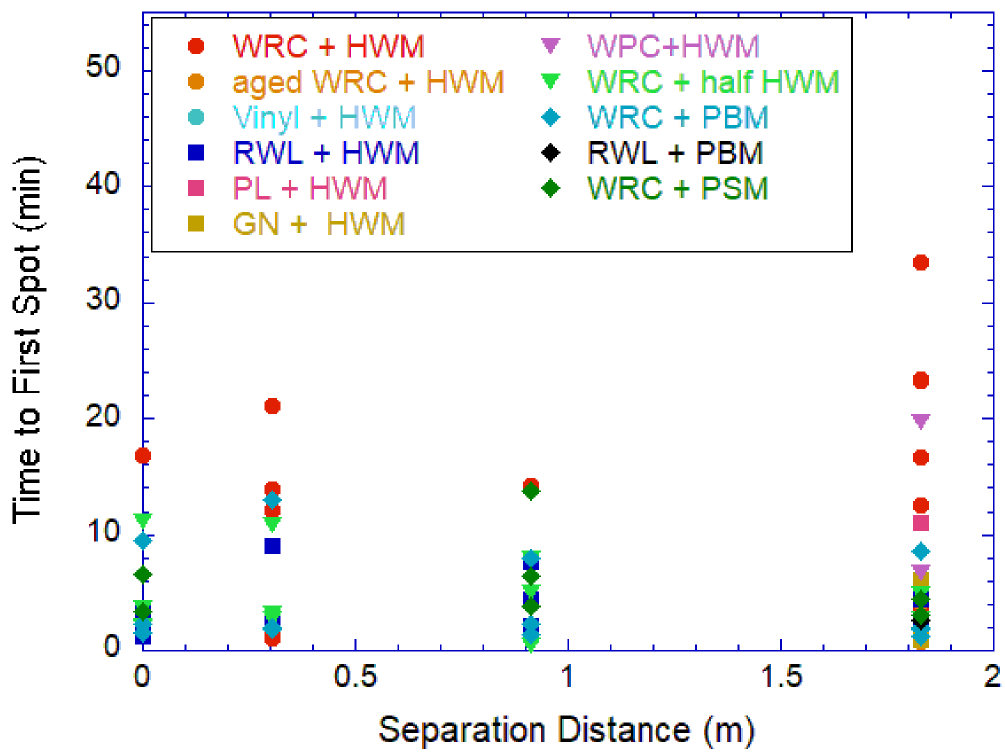

Fig. 111. Time to ignition of first spot fire vs. separation distance for fence plus mulch experiments.

Times for the ignition of the first spot fire to put flames against the wall and the first observation of flames on the wall are plotted in Fig. 112 and Fig. 113, respectively. Both measures show a tendency to decrease with increasing wind speed, in agreement with the times to first spot fire ignition. Although spot fires can take 20 min or more to reach the wall with flames after ignition, most do so within a few minutes. These are typically the spot fires that are ignited by firebrands deposited near the wall by the wind field.

Finally, Fig. 114 compares the first spot fire ignition times for the three sets of experiments discussed thus far: fence plus mulch, mulch only, and fence only experiments. This plot shows that the combination of fence and mulch considerably shortens the time to spread the fire through firebrands over mulch alone.

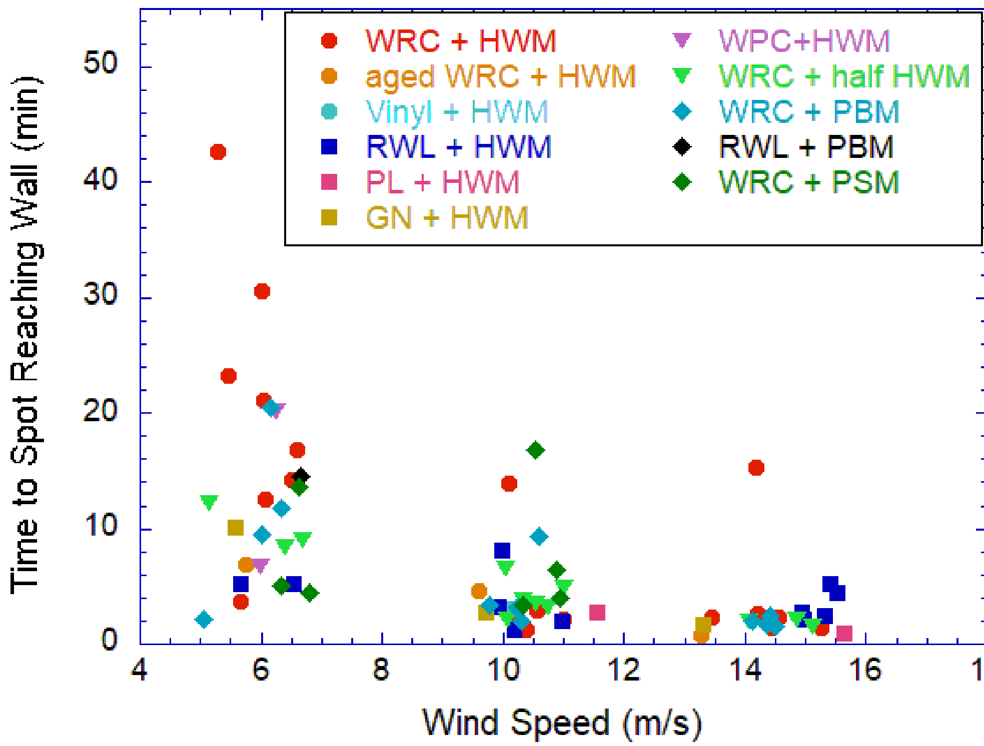

Fig. 112. Time to ignition of first spot fire to put flames against the wall vs. wind speed for fence plus mulch experiments.

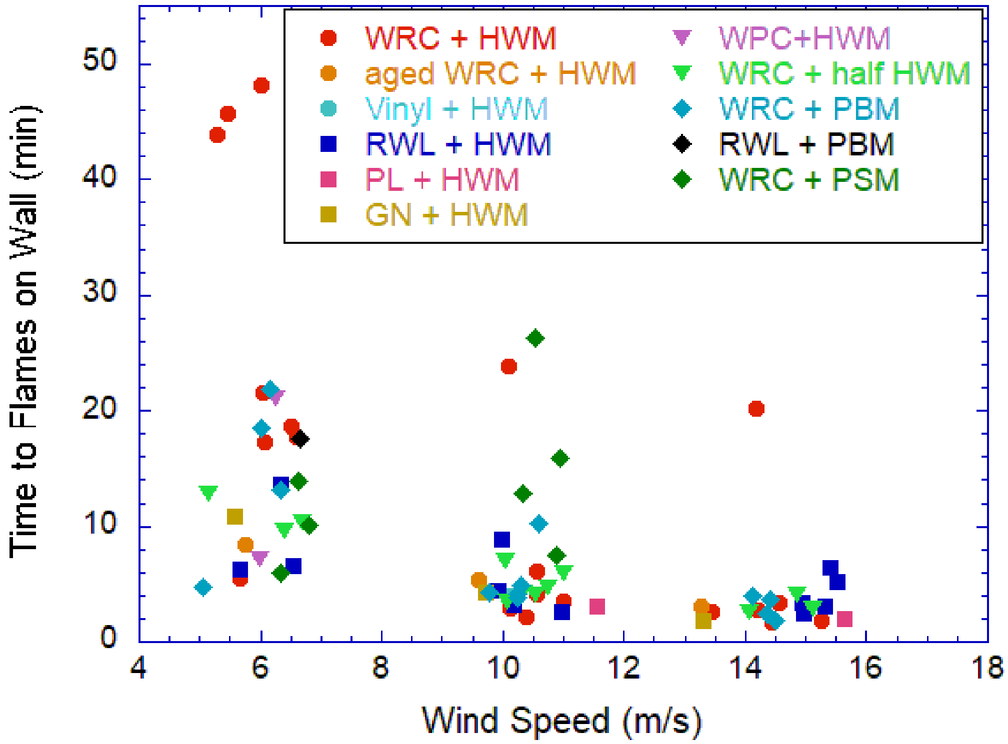

Fig. 113. Time to flames reaching the wall vs. wind speed for fence plus mulch experiments.

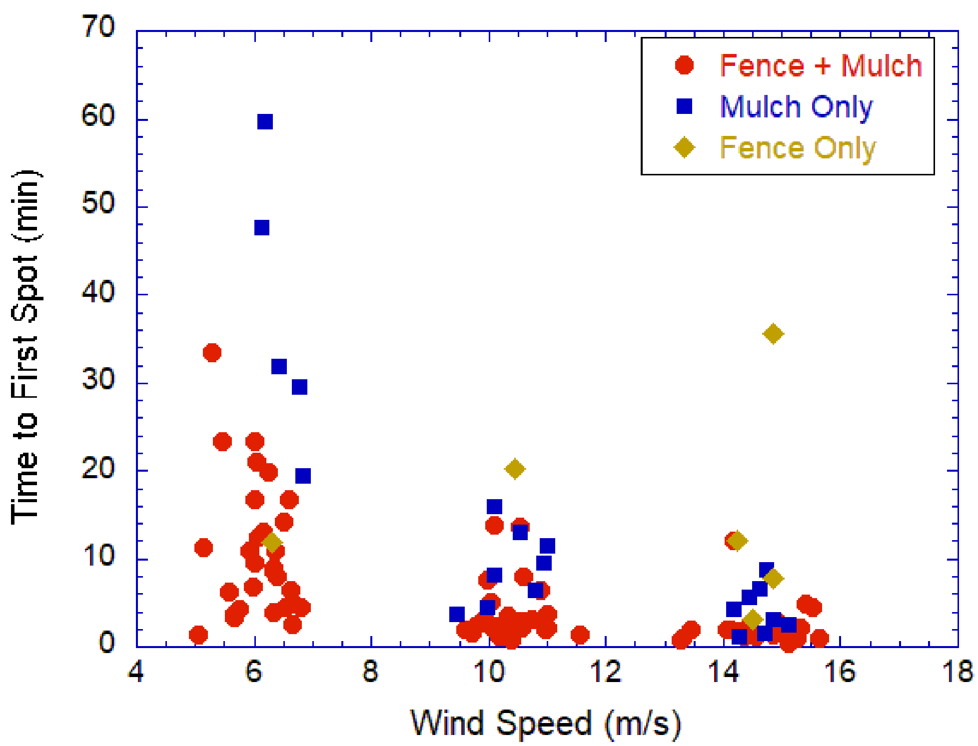

Fig. 114. Time to first spot fire as a function of nominal wind speed for experiments for fences with mulch (red), mulch beds only (blue), and fences only (gold).

4.3.6. Summary

A fence with mulch at its base is more hazardous than either the fence or the mulch bed separately. The mulch and fence interact to promote rapid flame spread downwind plus the generation of firebrands that can ignite other fuels in the vicinity. The fire behavior depends on fuel, geometry, and wind. More specifically, in these experiments the fire behavior depends on the types of fence and mulch, wind speed, and distance from the structure.

These experiments are also informative for a fence with vegetation planted close by or for a fence with windblown leaves, needles, and other debris at its base. Any fine fuels adjacent to a fence are likely to interact with it during a fire.

Key findings from this set of experiments include the following.

Fire spread behavior. Adding fine combustible materials to the base of a fence enables fire spread along the base of the fence, allowing the combination of fence and mulch to act as a wick transporting fire along the entire length of the fence.

- Combining a fence with mulch leads to a fire that is more intense and moves more rapidly than for either fuel on its own. The mulch carries fire continuously along the length of the fence. Adding a fence may reduce the time for the fire to reach the end of the mulch bed by a factor of two or more.
- Flame spread rate varies from one experiment to the next. In general, the flame front progresses faster with higher wind speed. This is most evident at the lowest wind speed, for which the flame front moves considerably slower than for medium and high wind speeds. In all cases, fire continued to spread toward the structure.
- When wood fences in a single plane (privacy or lattice fences) are ignited at ground level only, as in this study, flames typically remain below half of the fence height. Char patterns reflect the wind field. Flames spread higher on the fence with lower wind speeds.
- Stringers slowed the upward fire spread in these experiments by limiting the flame height on one side of the fence. In a WUI fire, however, they may enhance the fire spread by providing locations for firebrands to lodge and ignite new fires on the fence.
- Upward fire spread was fastest in the gaps between boards, aided by radiative and convective heat transfer between the edges of the boards.

Type of fence. Fire behavior depends to varying degrees on the style (privacy, lattice, good neighbor) and material (wood, vinyl, wood-plastic composites) of the fence with shredded hardwood mulch at its base. Because of the intensity of their fire behavior, wood-plastic composite fences are separated here from the description of other fence types.

- Wood privacy and lattice fences (western redcedar, aged, redwood, pine) exhibit similar fire behavior, including fire spread timing, spot fire ignitions through firebrands, and char patterns.
- The flame spread rate in the horizontal direction is similar for all wood fences, including privacy, lattice, and good neighbor fences. Away from the wind field near the structure, the fire spread from the ignition point to the end of the fence panel in

2 min to 5 min for high and medium wind speeds and 7 min to 12 min for low wind speeds. All fences carried fire.

- For wood good neighbor (board on board) fences, radiative and convective heat transfer between the boards connected to alternating sides of the stringer cause the flame to rise to the top of the fence downwind. Flaming combustion was more prevalent for good neighbor fences than for other wood fences combined with the same mulch type.
- With mulch at its base, vinyl privacy fences, including panel, bottom frame, and fence post, blacken and distort along the entire length of the fence. The bottom frame fails to confine the panel within a few minutes of ignition.

Wood-plastic composite fences. Limited preliminary data indicate that ignition of certain wood-plastic composite fences can result in high intensity fire behavior. Upcoming experiments are planned to study further the fire behavior of this category of fence.

- For one WPC fence type:
    - The entire fence became engulfed in flames.
    - The top and bottom frames distorted and released burning boards, which fell and extended the flaming region a distance equal to the fence height of 1.83 m (6 ft) to each side of the fence. Some softened boards fell forward in the wind, extending the flaming region beyond the fence as well.
    - Firebrands landing close to the wall of the shed, possibly from the mulch, ignited spot fires. Many fires in the target mulch bed were ignited by radiation and direct flame contact.
    - Smoke coming from the roof of the shed after the experiment indicated that a separation distance of 1.83 m (6 ft) between a fence and a structure was inadequate to prevent ignition from this burning fence.
- For a second WPC fence type:
    - The fire remained below the halfway point of the fence height.
    - Horizontal boards fell out of the frame and burned in line with the fence.
- More experiments are needed to uncover the reasons (materials, design) for the fire behavior of WPC fences. The significant difference in energy release between the two composite fences tested in this study highlights the need for a fence test method that can be used to assess the hazard of the material/design configuration.

Type of mulch. Fire behavior of a fence with mulch along its base varies with the type of mulch.

- Reducing the thickness of shredded hardwood mulch from 5 cm to 2.5 cm does not significantly affect flame spread rate or char patterns on the fence, except at low wind speeds.
- Mini pine bark mulch somewhat slows the flame spread over a western redcedar privacy fence as compared to shredded hardwood mulch, although the difference in time for the fire to reach the end of the fence panel may be less than 5 min.

- Adding a privacy fence to a pine bark mulch bed results in flames reaching the end of the mulch pan two to four times faster than for mulch only.
- Pine straw mulch burns rapidly with high intensity and ignites the fence quickly. When combined with a western redcedar privacy fence, the fire can reach the end of a panel within 1 min. After the pine straw mulch is consumed, the wood fence generates firebrands capable of igniting spot fires.

Mitigation. This set of experiments included an exploration of the effects of lifting a fence above a mulch bed below, as a potential way to decouple the mulch from the fence in a WUI fire.

- For shredded hardwood mulch, lifting a fence 15 cm (6 in) above the mulch decouples the burning behavior of the fence from the mulch between posts. This conclusion may not hold for mulches that burn with higher flames, such as pine straw or rubber mulch, or in the presence of vegetation.
- The benefits of raising the fence above the mulch may not be realized if a barrier is placed between them to keep wildlife out or pets in. Combustible debris such as leaves or needles that collect along the barrier will reduce the advantages of this design in a fire.

Firebrand spotting. Firebrands capable of igniting spot fires are generated by all combinations of fence and mulch tested.

- Spot fires are consistently ignited from firebrands within a few minutes of mulch and fence ignition.
- The time to first spot fire ignition decreases as wind speed increases. Spot fires occurred in less than 15 min in all medium wind speed cases and in less than 6 min in almost all high wind speed cases.
- Firebrands that are deposited by the wind field into fine combustible materials next to a structure may result on flames on the wall in a few minutes or less.
- Spot fires may occur after the flame front has reached the end of the fence and mulch bed combination and the initial flaming combustion has subsided.

4.4. Parallel Fence Experiments

The hazardous fire behavior of two fences parallel to each other was discovered through an attempt to reconcile observations from three research efforts. Diagonal lattice fence assemblies exposed to firebrand showers by Manzello et al. [61] became fully involved in flaming combustion after being ignited from the mulch bed at their base. This contrasted with the fire spread observed for combinations of lattice fence and mulch bed in this study and in a study of fences by IBHS [21, 22], in which the fire remained within the lower half of the fence for ground-level ignitions.

The discrepancy was resolved by changing the configuration of the lattice fence, from redwood lattice slats attached to two 2×4 stringers on a single side to the double-sided assembly used in the Manzello experiments. The difference was remarkable, as is shown in the comparison in Fig. 115. While the fire stayed low to the ground for the single lattice fence in video image (a), reaching the end of the fence nearest the structure in about 3 min, the double fence assembly in image (b) was fully engulfed in flame in half that time.

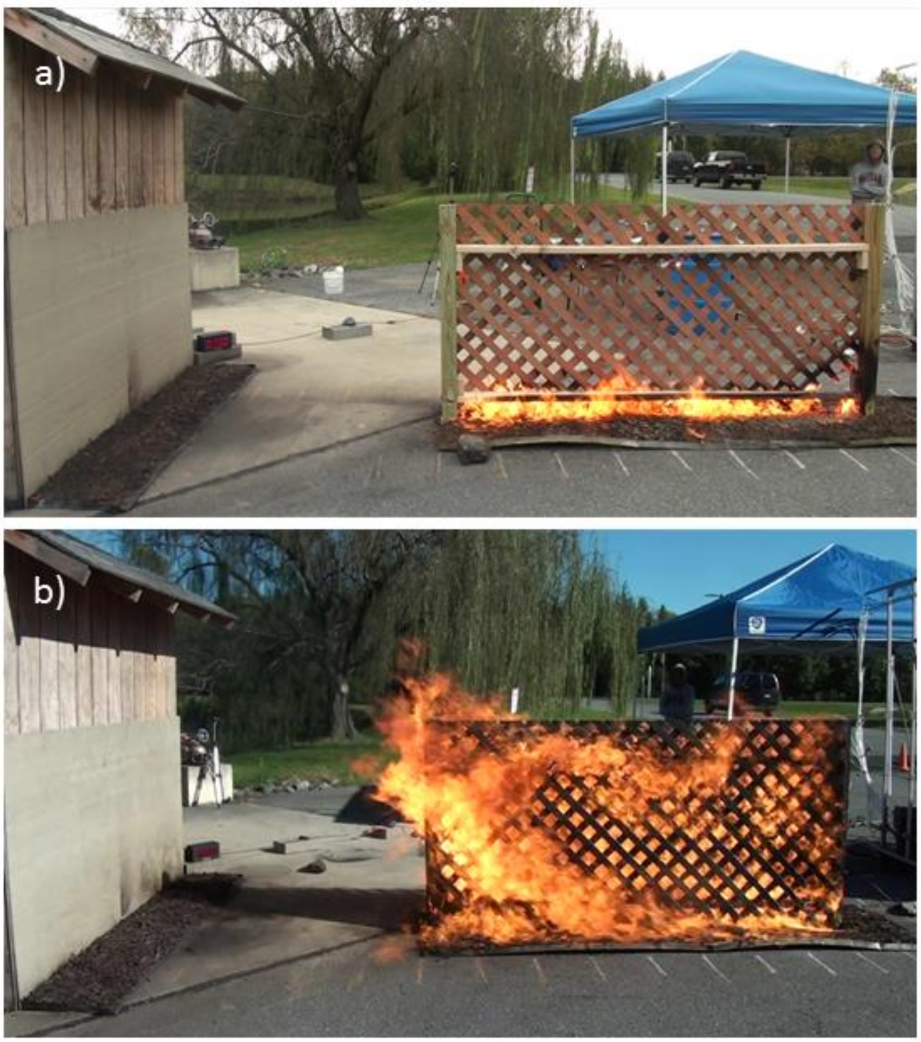

Fig. 115. Comparison of a) single (Test B-79 at t = 3 min) and b) double (Test B-75 at t = 1.5 min) RW lattice fences in medium wind speeds.

The existence of two very different burning modes for single and double lattice fences raised the more general question of whether fire behavior is enhanced for combustible fences that are parallel to each other. This arrangement may be common within residential communities. A homeowner may erect a fence close to the property line and adjacent to that of their neighbor due to aesthetic considerations or to meet differing needs for privacy or confinement. An example of this is shown in Fig. 12. In addition, fences are often built close to sheds or other auxiliary buildings. If these configurations are particularly hazardous in a WUI environment, then it is important to address them as part of a mitigation strategy for WUI fire reduction.

The selection of parallel fence experiments was based on the exploration of real-world scenarios that may be of concern. The effects of spacing were studied for parallel western redcedar privacy fences. WRC privacy fences were also paired with a cement board, a vinyl privacy fence, and a pine lattice fence to look at the effects of combinations of different materials and design. Most experiments, including a comparison of redwood and pine lattice fences, were carried out under low wind speed conditions. The effects of wind speed were tested on redwood lattice fences. Several tests were run without mulch to see whether the mitigating effects of removing all fine combustibles, discussed in Section 4.1, also held for parallel fences. All experiments were performed with separation distances of 1.83 m (6 ft) from the structure. This placed the parallel fences outside of the effects of wind that dominate the region close to the structure.

The test matrix for Parallel Fence experiments is shown in Table D.6 and Table D.7 in Appendix D. The details of each experiment, including parameter values, images, flame spread data, wind plots, and summary values, can be found in Appendix I. In each case, timing was measured from the point after ignition when the fan was turned on.

4.4.1. Example

Figure 116 and Fig. 117 display the time sequence for the development of fire on parallel western redcedar privacy fences in a bed of shredded hardwood mulch. The faces of the boards were separated by 46 cm (18 in), and the average wind speed along the centerline for this experiment (Test C-6) was 6.6 m/s (14.9 mi/h). At each displayed time, the experiment is shown concurrently in images from videos recorded by the left and left front cameras. Insights on the processes contributing to the rapid growth of fire on parallel fences can be obtained by comparing the fire behavior between the panels with the observations on the outside.

As shown in Fig. 116, for the first two minutes after the upwind end of the fence and mulch bed were ignited, the flames propagated along the base of the fence in a similar manner as observed for the single panel WRC fence/HW mulch combination in Fig. 69. The char pattern and flames between the two fence panels and on the outside remained below the first stringer. At 2 ½ min, however, there were signs that the space between the panels was heating up quickly. Along the base of the fence ahead of the flames, there was a line of white smoke that indicated that water was being driven out as water vapor or steam, and the left front view shows that the fires along the base of each panel had merged and increased in intensity. Within another 15 s, white smoke was emerging from the end of the parallel fences, followed shortly by flames, as shown in the image on the left at t = 3 min.

Fig. 116. Time sequence for parallel WRC privacy fences with shredded hardwood mulch at 46 cm (18 in) spacing and low wind speed [Test C-6], showing first three minutes.

Subsequent development of the parallel fence fire is shown in Fig. 117. After the flames reached the downwind end of the fence panel, they climbed the inner and outer surfaces, exceeding the height of the fence 3 ½ min after the fan had been turned on. The flames then worked their way upwind between the panels until by t = 4 min the entire fence was engulfed.

Fig. 117. Time sequence for parallel WRC privacy fences with shredded hardwood mulch at 46 cm (18 in) spacing and low wind speed [Test C-6], for times from 3 ½ min to 6 min.

4.4.2. Type of Fence

This section compares the fire behavior for parallel western redcedar privacy fences, double redwood, and double pine lattice fences, in which both fences were identical. These fence configurations and their motivations were described in Section 2.5.6. Shredded hardwood mulch was arranged below the fences in each of these cases.

The effects of parallel fence spacing, wind speed, lack of mulch below the fences, and dissimilar fences are described in Sections 4.4.3 through 4.4.5.

4.4.2.1. Parallel western redcedar privacy fence

As observed in the example at the beginning of this section, the space between fence panels plays a key role in the enhanced fire behavior of parallel WRC privacy fences in HW mulch beds. After ignition of the mulch bed and fences at the upwind end, the temperature rises in this space, and radiative feedback and convective heat transfer cause highly nonlinear fire growth that engulfs the entire fence within minutes. Figure 118 shows the condition of parallel WRC privacy fences spaced 20 cm (8 in) apart at a time five minutes after the fan was turned on. As indicated by the arrow, flames extended more than 0.6 m (2 ft) above the fence.

Fig. 118. Parallel western redcedar privacy fences with shredded hardwood mulch at 20 cm (8 in) spacing and low wind speed, at t = 5 min [Test B-82].

4.4.2.2. Double redwood lattice fence

Although the ignition process was different (gas burner rather than firebrand shower), these experiments agreed with the observations in Manzello et al. [61] that double lattice fences in a mulch bed become fully involved in a fire. Figure 119 displays a video image of a double redwood lattice fence near peak fire intensity, three minutes after the fan was set to a low wind speed. By its nature, the lattice fence is significantly more porous than a privacy fence. This may alter the balance of heat transfer and combustion processes, with both enhanced entrainment through the sides of the fence assembly and reduced isolation of the space between fences from the surrounding environment affecting the convective heat transfer. For the double lattice fence, a lattice fence is attached to each side of the stringers. At 9 cm (the width of the stringers), the spacing between the lattice fences is considerably smaller than the spacing of 20 cm to 91 cm in the parallel privacy fence experiments in this study, which changes the radiative feedback. More research, including analysis and modeling, is needed to fully understand the physical processes responsible for this fire behavior.

Fig. 119. Double redwood lattice fence with pine bark mulch at low wind speed, at t = 3 min [Test A-103].

4.4.2.3. Double pine lattice fence

Changing the type of wood used for the diagonal lattice from redwood to pine did not make a difference in the rapid fire growth behavior for the double lattice fence. Figure 120 shows a pine lattice fence experiment carried out under the same conditions as the redwood lattice experiment in Fig. 119. At the moment pictured, at 3 min 15 s after the fan had been turned on, the fire continues to exceed the height of the fence, having already consumed a large portion of the lattice upwind. Spot fires caused by firebrands have spread across the target mulch bed at the base of the structure from front to back.

Fig. 120. Double pine lattice fence with shredded hardwood mulch at low wind speed, at about t = 3:15 [Test C-29]. Note spot fires in the target mulch bed at the base of the structure caused by firebrands.

4.4.3. Fire Spread Behavior

Parallel WRC privacy fences and double RW and pine lattice fences in HW mulch beds were found to be significantly more hazardous than single fences of the same type with mulch. Under the tested conditions, the entire fence was engulfed in flames within a few minutes of imposition of wind. Our understanding of situations that could result in this dangerous fire behavior was expanded by studying the effects of spacing between the parallel privacy fences and of doubling the fence length, and the effects of wind speed on fire spread for a double lattice fence.

4.4.3.1. Effects of fence spacing and length

The first experiment on parallel WRC privacy fences in a bed of HW mulch was designed to represent a scenario in which two neighbors erected separate fences very close to the property line because both neighbors wanted to view the “good side” (i.e., the smooth side) of their fence. The fences were thus arranged with the stringers on the inside and the inner surfaces of the boards spaced 20 cm (8 in) apart. After finding that this configuration led to severe fire behavior, the next question was how far apart these fences would need to be for their fire behavior to decouple into that of two individual privacy fences.

Figure 121 shows the fire behavior near maximum flame height for parallel privacy fences at increasing spacings. For spacings from 20 cm (8 in) to 46 cm (18 in), the flames exceeded the height of the fence within 3 min to 5 min after ignition. At 61 cm (24 in), in Fig. 121 (d), the time for rapid flame growth to occur increased to 14.5 min. The outer char marks in this final case suggest that the flaming remained below the central stringer until rapid growth occurred.

In all of these cases, flames extended above the fence by a meter (3 ft) or more. Flames also extended downstream of the fence panel by at least 0.3 m to 0.6 m (1 ft to 2 ft).

End views for each of these parallel privacy fence cases are shown in Fig. 122. During the period of most intense burning shown in these video images, flames attached to the two fence panels and the mulch burned on the ground throughout the space between. As in the example, the fire between the two fence panels in each case started spreading low along the fence as it

Fig. 121. Flames extending above and downwind of parallel WRC privacy fences at fence panel spacings of a) 20 cm at t = 5:00 [Test B-82], b) 30 cm at t = 5:00 [Test C-5], c) 46 cm at t = 4:00 [Test C-6], and d) 61 cm at t = 14:30 [Test C-7].

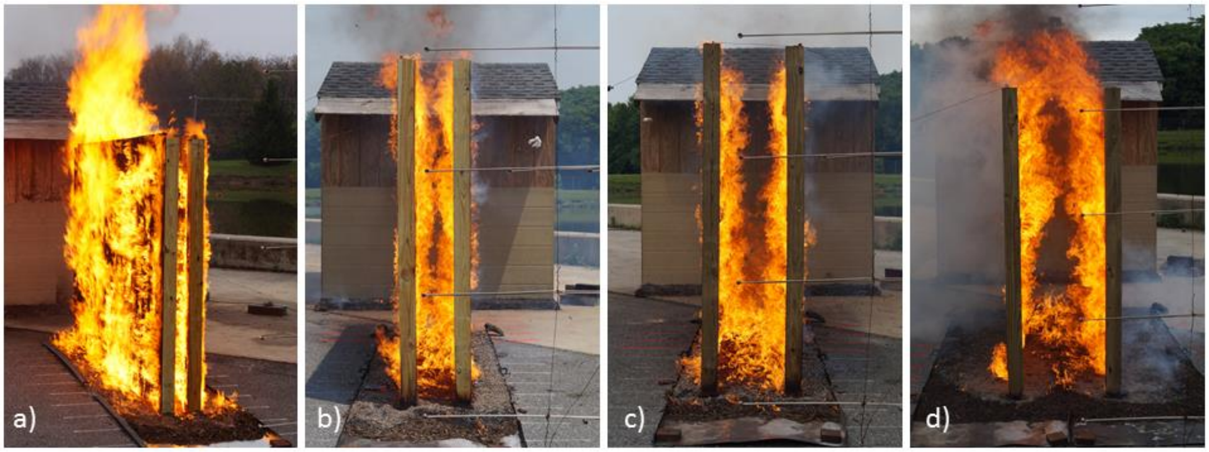

Fig. 122. Fire behavior of parallel WRC privacy fences at fence panel spacings of a) 20 cm [Test B-82], b) 30 cm [Test C-5], c) 46 cm [Test C-6], and d) 61 cm [Test C-7].

moved downwind from the ignition point, then moved up the panels at the end nearest the structure, and then spread back upwind toward the fan along the full height of the panels.

The increased time to reach rapid flame growth for experiment C-7 suggested that a critical point was approaching that might be reached by increasing the panel spacing beyond 61 cm (24 in). The expectation for that critical spacing was that the interactions between the two fence panels would drop below the threshold for severe fire behavior. With a spacing of 91 cm (36 in), the fire in experiment C-8 was indeed confined to the individual fence panels, as shown in Fig. 123.

Fig. 123. Fire behavior for parallel privacy fences spaced apart by 91 cm [Test C-8] showing a) end view and b) left side view at t = 18:00.

However, a closer look at the results revealed some differences between the parallel fence experiment in Fig. 123 and the experiments on single privacy fences under similar conditions. The final char pattern on the exterior of the parallel fences rose linearly in height near the structure, as illustrated by the red line in Fig. 123 (b). In addition, the flames on the inner surfaces of the fence panels moved backward against the applied wind, generating the discrete blackened char marks to the right of the red line and above the continuous char pattern closer to the mulch. These observations indicated that the critical panel spacing for separating the fire behavior for the parallel fences had not yet been achieved, and that the fire growth for this case may have been limited by the length of the fence.

To test the latter hypothesis, a final experiment was performed with an extra set of panels to double the fence length at the same parallel fence spacing of 91 cm. In this experiment, the flames over the first (upwind) set of panels were limited in height by the lowest stringer, as shown in the end and left side views in Fig. 124 from t = 5 min after the fan was turned on. After another 30 s, however, large flames were visible through the gaps between the boards of the second (downwind) panel, and by t = 6 min the downwind panel was fully engulfed in flames. The resulting large fire is shown in Fig. 125, with flames extending more than a meter (3 ft) above the fence.

It was not possible to use this experimental setup to investigate spacings between parallel fences wider than 91 cm because of the limited width of the wind field provided by the single large fan.

Fig. 124. Fire behavior at t = 5:00 for two-panel length parallel privacy fences at 91 cm spacing [Test C-13].

Fig. 125. Fire behavior at t = 6:15 for two-panel length parallel privacy fences at 91 cm spacing [Test C-13].

The conclusion from this set of experiments was that fences should not be built parallel to each other in a WUI environment, even when they are spaced apart by a meter (3 ft). In addition to providing a conduit for fire, this design introduces a severe flame and radiation hazard to the community.

A quantitative comparison of the flame spread for parallel WRC privacy fence experiments is displayed in Fig. 126. The plot shows the closest distance of char on the fence from the wall of the structure as a function of time. The horizontal black lines mark the locations of the fence posts. For experiments with spacings from 20 cm through 46 cm, an initial warmup period was followed by the fast flame spread rates (on the order of 5 cm/s) that mark the rapid development of severe fire conditions, with flames extending above the height of the fence. The flame spread was slower for Tests C-7 and C-8, with panel spacings of 61 cm and 91 cm respectively. The transition to flame engulfment of the parallel fence in Test C-7 did not occur until after the flames had traveled the full length of the fence panels, and thus does not appear as a steeper slope on this plot. Test C-8, with the largest panel spacing, never transitioned to rapid fire growth, although the progress of the fire along the base of the fence was faster than for Test C-7. The cause of timing differences between Tests C-7 and C-8 was not clear.

The uncertainties for the plots in Fig. 126 are described in the uncertainty analysis for fences in Appendix A.4.2.

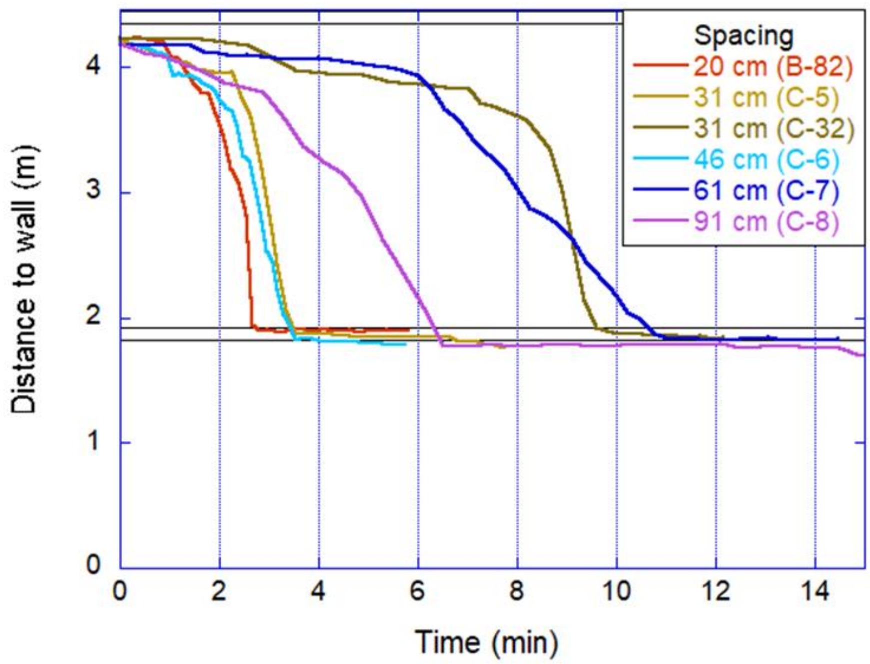

Fig. 126. Extent of charring as a function of time for parallel WRC privacy fences with spacings between fence panels from 20 cm to 91 cm.

The experiment for parallel WRC privacy fences with a spacing of 30 cm (12 in) was repeated at a different time of the year. Fig. 126 shows that the time period before rapid fire growth was significantly longer for Test C-32, which was carried out under significantly colder conditions than Test C-5. The average ambient temperature for Test C-32 was 13.6 °C (56.5 °F), compared to 28.8 °C (83.8 °F) for Test C-5. The large difference in initial fire spread demonstrates the potential effects of the ambient environment, as well as the inherent variability in these experiments. After the fire started to grow rapidly between the fences, however, both experiments proceeded in similar ways, with flames engulfing both fences.

Flame spread for the one-panel and two-panel length parallel WRC fence experiments (Tests C-8 and C-13 respectively) are compared in Fig. 127. The panel spacing for both experiments was 91 cm (36 in). As can be observed from the plot, the flame spread over the first panel of the two-panel length experiment (Test C-13) was somewhat faster than the flame spread over the one-panel set of parallel fences (Test C-8). In Test C-13, the fire took slightly over 5 min to travel from the ignition point to the center post. Although the plot then shows a pause in the progress of the charred area on the exterior of the boards, flames in the space between fences were visible between the boards during this time. After traversing the center post, the conditions in the space between the panels led to rapid flame engulfment over the second set of fence panels, shown in the plot by a steep drop in the flame spread curve. It can be speculated that the farther progress of flames along an extended length of parallel fences would occur in mere seconds. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

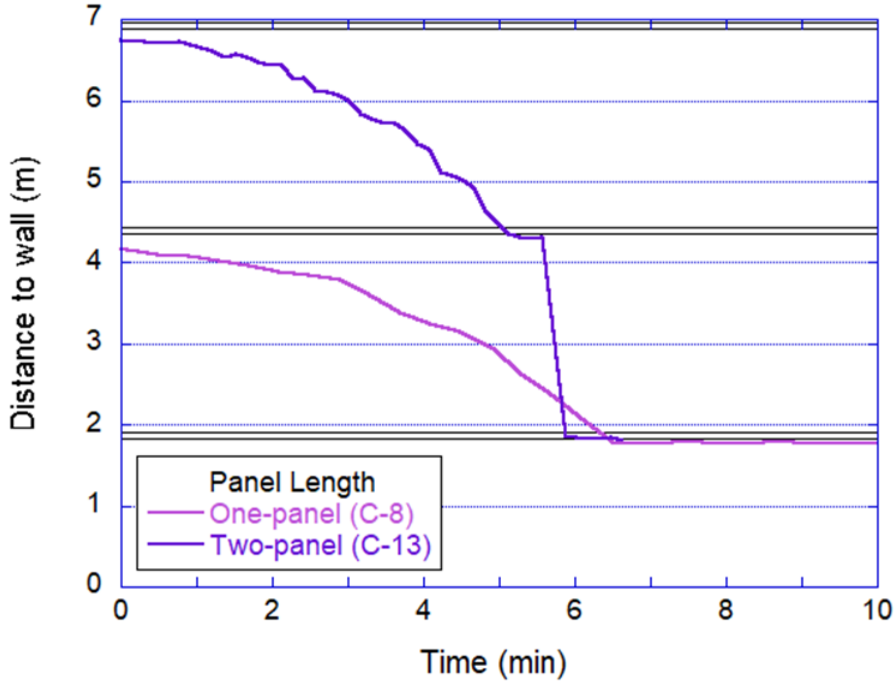

Fig. 127. Location of char front closest to the wall as a function of time for one- and two-panel length parallel WRC privacy fences with 91 cm spacing. Black horizontal lines indicate positions of end and center posts.

4.4.3.2. Effects of wind speed

The effects of wind speed on parallel fences were studied using double redwood lattice fences with shredded hardwood mulch beds. Video images from experiments at low, medium, and high wind speeds respectively are shown in Fig. 128.

The video images are from times shortly after each fence is engulfed in flames. As shown here, low wind speeds were observed to result in the highest flames and the longest time to rapid fire growth. As wind speed increased, the flames were lower on the fence and fire development was faster. At the highest wind speed, Fig. 128 (c) shows that the top few inches of the fence were not yet involved at this point in the development of the fire. The high temperature plume may have extended farther downwind than for lower wind speeds, but this was not measured.

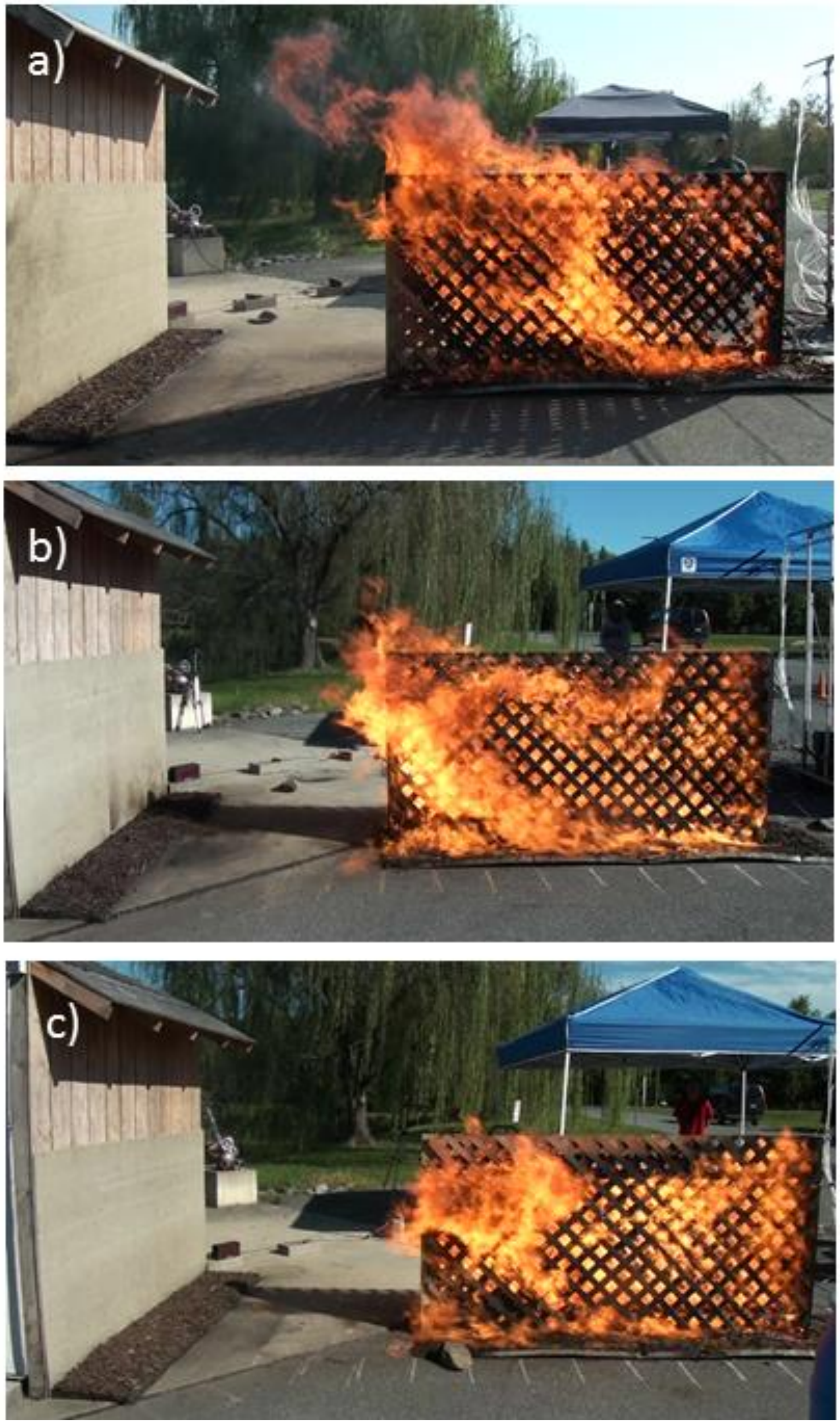

Fig. 128. Double redwood lattice fences with hardwood mulch as a function of wind speed: a) low wind (Test A-103 at t = 3:00), b) medium wind (Test B-75 at t = 1:30), and c) high wind (Test B-62 at t = 1:30).

The flame spread data associated with these experiments are presented in Fig. 129. This set of plots confirms that the fire took the longest time to reach the end of the fence for the low wind speed, while flame spread in high and medium wind speeds took the shortest time. Little difference was observed between flame spread plots for double pine lattice fences (Test C-29) and double redwood lattice fences (Test A-103) under low wind speed conditions. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

All double lattice fences combined with mulch beds were fully engulfed in fire within 5 min in these experiments. The speed and high hazard of fire development on double wood lattice fences is in agreement with those of parallel WRC privacy fences.

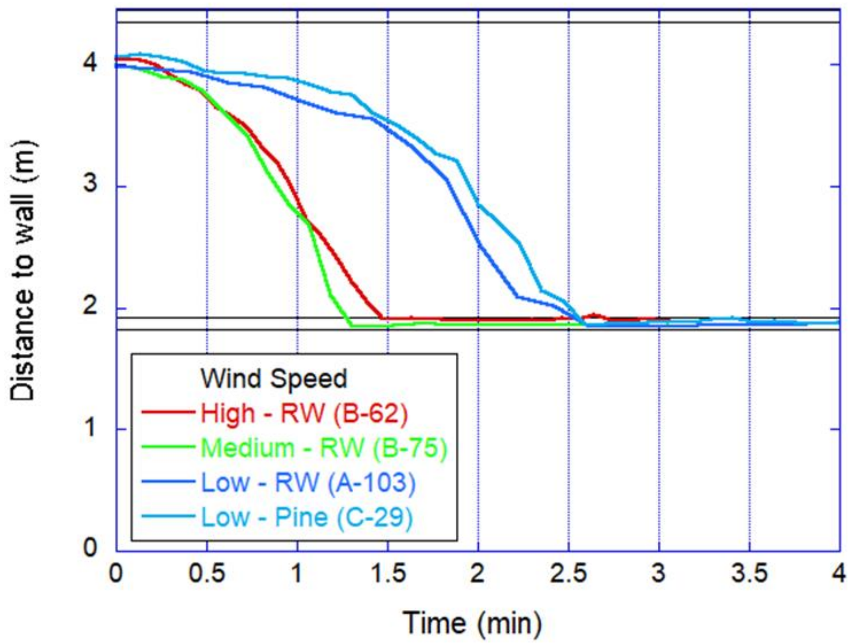

Fig. 129. Location of char front closest to the wall as a function of time for double parallel redwood and pine lattice fences with HW mulch at various wind speeds.

4.4.4. Parallel Fences Without a Mulch Bed

It is difficult to keep parallel privacy fences free from fine combustible materials. The space between fences erected along neighboring property lines is subject to the growth of weeds and the accumulation of leaves, needles, and other debris. In addition, materials may blow directly into this space from the corner where the fences enclosing each property separate.

Despite the improbability of encountering parallel fences free of debris, looking at this situation allows us to bound the problem and better understand the mechanisms. The study included a small number of parallel fence experiments without a mulch bed at the base. In the absence of the feedback from fine combustibles, a large fire was indeed more difficult to establish. In all but one case, removing the mulch beneath the parallel fences resulted in slow charring starting at the point of ignition, similar to the fire behavior for single fences without mulch described in Section 4.1.

Closeups near the point of ignition are shown in Fig. 130. The only case in which the fire moved beyond the corner where ignition took place was the double redwood lattice fence at low wind speed, shown in Fig. 131.

The color key for the matrix of parallel fence experiments in Tables B.5 and B.6 reflects these findings.

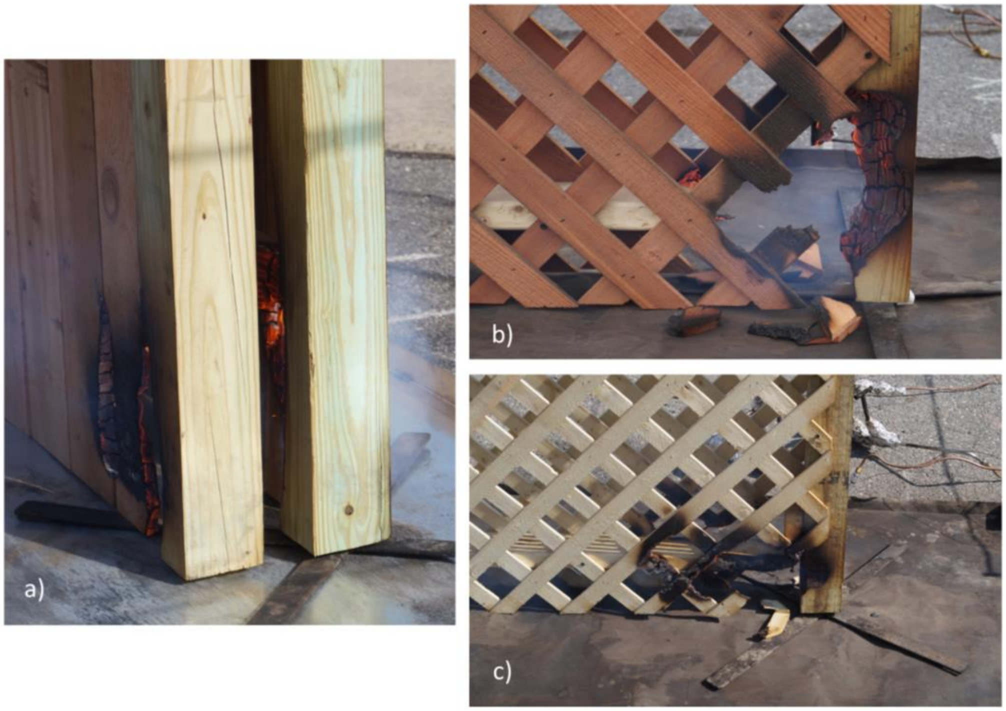

Fig. 130. Parallel fences without mulch: a) western redcedar privacy fence with 15 cm (6 in) spacing [Test B-84], b) redwood lattice fence at medium wind speed [Test B-80], and c) pine lattice fence at low wind speed [Test C-20].

Fig. 131. Double redwood lattice fences without mulch at t = 4 min with low wind speed [Test A-110].

4.4.5. Mixed Parallel Fences

Having established that wood privacy and lattice fences erected next to each other exhibit dangerous fire behavior, the next question was whether a fence built in close lateral proximity to a shed, garage or other type of fence might also present a risk. For an initial look at this issue, experiments were performed on a WRC privacy fence parallel to a cement board, a vinyl privacy fence, and a pine lattice fence. All experiments were performed with a bed of shredded hardwood mulch at the base, under low wind speed conditions, and at 1.83 m (6 ft) separation distance from the shed. Spacings between fence surfaces were either 31 cm (12 in) or 46 cm (18 in).

4.4.5.1. Cement board parallel to WRC privacy fence

Experiments at two different spacings were performed for a noncombustible cement board placed parallel to a western redcedar privacy fence. (The cement board was the same type as that attached to the shed wall, described in Section 2.3.) Figure 132 shows three images taken at the same time from different points of view for an experiment (Test D-7) with 31 cm (12 in) spacing between the fence panel and the cement board. Figure 132 (a) shows the space between the fence and cement board, and (b) and (c) provide side views of the WRC privacy fence and the cement board, with gold arrows pointing in the direction of the applied wind. The cement board was discolored near the burning mulch without further damage. The video images were captured at t = 6 min, shortly before the experiment was ended when a spot fire igniting close to the shed reached the shed wall.

The char pattern in Fig. 132 (b) rises from the area of ignition toward the end of the privacy fence and then decreases slightly in height, remaining below the center stringer. This is similar to the humped char profile shape observed previously for WRC privacy fences combined with HW mulch. In the discussion in Section 4.3.2, the humped shape of the char profile was attributed to the wind field, which separates into a lower vortex and a flow stream that passes over the roof as the air flow approaches the shed. In this case, however, the nearby cement board is expected to cause an asymmetry in the flow field and thermal environment around the burning WRC fence. In the presence of the cement board, the flame spread was considerably faster, with flames reaching the end of the fence in 3 min. This raised the question of whether a larger spacing between the WRC privacy fence and the cement board would give results intermediate between narrow spacing and a single panel WRC fence, with a similar char pattern and a slower flame spread.

Fig. 132. Cement board (noncombustible) parallel to WRC privacy fence with 31 cm (12 in) spacing, near end of experiment (t = 6 min), in camera views from a) near the fan, b) left side, and c) right side [Test D-7]. Arrows indicate wind direction.

In fact, the fire behavior changed when the spacing between privacy fence and cement board was increased to 46 cm (18 in). Figure 133 shows images from late in this experiment (Test C-15), which ran for 32 minutes before a spot fire reached the shed wall. For this spacing, the fire did not extend above the level of the first stringer on the WRC privacy fence, as seen in Fig. 133 (a) and (b). The shape of the charred profile did not display the hump seen for fence and mulch experiments in Section 4.3.2, possibly indicating disruption of the wind field by the cement board. Figure 133 (c) again showed discoloration of the cement board near the burning mulch on the ground. The wood post, bottom stringer, and HW mulch continued to burn throughout the test.

Fig. 133. Cement board (noncombustible) parallel to WRC privacy fence with 46 cm (18 in) spacing, near end of experiment, in camera views from a) near the fan, b) right side, and c) left side [Test C-15]. Arrows indicate wind direction.

The effects of placing the noncombustible cement board parallel to the WRC privacy fence and changing the spacing are summarized in Fig. 134 and Fig. 135. The similarities in the humped char pattern for the WRC privacy fence/cement board combination with a spacing of 31 cm (12 in) (Test D-7) and a single panel WRC fence (Test A-102) are apparent by comparing Fig. 134 (a) and (c), respectively. All experiments were performed under the same conditions: with hardwood mulch below the fences, in low wind flow, and with 1.83 m (6 ft) separation distance. The increase in flame spread rate by the addition of the cement board is shown in the plot of char front vs. time in Fig. 135. With the cement board in close proximity to the WRC privacy fence, the flames reached the end of the fence in 3 min, about a third of the time for the single panel privacy fence.

Increasing the spacing between WRC fence and cement board to 46 cm (18 in) in Test C-15 limited the char pattern over the wood fence to the lowest stringer, as seen in Fig. 134 (b) and slowed the flame spread. For this test, the fire reached the end of the western redcedar privacy fence about 11 min after the fan was turned on. As shown in Fig. 135, this was on the same order as the single panel WRC fence, although the char pattern suggests differences in the mechanisms of spread. The complexities of flame spread for a combustible fence next to a noncombustible fence or wall, with asymmetries in the thermal and wind environments on the free and confined sides of the combusting fence, deserve further investigation.

Fig. 134. Comparison of char patterns near the end of experiments with parallel WRC fence / cement board at a) 31 cm (12 in) spacing [Test D-7] and b) 46 cm (18 in) spacing [Test C-15] and c) single WRC panel [Test A-102]. Arrows indicate wind direction.

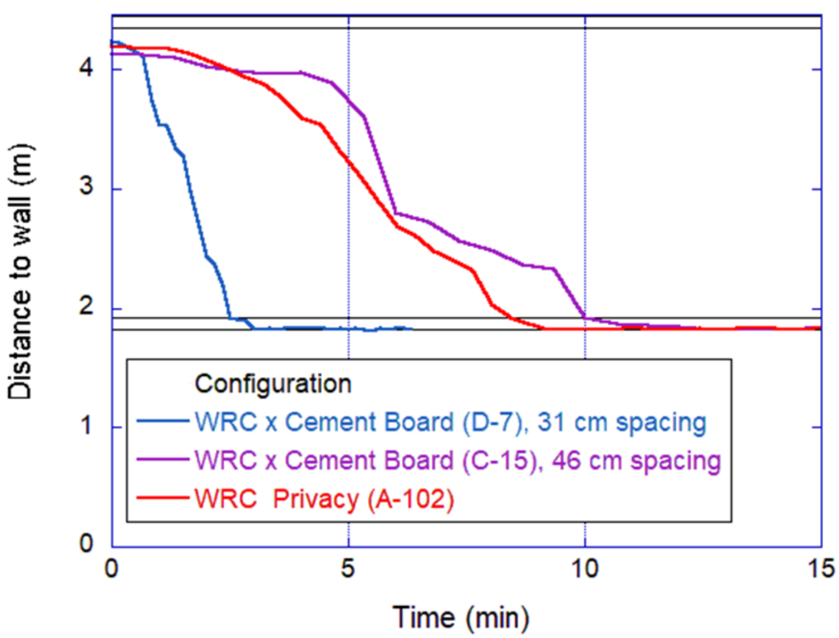

Fig. 135. Extent of charring as a function of time comparing parallel WRC fence/cement board combination at 31 cm (12 in) and 46 cm (18 in) spacings to single panel WRC fence.

The uncertainties for the plots in Fig. 135 are described in the uncertainty analysis for fences in Appendix A.4.2.

4.4.5.2. Vinyl privacy fence parallel to WRC privacy fence

Figure 136 shows the burning characteristics for a WRC privacy fence arranged parallel to a vinyl privacy fence with a spacing of 46 cm (18 in) (Test C-16). Photo (a) was taken about 21 min after the fan was turned on, and photos (b) and (c) were taken near the end of the experiment, which was allowed to run for 78 min before it was ended. A spot fire separately ignited the WRC fence near the downwind post at about t = 16 min, but no spot fires were detected in the target mulch bed. Like the WRC privacy fence/cement board combination at the same spacing described in the previous section, the char marks on the WRC privacy fence panel were unusual compared to other burn patterns seen throughout this study, in that the fire did not extend above the bottom stringer except close to the point of ignition. The burning mulch caused the vinyl fence to distort at its base, leaving the boards without support and eventually causing them to fall out of the frame, as shown in Fig. 136 (c).

Fig. 136. Vinyl privacy fence parallel to western redcedar privacy fence near end of test in camera views from a) near the fan, b) right side, and c) left side [Test C-16].

The continuous flame spread was slow for this combination of fences, taking 27 min to reach the end of the western redcedar privacy fence. This was more than double the flame spread time for a single WRC privacy fence combined with hardwood mulch under the same conditions, as shown in Fig. 137. This was also double the time for the flames to reach the end of the WRC privacy fence/cement board combination discussed in the previous section.

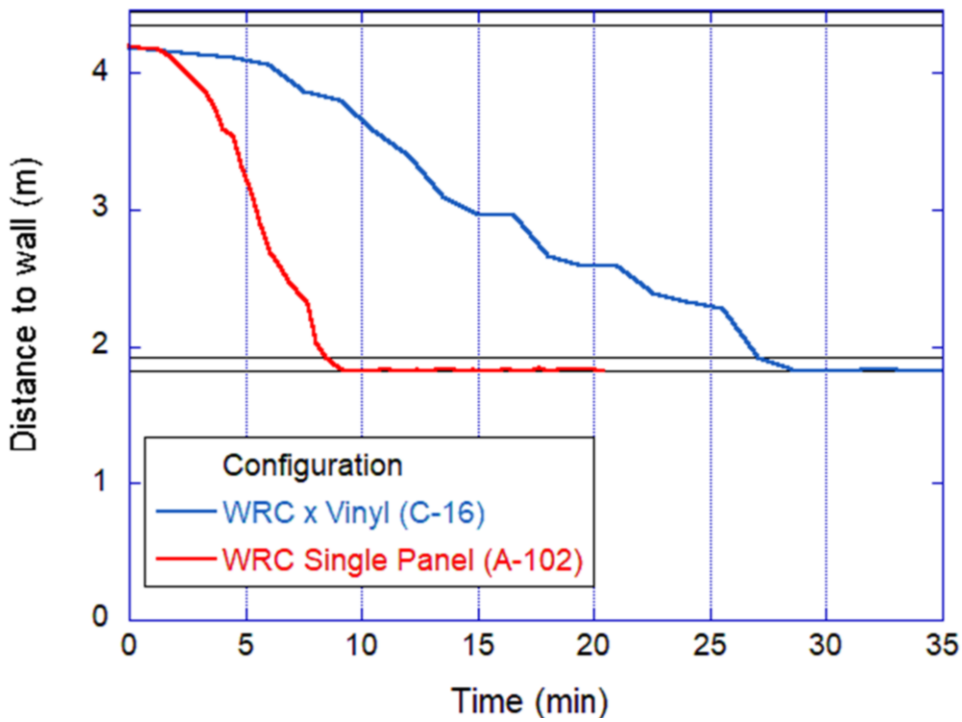

Fig. 137. Flame spread comparison of parallel WRC fence/vinyl fence combination at 46 cm (18 in) spacing to single panel WRC fence.

The uncertainties for the plots in Fig. 137 are described in the uncertainty analysis for fences in Appendix A.4.2.

4.4.5.3. Pine lattice fence parallel to WRC privacy fence

A western redcedar privacy fence was paired with a pine lattice fence at spacings of 31 cm (12 in) and 46 cm (18 in). With 31 cm spacing (Test D-8), this combination of fences behaved similarly to parallel WRC fences, as shown in Fig. 138. The fire grew rapidly over both fences until flames extended above the top of the privacy fence and beyond the end of the fences. The images in Fig. 138 show the state of both fences at t = 2:15, when the flames were longest and filled the space between the two fences.

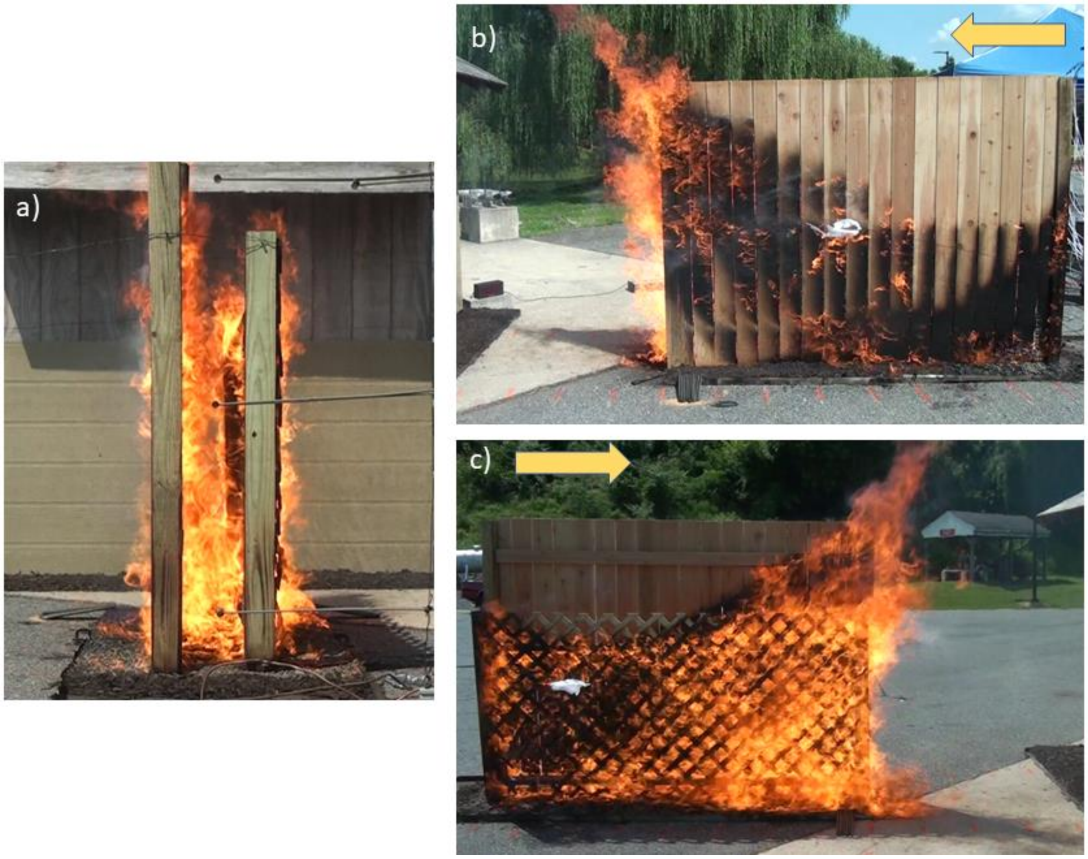

Fig. 138. Pine lattice fence parallel to western redcedar privacy fence with 31 cm (12 in) spacing, at maximum flame length (t = 2:15), in camera views from a) near the fan, b) left side, and c) right side [Test D-8].

When the spacing was increased to 46 cm (18 in) (Test C-17), the fire behavior for the parallel WRC privacy fence / pine lattice fence agreed with the observations for each fence burning individually under similar conditions. Figure 139 shows the burning characteristics of the parallel fences shortly before the experiment ended at t = 15 min. The burn patterns for both fences remained below the halfway point during the experiment and rose at the end closest to the structure. The patterns can be compared with Fig. 74 (d) and (h) for WRC privacy and redwood lattice fences respectively, under the same conditions of a HW mulch bed at low wind speed and 1.83 m (6 ft) separation.

Fig. 139. Pine lattice fence parallel to western redcedar privacy fence with 46 cm (18 in) spacing, near end of test, in camera views from a) near the fan, b) right side, and c) left side [Test C-17].

For a more concise look at the effects of spacing with mixed privacy and lattice fences, Figure 140 compares images from the WRC fence side of these two experiments with an image from a single panel WRC experiment performed under the same conditions. Similarly, Fig. 141 compares images from the pine lattice fence side with a single panel pine lattice experiment. In each case, the similarity of the parallel fence case with 46 cm (18 in) spacing compared with the single panel case is evident. The plots of maximum char extent as a function of time in Fig. 142 show similar flame spread behavior for the 46 cm (18 in) spacing case compared with single panels, while the flame spread is much more rapid for the 31 cm (12 in) case. The uncertainties for these plots are described in the uncertainty analysis for fences in Appendix A.4.2.

For this combination of fences, therefore, the evidence supports the conclusion that a spacing of 46 cm (18 in) was sufficiently large to decouple the fire behavior.

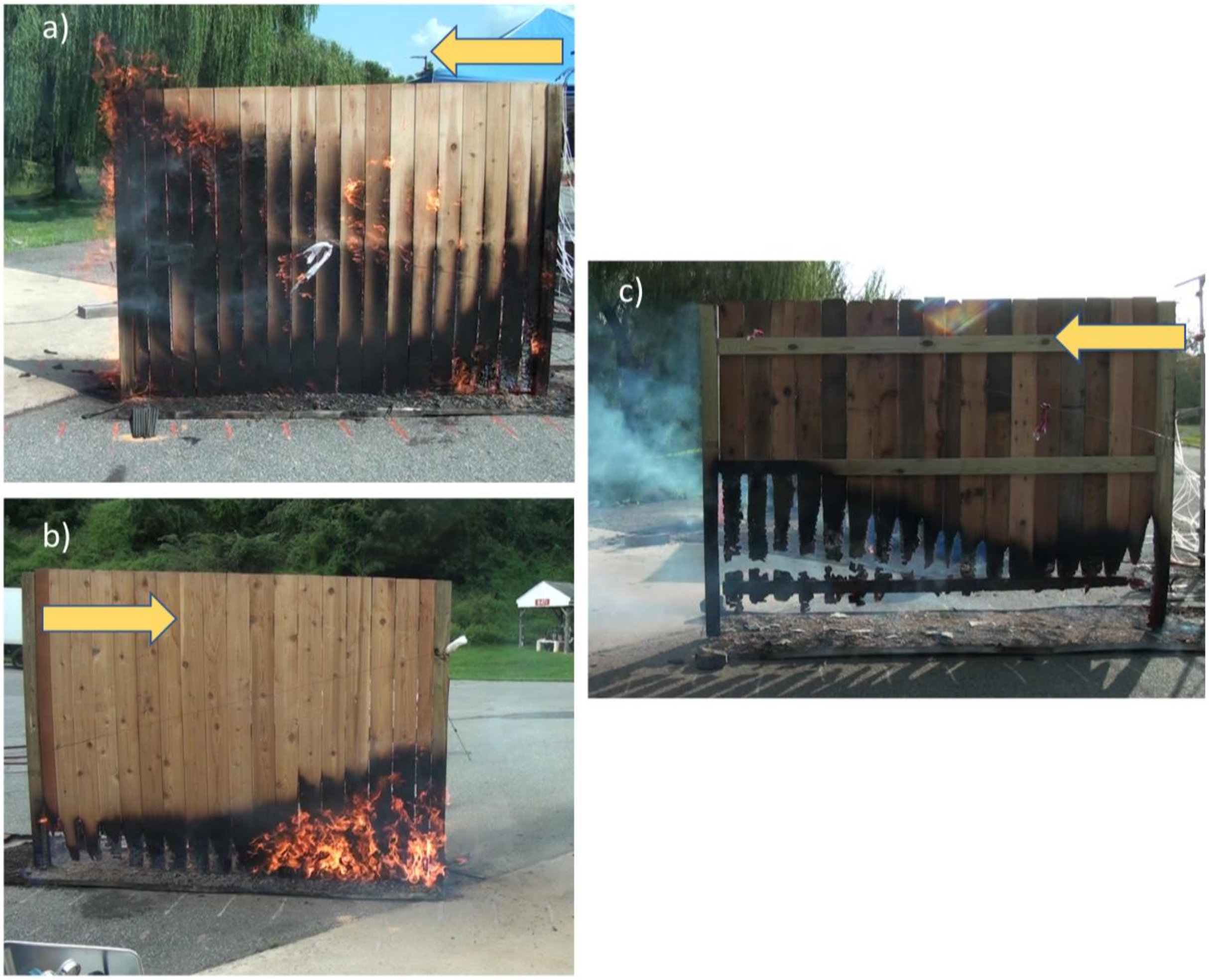

Fig. 140. Comparison of flame spread patterns for WRC privacy fence parallel to pine lattice fence at spacings of a) 31 cm (12 in) [Test D-8] and b) 46 (18 in) [Test C-17] with c) single panel WRC privacy fence [Test A-102]. Arrows indicate wind direction.

Fig. 141. Comparison of flame spread patterns for WRC privacy fence parallel to pine lattice fence at spacings of a) 31 cm (12 in) [Test D-8] and b) 46 (18 in) [Test C-17] with c) single panel PL fence [Test C-21]. Arrows indicate wind direction.

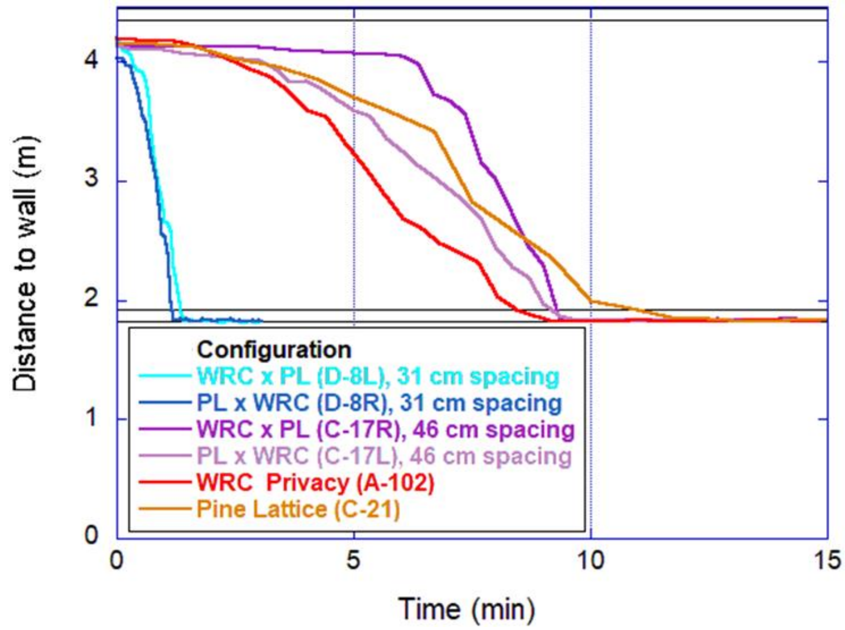

Fig. 142. Flame spread comparison of parallel WRC privacy fence/pine lattice fence combination at 31 cm (12 in) and 46 cm (18 in) spacing to single panel WRC privacy fence and pine lattice fence.

4.4.6. Firebrand Spotting

Almost all parallel fences combined with mulch resulted in spot fires in the target mulch bed next to the shed, as listed in Table 4. The single exception was the vinyl fence paired with a western redcedar privacy fence, which burned in low wind speeds for over 75 min without a spot fire ignition. This table summarizes the information about fire spread to the shed through firebrands from parallel fence experiments with mulch in Table D.6 and Table D.7, where a dark green background indicates flames above the fence, light green indicates spread to the shed through spot fires, and pink indicates no spot fires. All experiments with flames extending above the fence generated spot fires.

Table 4. Number of experiments producing spot fires for each combination of parallel fences with mulch.

Parallel Fence and Mulch Combination	Number of Experiments With Spot Fires	Number of Experiments Without Spot Fires
2 × Western redcedar privacy fence (WRC) / Shredded hardwood mulch (HWM)	8	0
2 × Redwood lattice fence (RWL) / Shredded hardwood mulch (HWM)	2	0
2 × Redwood lattice fence (RWL) / Pine bark mulch (PBM)	1	0
2 × Pine lattice fence (PL) / Shredded hardwood mulch (HWM)	1	0
Western redcedar privacy fence (WRC) / Cement board / Shredded hardwood mulch (HWM)	2	0
Western redcedar privacy fence (WRC) / Vinyl privacy fence / Shredded hardwood mulch (HWM)	0	1
Western redcedar privacy fence (WRC) / Pine lattice fence (PL) / Shredded hardwood mulch (HWM)	2	0

The times to ignition of the first spot fire are plotted as a function of wind speed in Fig. 143. Only two experiments were performed at medium and high wind speeds; although the times to ignition for both were short (less than 2 min), the relationship with wind speed for parallel fences cannot be determined from these experiments. Spot fires ignited in less than 12 min in all cases.

All parallel fence experiments were performed at a separation distance from the shed of 1.83 m (6 ft), so no data exists to determine the effects of separation distance.

Times for the ignition of the first spot fire to put flames against the wall and the first flames to reach the wall are plotted in Fig. 144 and Fig. 145, respectively. With a single exception, flames reached the wall within a few minutes of first spot fire ignition.

Figure 146 compares spot fire ignition times for the parallel fences with mulch to the single fences with mulch discussed in Section 4.3.5. As a category, firebrands from parallel fences ignited spot fires in the target mulch bed more quickly. This is reasonable, since the large area on fire in these cases may increase the rate of firebrand generation over that of the single fence that is burning only low to the ground, and the higher fire intensity may loft more firebrands from both mulch and fence into the vortex that carries them toward the shed wall.

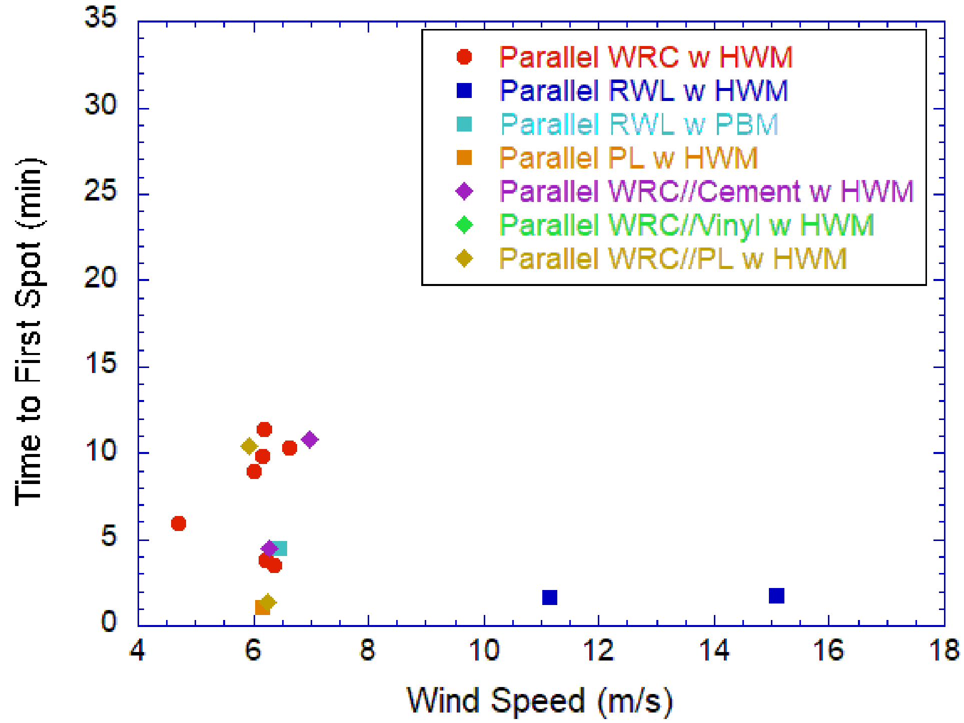

Fig. 143. Time to ignition of first spot fire vs. wind speed for parallel fence plus mulch experiments.

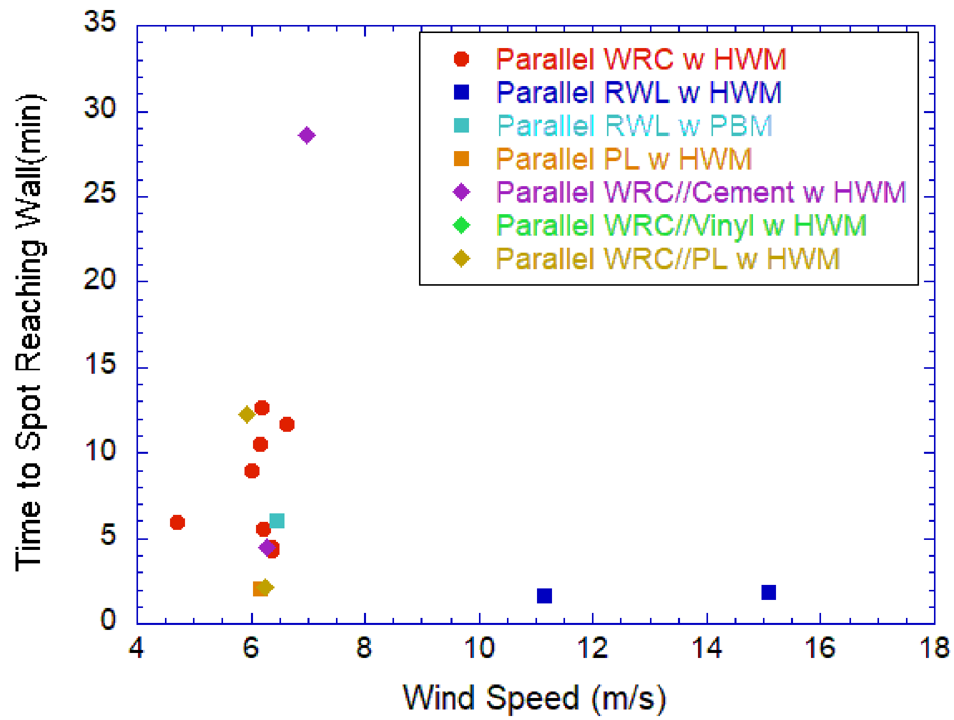

Fig. 144. Time to ignition of first spot fire to put flames against the wall vs. wind speed for parallel fence plus mulch experiments.

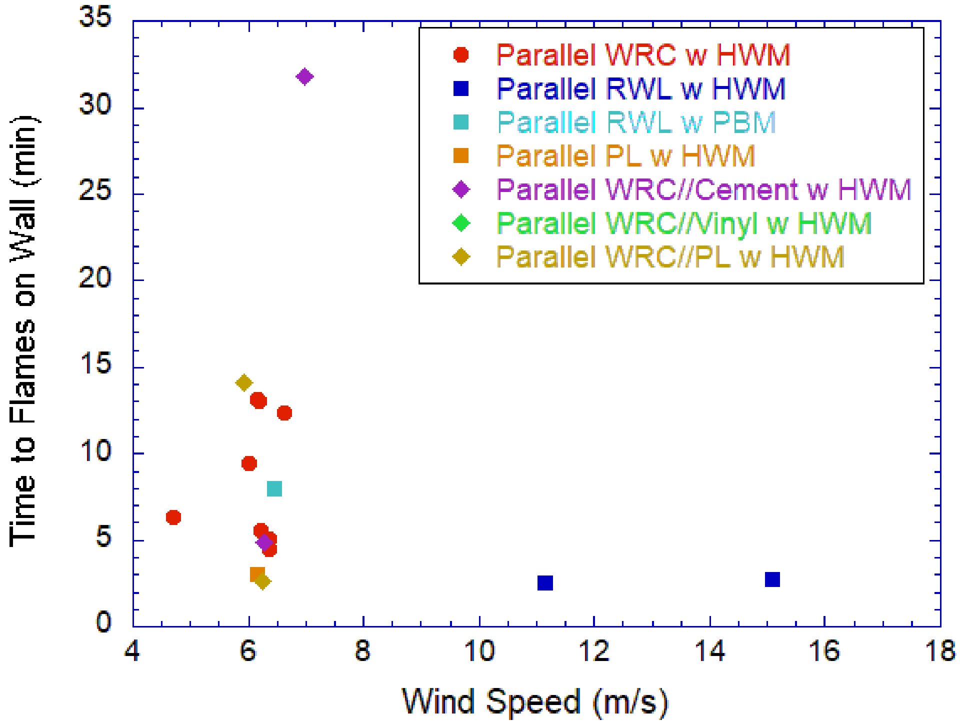

Fig. 145. Time to flames reaching wall vs. wind speed for parallel fence plus mulch experiments.

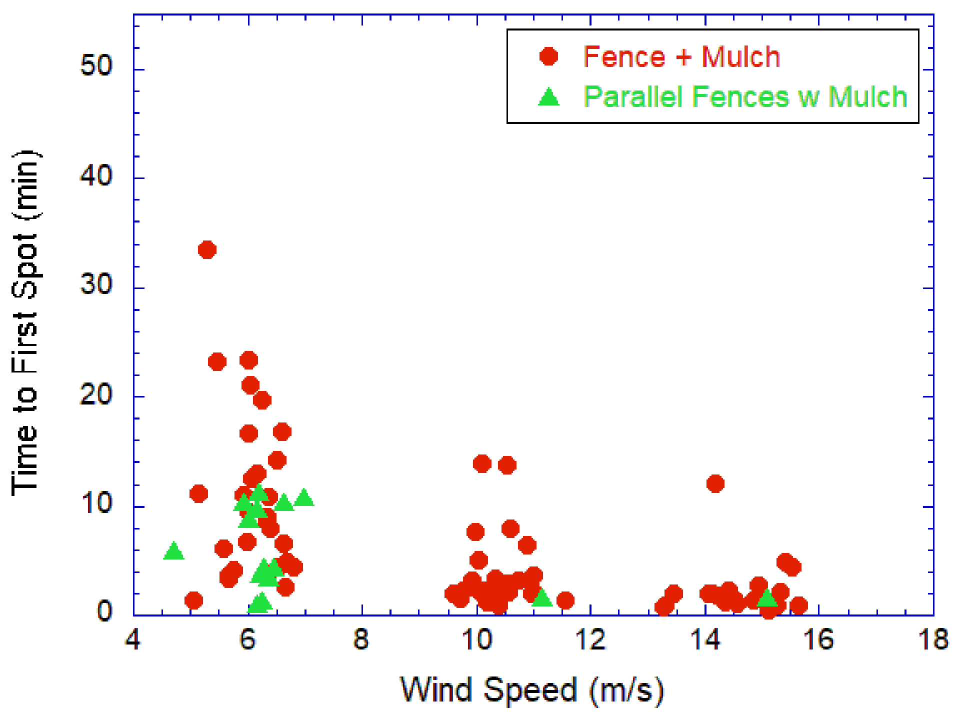

Fig. 146. Comparison of times to ignition of first spot fire between single fences and parallel fences with mulch as a function of wind speed.

In the absence of mulch beneath the fence, all three double redwood lattice fence experiments resulted in firebrand spotting. This included the case at low wind speeds that developed large flames and experiments at medium and high wind speeds that showed little flame spread beyond the area of ignition. There was little spread over either the parallel WRC privacy fence or double pine lattice fence, and no spot fires were observed in these experiments. Table 5 summarizes this information, which relates to the parallel fence experiments without mulch listed in Table D.6 and Table D.7.

Table 5. Number of experiments producing spot fires for parallel fences without mulch.

Parallel Fence Combination	Number of Experiments With Spot Fires	Number of Experiments Without Spot Fires
2 × Western redcedar privacy fence (WRC)	0	1
2 × Redwood lattice fence (RWL)	3	0
2 × Pine lattice fence (PL)	0	1

The times to first spot fire ignition for all experiments without mulch that produced spot fires are plotted in Fig. 147 as a function of wind speed. The plot includes the three double redwood lattice fences discussed in this section as well as the fence only experiments discussed in Section 4.2.4. When spot fires occurred in cases without mulch present, they took anywhere between 2 min and an hour to ignite. No relationship with wind speed was observed.

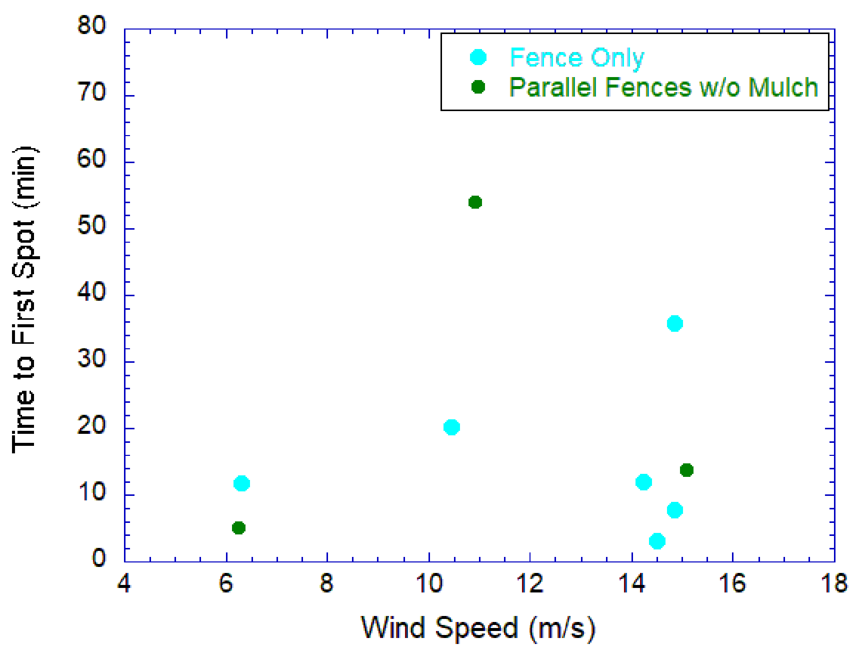

Fig. 147. Time to first spot fire as a function of nominal wind speed for experiments on single (blue) and parallel (green) fences only (without mulch) in which spotting occurs.

4.4.7. Discussion

This set of experiments showed that wood fences erected parallel to each other result in a mode of fire behavior that is much more dangerous than that for single fences. In this mode, the flame spread suddenly accelerates, leading to large flames that engulf the fence and threaten nearby structures through direct flame, radiation, and enhanced convection, as well as firebrands that are lofted into the air. Similar behavior was found for western redcedar privacy fences spaced up to 91 cm (3 ft) apart and for double redwood and pine lattice fences, with a lattice attached to both sides of a two-by-four wood beam.

Parallel fences exhibit eruptive fire behavior, which is described as a sudden change in the rate of fire spread and in energy release within a very short time period [62]. The fences exchange thermal radiation between the surfaces, and the heat feedback is enhanced by convective heat transfer through the interior space between the fences. The applied wind transports the hot air downwind from the point of ignition, and buoyancy carries the hot air upward to preheat the upper parts of the fences. After the entire downwind end of the fence has ignited, the fire spreads backwards within the interior space.

It was initially postulated that the entrainment of air through the highly porous sides of the lattice fence may be an important factor in the fire behavior of parallel fences (i.e., a chimney effect). However, the experiments on WRC privacy fences showed that this was not the case. The gaps between the boards of the privacy fences may allow some air flow, but it seems more likely that the fire behavior results from a combination of radiation between the parallel planes and convection of gases from the hot plume downwind and rising (through buoyancy) lengthwise through the space between the fences. Improved understanding of this fire behavior will shed light on other fence designs, such as good neighbor fences, that may also demonstrate inherently hazardous fire behavior.

In addition to the privacy and lattice fences, with sides that face each other directly, it should be mentioned again that the good neighbor fence, whose boards are offset, demonstrated some of the characteristics of the fire behavior of parallel fences. The discussion in Section 4.3.3.6 observed that the flames spread upward on the good neighbor fence and reached the top of the fence within 14 min. This differed from the flame spread over other single wood fence panels in a mulch bed, which was generally confined to the lower half of the fence after ignition at the base.

The rapid progress of flames along a set of parallel fences can be expected to be much faster once the fire has been established. Multiple ignitions by firebrands along the base of the fence or igniting debris between the fences would make this an even faster more hazardous feature.

4.4.8. Summary

Findings from this set of experiments include:

Fire spread behavior. Parallel combustible fences with fine combustible material at the base are a highly hazardous configuration for WUI fires, allowing rapid development of large fires.

- Fire behavior of parallel wood fences is greatly enhanced compared to that for a single line of fencing. The behavior is eruptive, undergoing large changes in fire spread and energy release in a short time.
- Parallel wood privacy fences and double wood lattice fences can be engulfed in flame within a few minutes of ignition.
- A large fire occurs even when wood privacy fences are separated by 91 cm (3 ft). A safe spacing distance between parallel combustible privacy fences was not determined from this set of experiments.
- The hazard of parallel fences increases with length. Two-panel-long parallel privacy fences spaced apart by 91 cm (3 ft) showed eruptive fire behavior that was not observed for one-panel-long parallel fences under the same conditions. After thermal conditions between the fences have intensified due to the initial ground fire between the panels, flames engulf the parallel fences in 30 s to 1 min. It can be speculated that the farther progression of flames along an extended length of parallel fences would occur in mere seconds, and that multiple ignitions along or between the fences in a WUI fire would make this an even faster and more hazardous event.
- Low wind speeds result in the highest flames. The time to rapid fire growth was longer by about a minute for low compared to medium or high wind speeds.
- The difference between the fire behavior of single and parallel fences is a good example of the need to test not only materials but assemblies for accepted use in WUI environments.

Type of fence. Similar fire behavior was observed for parallel wood privacy fences and double wood lattice fences.

- Parallel WRC privacy fences and double redwood and pine lattice fences showed similar fire behavior, with a fire ignited at the base moving downwind along the ground for a meter or so and then quickly rising to envelop the entire height of the fence panel, with large flames extending above and beyond the fence.
- The time for parallel WRC privacy fence panels at a spacing of 46 cm (18 in) or less to become fully engulfed by flames was as little as 4 min. The time for flames to engulf redwood and pine lattice fences separated by stringers 8.9 cm (3.5 in) thick was even less at 1.3 min to 2.5 min. It is unclear whether this difference is influenced more by the design (lattice vs boards) or the spacing between fence panels.
- Changing the type of wood used for the diagonal lattice from redwood to pine did not make a difference in the rapid fire growth behavior for the double lattice fence.

Mixed parallel fences. A WRC privacy fence mounted next to a noncombustible cement board or a vinyl privacy fence in a HW mulch bed did not display the eruptive fire behavior of parallel wood fences. The severity of the fire behavior for a WRC privacy fence next to a pine lattice fence depended on spacing.

- Eruptive fire behavior was not encountered for a WRC privacy fence mounted next to a cement board or a vinyl privacy fence at spacings of either 31 cm (12 in) or 46 cm (18 in).

- A WRC privacy fence separated from a noncombustible cement board by 31 cm (12 in) resulted in a char pattern similar to that of a single panel WRC privacy fence, although flame spread was about three times faster.
- For a spacing of 46 cm (18 in), the fire behavior was less intense for a WRC privacy fence in combination with either a cement board or a vinyl privacy fence, as compared to a single panel WRC fence. The char pattern remained below the bottom stringer and the flame spread was at the same rate or slower.
- A WRC privacy fence next to a pine lattice fence showed eruptive behavior for 31 cm (12 in) spacing. For 46 cm (18 in) spacing, the char patterns on each fence were similar to those for the individual fences on their own.
- Further research is needed to fully investigate the possible fire hazards of combustible fences built next to auxiliary structures or to other fences.

Parallel fences without mulch. Keeping the base of parallel fences and the space between them free of fine combustibles would be a challenging maintenance task, and this is not considered to be a viable mitigation approach.

- Without fine combustibles at the base, a large fire is less likely to develop over parallel or double fences.
- At low wind speeds, large flames developed over the double redwood lattice fence even in the absence of mulch.

Firebrand spotting. Firebrands capable of igniting spot fires are generated by all combinations of fence and mulch tested.

- Spot fires are ignited within a few minutes of mulch and fence ignition.
- No parallel fence experiment (other than the vinyl/WRC one) took longer than 12 min to ignite the target mulch bed. This is not surprising, given that the fences were engulfed in flame. This could have both increased the rate of firebrand generation over the single fence that is burning only low to the ground and lofted the firebrands higher due to the energy in the plume. Higher firebrands are expected to travel farther in the same wind field and thus ignite more fires downwind.

Opportunities for model development: There is a need to better understand the physics behind the fire behavior of parallel fences in order to identify certain high hazard designs to be avoided in WUI areas. The results in this section may be helpful in validating a physics-based fire model, including:

- Fire behavior of parallel fences compared to single fences.
- Dependence on parallel fence spacing for time at which flames engulf the fences.
- Dependence of fire behavior on parallel fence length, including the spacing for which a second panel length results in explosive fire growth, and the time for fire to spread down a long fence.
- Lack of hump in char pattern for a wood privacy fence parallel to a noncombustible or vinyl fence, and its relationship to the wind field.

4.5. Long-Range Firebrand Experiments

A final question addressed by this work was the ability of firebrands from landscaping elements to ignite combustible objects far from the burning source. This was considered in three experiments in which the shed was removed and the burning source placed far from the target mulch bed.

4.5.1. Experimental Design

The long-range firebrand experiments were performed at the Frederick facility described in Section 2.1, in an orientation along the pond that allowed for maximum distance downwind. The applied wind field was directed from the SSE at an angle of 148° ± 1°. The structure was not included in this test setup. The target mulch bed was situated at a distance 50 m (164.5 ft) from the upwind edge of the burning object (firebrand source), with the wind machine propeller 3.7 m (12 ft) farther upwind. The surface between the source and the target was asphalt and concrete, representing a worst case scenario due to the ease of transport of firebrands over the ground. Roads and driveways make this a realistic condition for WUI neighborhoods. Since the purpose of the burning object in these experiments was to serve as a source of firebrands, the wind speed was varied, with lower wind speeds to promote flame growth at the burning source and higher wind speeds (up to about 15 m/s) to promote firebrand transport toward the target mulch bed. The wind machine was shut off or set to idle at times during each experiment to permit replacement of burned mulch in the target bed.

The bidirectional probe array was used to monitor wind speeds upwind of the burning source. Over the long distance from the wind machine to the target mulch bed, the applied wind field expands and diffuses, decreasing the wind speed at the target. The wind speed levels reported in this section were measured near the fan. No measurements were taken to quantify the wind speed near the target mulch bed.

4.5.2. Firebrand Spotting

Firebrand sources for the three long-range experiments were a double redwood lattice fence and two beds of shredded hardwood mulch. Figure 148 and Fig. 149 provide views from the double lattice fence and one of the hardwood mulch beds, respectively, looking toward the target mulch bed in the distance.

In both cases, spot fires ignited in the target mulch bed located about 47 m (155 ft) from the firebrand source within 3 min after the wind machine was set to a high wind speed.

Fig. 148. Double lattice fence experiment without a structure and with a target mulch bed situated 47.6 m (156 ft) from the downwind end of the fence [Test C-3].

Fig. 149. Shredded hardwood mulch experiment without a structure and with a target mulch bed situated 47.0 m (154.5 ft) from the downwind end of the mulch bed [Test C-2].

Images from Test C-3 are presented in Fig. 150. In Fig. 150 (b) and (c), the double redwood lattice fence is shown at t = 7 min and t = 10 min after the fan was started. For this experiment, the fan was alternated between low and medium wind speeds for about 7 ½ min, during which time no ignitions were observed. The fan was then increased to a high wind speed. A little more than 2 min later, a spot fire ignited in the target mulch bed 47.6 m (156 ft) downwind from the double fence. Figure 150 (a) shows this spot fire at t = 10 min, at which time the double lattice fence had fully collapsed, as seen in (c).

Fig. 150. Spot fire ignition resulting from double redwood lattice fence, showing a) the target mulch bed at t = 10 min, after 2 min at high wind speed, and the double lattice fence at b) t = 7 min and c) t = 10 min after the fan was turned on [Test C-3].

Figure 151 and Fig. 152 show the source and target mulch beds during Test C-2. For this experiment, the fan was turned on to a high wind speed and held there for 6 ½ min. Two spot fire ignitions were identified during this period, with smoke appearing at about t = 5:40 and t = 6:15. Figure 151 shows the state of the source mulch bed and the spot fire in the target mulch bed during this period, at t = 6 min. The spot fires were then extinguished and replaced with fresh mulch, and the fan was set to a medium wind speed for 4 min. During this time, no ignitions were observed. At t = 13:40, the fan speed was increased again to produce a high wind speed, and several spot fires ignited between 1 min and 2 min later. Photos of the source and target mulch beds at t = 16 min are shown in Fig. 152.

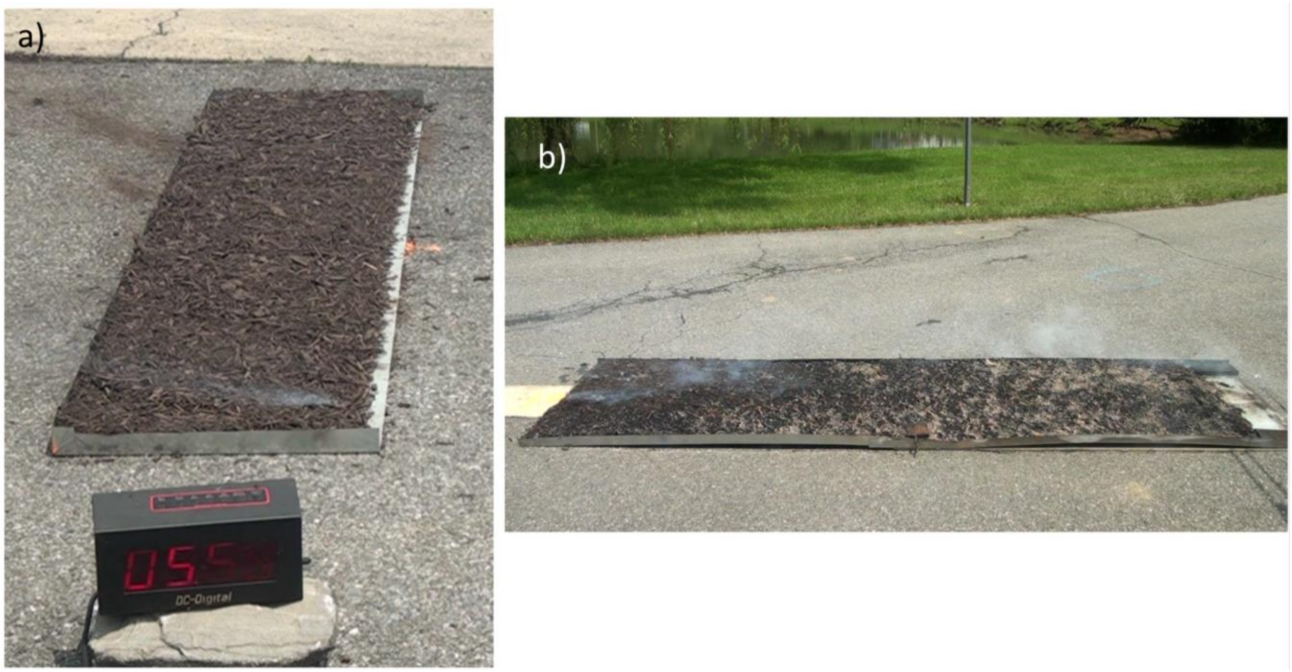

Fig. 151. Spot fire ignition in a) target mulch bed resulting from b) burning shredded hardwood mulch at t = 6 min, with high wind speed [Test C-2].

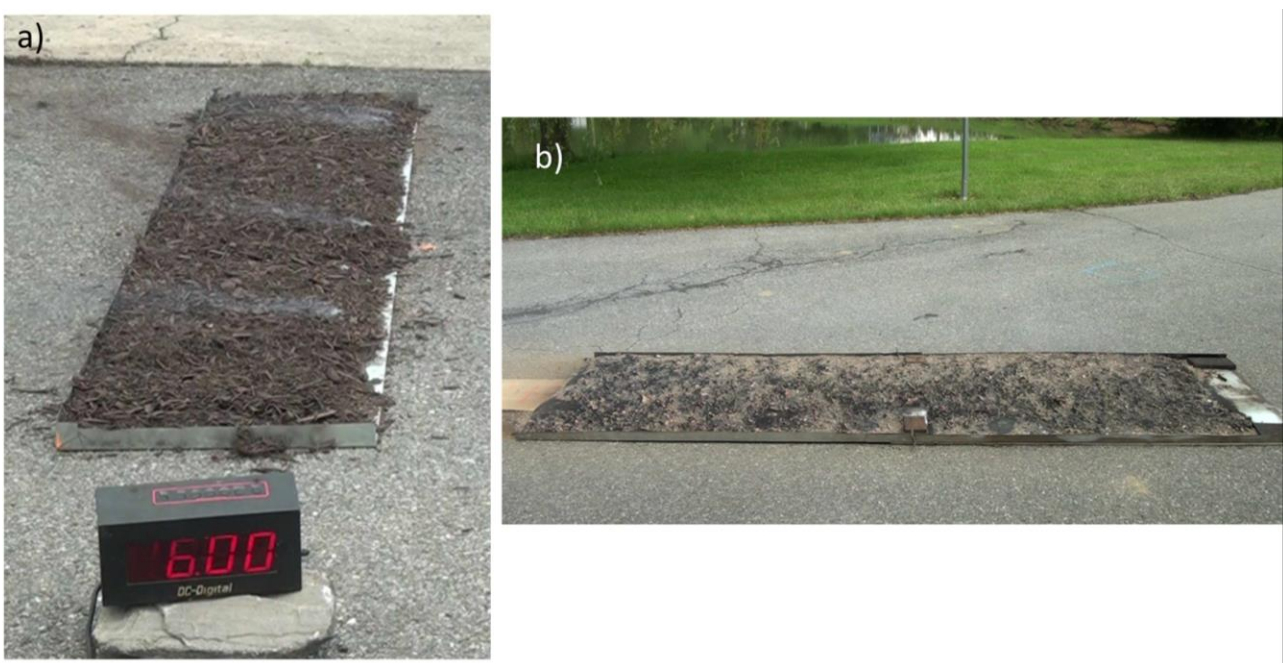

Fig. 152. Spot fire ignitions in a) target mulch bed resulting from b) burning shredded hardwood mulch at t = 16 min, after 2 min at high wind speed [Test C-2].

Many of the spot fires occurred in the middle of the target mulch, indicating that some firebrands were lofted rather than simply moving across the ground. To test this idea, an experiment was carried out in which the target mulch bed was elevated above the ground by 20 cm (8 in). Figure 153 shows the setup for this experiment from the point of view of the raised target, with the source mulch bed and the wind machine in the background. The target mulch bed was placed 38.1 m (125 ft) from the downwind end of the mulch bed. The fan was initiated at a high wind speed, and the spot fire seen in Fig. 154 appeared 4 min later.

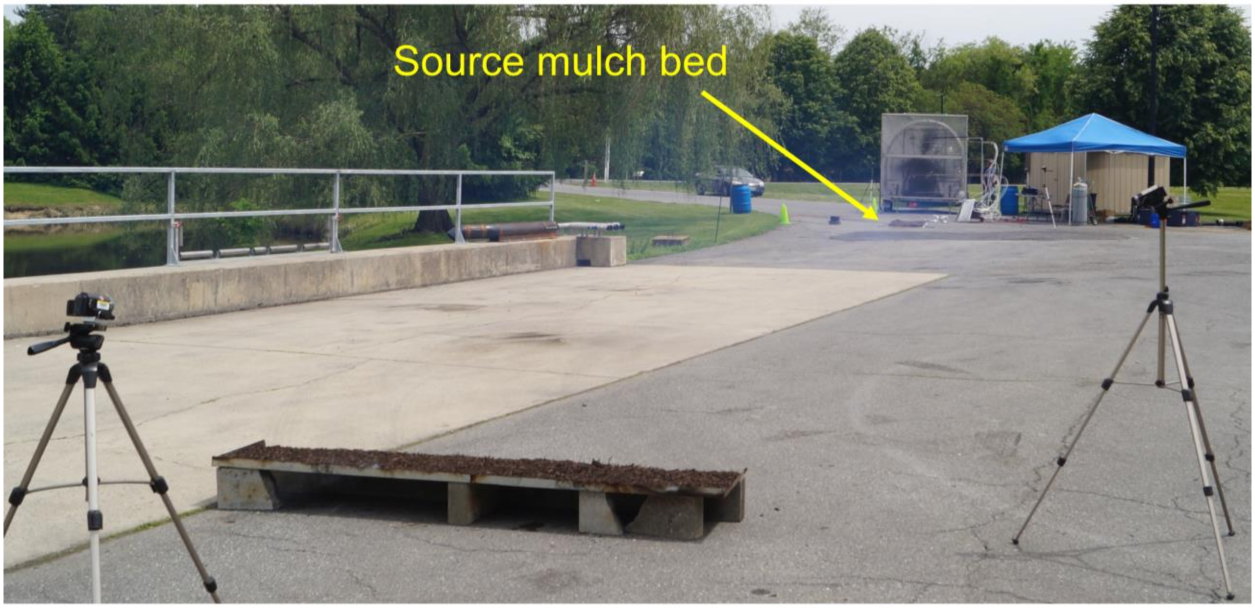

Fig. 153. Setup for shredded hardwood mulch bed without a structure and with an elevated target mulch bed situated 38.1 m (125 ft) from the downwind end of the mulch bed [Test D-1].

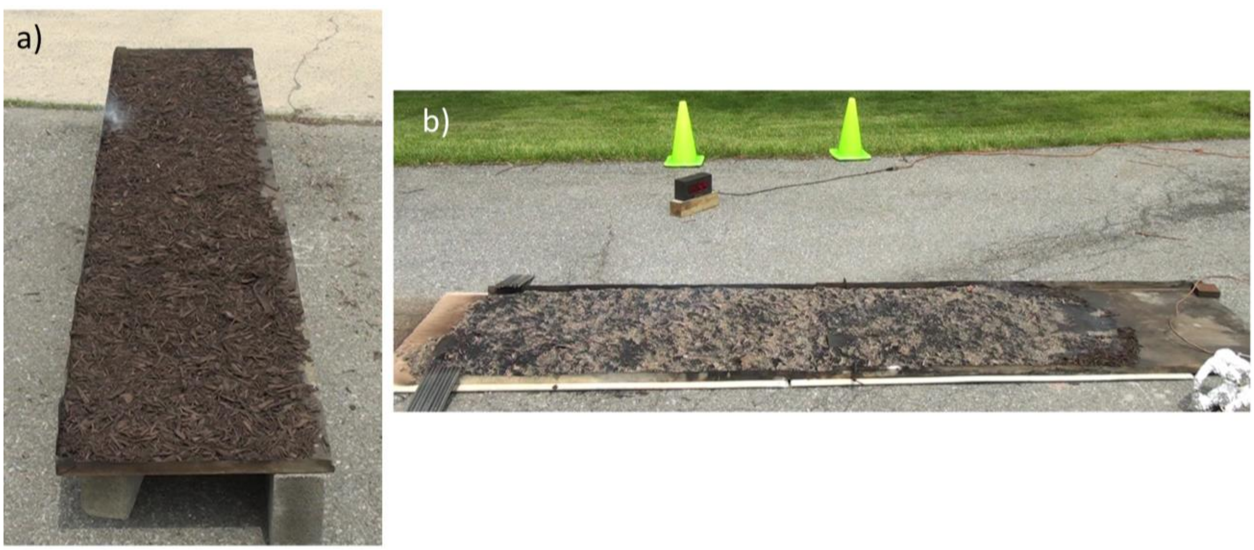

Fig. 154. Spot fire ignition in a) target mulch bed resulting from b) burning hardwood mulch at t = 6 min [Test D-1].

As an example of the universality of these findings, ignitions in a target mulch bed were also obtained from a stacked woodpile of maple firewood. In this case, the target mulch bed was 26.8 m (88 ft) from the upwind end of the woodpile, and the wind machine propeller was 3.4 m (11 ft) farther upwind. The woodpile was 1.2 m (4 ft) long. The images in Fig. 155 (a) and (b) are from target mulch bed and woodpile videos respectively, at about 20 min after ignition of the woodpile and 3 min after the wind machine has been set to a high wind speed. At this time, two spot fires are well-established in the target mulch bed, the first having ignited within 2 min from the start of high wind speeds. When the wind speed was reduced to medium levels, no further ignitions occurred.

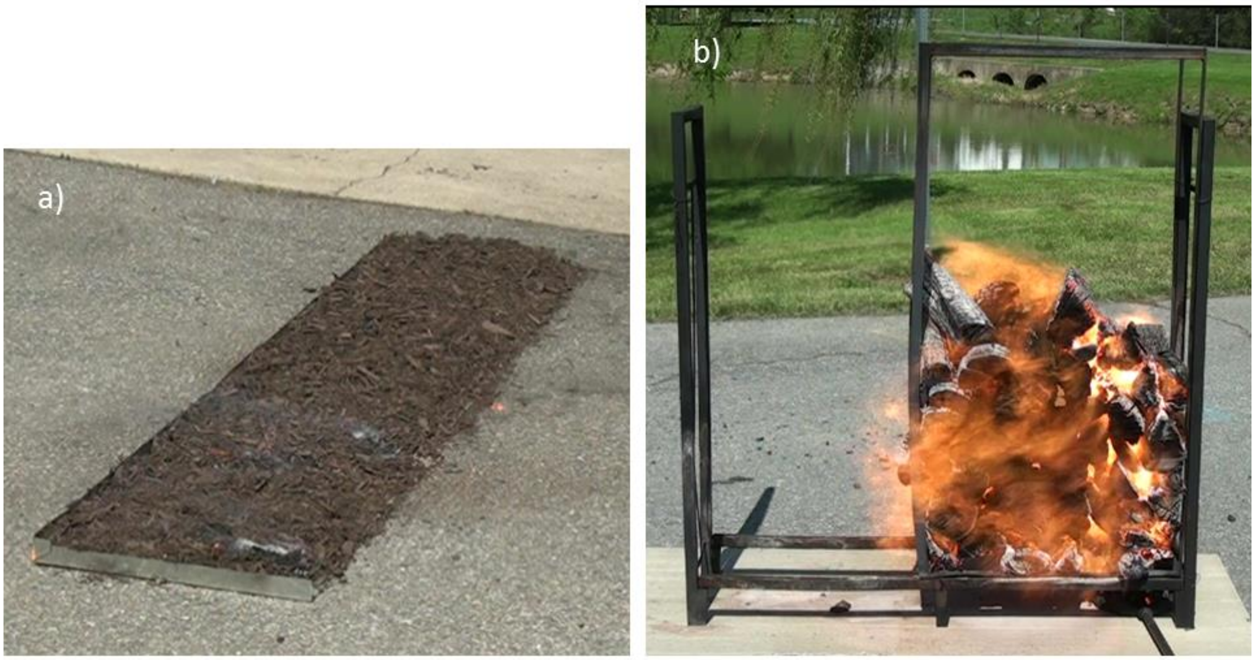

Fig. 155. Woodpile experiment without a structure and with a) a target mulch bed situated 25.6 m (84 ft) from the downwind end of b) the woodpile [Test C-1].

4.5.3. Summary

Findings from this set of experiments include:

Firebrand spotting. Ignition of spot fires was demonstrated from firebrands transported by the wind over long distances.

- Firebrands from fences and mulch are capable of igniting spot fires in combustible material located at least 47.6 m (156 ft) from the burning item under high wind conditions and over a paved surface. Spotting may have occurred at greater downwind distances, but this was the maximum distance evaluated at the test site. Even at this distance, these experiments demonstrate the spotting potential of these landscape fuels both within and beyond residential parcels.
- Some firebrands capable of igniting spot fires are lofted in high wind conditions.

5. Discussion

5.1. Hazardous Scenarios

The fire behavior found for combinations of fences and mulch in this study can be applied to fire codes/standards and best practices for communities.

Highly hazardous fire behavior was found for parallel fences and one type of wood-plastic composite fence. Fire spread rates varied with fence design, wind speed and the presence or absence of mulch; however, all combustible fences spread fire and burned downwind. In large WUI incidents, first responders may not be available to suppress these fence fires for many hours. While rates varied, during WUI events even relatively small fire spread rates can bring the fire to the structure and/or other combustibles before defensive actions by first responders can stop possible structure ignitions. Fences can act as a ladder fuel, over which a fire burning low to the ground can climb to ignite combustible items at higher levels, such as eaves, roofing, or tree branches. Multiple ignition points along the fence and the presence of nearby vegetation will worsen the hazard.

Fences may impact egress. High fire hazard fences create a line of flames that can render adjacent pathways impassable. This study identified one high hazard fence whose boards fell out of a frame and continued to burn on the ground, creating a linear flaming obstacle whose width was twice the height of the fence. The fences tested were 1.8 m (6 ft) tall. Taller fences than those tested will likely result in wider impassable paths.

A more detailed discussion on implementing guidance based on the relationships among fuel layout, fire hazard, and structure hardening can be found in the recently published NIST report entitled *WUI Parcel/Structure/Community Fire Hazard Mitigation Methodology* (HMM) [16].

Some sample ignition scenarios are shown in Fig. 156, which is reproduced from the HMM report. This figure illustrates some ways in which combustible fences and mulch beds may transport fire to multiple residences in a neighborhood. The illustrated scenarios combine this experimental study with data collected by NIST from the Camp Fire study [14]. These are only a few examples; many other pathways involving combustible fences and mulch may be constructed and are seen in the field.

Four different ignition pathways are illustrated in this figure. The wind is blowing from right to left.

- In scenario A, a firebrand ignition occurs in windblown leaf debris against a combustible privacy fence. The fire spreads downwind and gains intensity (A1), acting as a ladder fuel to carry the fire into the branches of a nearby tree. Once the tree is ignited, the fire quickly spreads to the eaves of Residence 1 (A3), even though this home is separated from adjacent parcels by a noncombustible steel chain link fence. This scenario was observed during the Camp Fire [14] and resulted in the destruction of the residence, highlighting how fire hazards from a neighboring parcel can impact the adjacent property and result in residential loss.

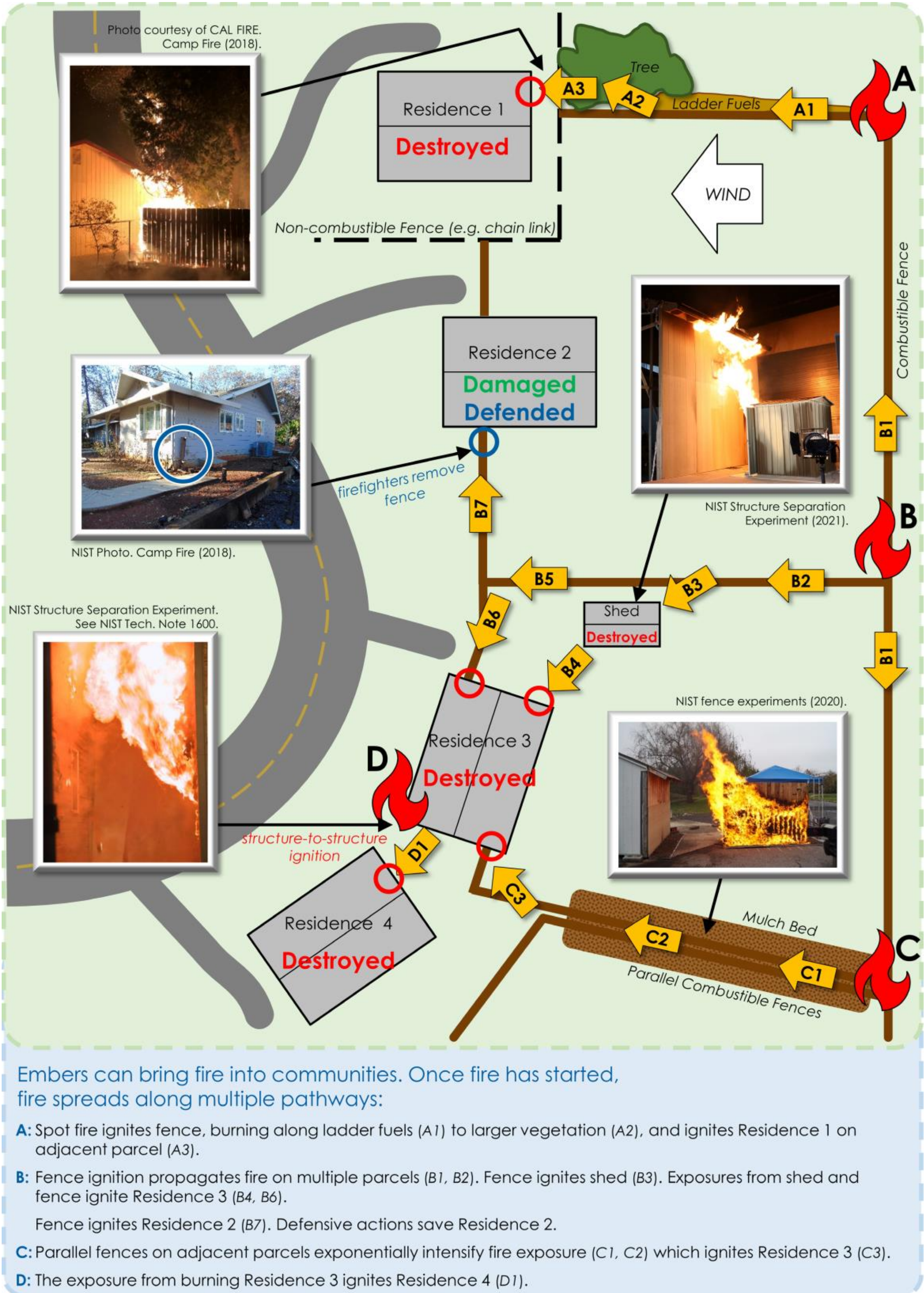

Fig. 156. Illustration of numerous fire spread pathways among neighboring parcels via linear features and other combustibles. Inset photographs are from field observations and experiments. Reproduced from [16], Fig. 10.

- In scenario B, ignition of accumulated leaf litter supports a fire spreading along the combustible privacy fence outlining adjacent properties. The fire spreads along path B2, as discussed in Section 4.3, toward a combustible shed. When the fire reaches the shed, the narrow space between the fence and shed results in rapid fire growth of large flames (B3), similar to the parallel fence experiments described in Section 4.4. The resulting shed fire then ignites Residence 3 along path B4, through direct flame and radiation. This shed-to-structure ignition path is currently being studied at NIST [63, 64].

  The fire along the fence from ignition B continues to spread toward Residence 3 on path B6 and Residence 2 on path B7. This results in a second point of ignition for Residence 3, which is already on fire due to the burning shed. Luckily, Residence 2 is defended by first responders, who remove the fence at the point where it connects with the house. The associated photo shows a documented example from the Camp Fire in which such an intervention prevented fire from reaching the residence.

- In scenario C, two neighbors have erected combustible privacy fences on their respective properties, with mulch beds or other ground litter on each side. Leaf litter and other debris have also accumulated in the narrow space between these parallel fences. As we know from Section 4.4, this is a rapid growth scenario that quickly results in large flames. The fire continues along path C3 and provides a third ignition point on Residence 3.

- Finally, scenario D describes the structure-to-structure ignition of Residence 4 by nearby Residence 3, which is now fully involved in fire. This scenario has previously been studied at NIST [65].

These scenarios describe structural ignitions from direct fire exposures in moderate to high density WUI residential communities and illustrate the critical role combustible fences can play in carrying fire between and within parcels. If the combustible fences in this illustration are made out of wood, they will also generate firebrands, causing further ignitions and likely threatening additional structures far downwind. Noncombustible fences, such as those composed of masonry, concrete or metal, will not generate firebrands or spread fire between and within parcels. However, maintenance is necessary to keep all fences free of leaf litter and other combustible debris that can accumulate next to any obstacle and itself create a fire hazard.

Field observations from NIST WUI case studies and the NIST experiments have identified the need to restrict the presence of high fire hazard fences in high density WUI, to spatially segregate fuels to prevent direct flame propagation, and to limit the nonlinear effects of multiple fuels in contact with each other. Solutions to reduce the structure ignition hazards posed by high fire hazard fences include but are not limited to:

  – Best practices guidance for homeowners
  – Homeowners Association (HOA) requirements on placement of high fire hazard fences
  – County or State regulations on the placement of high fire hazard fences
  – National or international codes and standards

More information on these approaches may be found in the HMM report [16].

5.2. Limitations

This study was a survey of the fire behavior in wind of a variety of combustible fences and mulches near a structure. It illuminated the differences in behavior for selected materials and fence designs and demonstrated certain trends. An understanding of the limitations of this work will help to direct its applications and to plan additional research to improve our knowledge. The scenarios studied in this report did not include multiple ignition points along the fence or mulch bed, the presence of nearby vegetation, sloping terrain, or other factors that can increase the ignition propensity, rate of fire spread, and fire intensity. These experiments may therefore underpredict the fire hazard associated with fences in actual WUI fires.

A small number of common fence types and mulches were considered in this study. In communities, there are infinite combinations of fences, mulches, landscape designs, orientations, proximity to other fuel sources, and ambient conditions. Continuing attention to fire pathways observed in WUI fires and development of a standard fire test focused on fences will help to identify other situations that should be addressed.

Some other limitations of this research include:

Combinations of fuels were limited: The experiments looked at the hazards associated with certain combinations of fences and mulch that may be found in the WUI. Many materials and fence designs were not included in the study. The experiments also did not capture the hazard from fences placed near other fuels like woodpiles or vegetation or fences running parallel to a combustible shed. Some experimental configurations were not tested because of concerns for extensive flaming that could threaten the survivability of the shed and personnel safety – in some cases, the shed had to be actively cooled to prevent ignition.

Few experiments were repeated: Most experiments were performed once. The ability to quantify the effects of the parameters in this study was severely limited by the sparsity of replications, the stochastic nature of fire phenomena, and the variables that could not be well-controlled, such as ambient conditions. The analysis of these data was therefore focused on uncovering trends and on discovering different modes of behavior, rather than on quantitative results.

Distance downwind was limited for long-range spotting study: At high wind speeds around 14 m/s (31 mi/h), firebrands from burning fences and mulch caused spot fire ignitions in a mulch bed up to 47.6 m (156 ft) downwind. This was the longest distance that could be tested at the test site and therefore likely underrepresents the spotting potential.

Fuels were ignited at a single location on or near the ground: The test protocol provided repeatable conditions to characterize fire performance and identify both dangerous and potentially desirable attributes of landscape features. In WUI fires, however, firebrands can ignite fences, mulch, and leaf or needle debris at multiple locations on the ground and at higher locations along fence stringers. It is likely that this would result in a faster spreading fire. Burning vegetation can ignite fences at locations above the ground.

Ignition was by gas burner rather than a natural source: In these experiments, the fence and/or mulch bed were ignited at a single point at ground level by a gas burner. The method differs from natural ignition in WUI fires in multiple ways. A gas burner is a severe ignition source, igniting by continuous flame contact and differing in heating rate and geometric extent from most natural ignition sources in a WUI fire.

The orientation of wind to the structure wall was limited: The experiments documented in this report were conducted with the shed wall perpendicular to the fence and mulch bed. Alignment of the fence with the wind was found to maximize fire spread rate in a previous fence study that did not include a structure [23]. The addition of a structure wall at right angles to the imposed wind produced a wind field with a recirculation zone at the base of the wall, which influenced both firebrand trajectories and flames. Reorienting the structure at an angle to the wind is expected to reduce the recirculation zone and enhance the flow around the structure. This would increase the flame spread rate nearing the structure. It could also shorten the time for firebrands to ignite spot fires at the base of the wall, change the spread of spot fires toward the wall, and affect the flame length and plume flow near the structure for large fires.

The mulch was preheated by heat conduction through the steel pan: The use of steel pans to hold the mulch and/or fence being tested introduced a heat transfer mechanism that does not contribute to fire spread under real conditions. The thermally conductive metal pans evaporated water and preheated the mulch ahead of the fire front. Soil has a much lower thermal conductivity, for which preheating is negligible. White smoke or steam downwind of the flame front was often observed and was particularly noticeable in pine bark mulch experiments.

Accumulation of windblown debris was not considered in Fence Only experiments: This study considered the fire behavior of fences free of fine combustible mulch at their base, as an ideal. These fence experiments likely underestimate the hazard associated with combustible fences. Catastrophic WUI events most frequently occur during windy conditions. During such an event, a fence that extends to the ground, even if kept clear and well-maintained, can accumulate windblown debris at its base. If this occurs, the combination of fence and combustible materials at its base may ignite and generate significant flame and firebrand exposures.

Effects of terrain were not studied: The experiments documented in this report were conducted on level ground. Terrain may significantly impact fire development. In general, fire spreads upslope faster than downslope. The interaction of terrain with wind can greatly affect fire spread, flame lengths and ember generation, transport, and ignitions.

Smoke toxicity was not included: This study was focused on fire behavior and did not include smoke toxicity as a factor in the total hazard from burning fences or mulch.

6. Conclusions

Combustible fences and mulch provide pathways by which wildland-urban interface (WUI) fires may reach and potentially ignite structures in a community. Once ignited, these fuels become sources that may ignite nearby objects through radiation, direct flame contact, and firebrands. It is important to understand the mechanisms by which these combustible landscaping elements can transport fire to a home in order to find ways to address the risk. Such knowledge helps with proactive design within the community. It informs homeowners on what they can do to protect themselves and their properties. It also helps fire departments to plan defensive strategies, placing resources and assigning tasks where they will be the most effective. The goal is to enhance the safety of members of the public and first responders.

This section pulls together the main findings of this report and presents the primary recommendations. General findings on fire spread for fence/mulch combinations are followed by findings categorized by very high, high, medium, and low hazard. Organizing the findings in this way suggests how mitigation may be prioritized in order to reduce the potential fire exposure of nearby structures.

6.1. Key Findings

The experiments in this study demonstrated a range of fire spread hazards from various types (materials/design) and configurations of fences and mulch ignited close to a structure in a wind field, as well as the importance of maintenance. General findings are listed first and followed by very high, high, medium, and low hazard configurations. The findings are labelled according to the following categories:

- FH Fire Hazard
- LS Life Safety
- HR Hazard Reduction – materials, assemblies, implementation/housekeeping
- IC Improved Characterization – recommended future work to characterize these fuels more fully

6.1.1. General Findings

The results from these experiments on fire spread demonstrated that:

F1. As combustible materials are combined, the hazard increases disproportionately. (FH)

Fuel agglomeration provides significant increase in energy release and increases fire and ember exposures. For a single combustible fence panel by itself, the fire behavior was limited to glowing combustion near the area of ignition, with firebrands generating spot fires only on rare occasions. When a combination of a wood fence and shredded hardwood mulch was ignited at the base, the flames progressed steadily in the direction of the wind, although they did not rise above the lower half of the fence. Adding a second wood fence parallel to the first resulted in flames engulfing the fences within a few minutes of ignition.

F2. Fences may impact egress. (LS)

In a WUI fire, high and very high hazard fence configurations may result in a line of flames close to egress paths from a house or auxiliary dwelling. In one set of experiments on a wood-plastic composite fence, the top and bottom frames distorted and allowed burning boards to fall to either side. This created a 4 m (12 ft) wide zone of flames along the fence line.

F3. Fire spread rates vary with fence materials and design, wind speed, and fuel configuration, including the presence or absence of mulch. (FH)

This report provides data on a variety of fence and mulch materials, designs, and configurations.

F4. Spot fires due to firebrands may ignite within a few minutes, even over a distance of 47.6 m (156 ft) or more from the burning item, and may continue to ignite long after the initial flaming combustion has subsided. (FH)

Firebrands capable of igniting spot fires downwind were generated by nearly all combinations of fence and mulch tested in this study. All wood fences with mulch at the base caused spot fires in the target mulch bed. Spot fires were often ignited within a few minutes of mulch and fence ignition. Shredded hardwood mulch and pine bark mulch burned and emitted firebrands for longer than an hour. Ignition of spot fires was also demonstrated from firebrands transported by the wind over distances as far as 47.6 m (156 ft) from the burning item under high wind conditions and over a paved surface. The wind field may deposit firebrands close to the wall of the structure. If a home is undefended during a WUI fire and not properly hardened, these firebrands may pose a serious threat to the home.

F5. A standard test method is needed to evaluate the fire characteristics of fences. (IC)

A standard test method is needed to assess the fire performance of fences. The method should consider not only materials but assemblies and be carried out in a vertical orientation. It should be able to distinguish the fire behavior of various materials, including wood-plastic composites, wood, and vinyl, and designs, including privacy, lattice, and good neighbor.

6.1.2. Very High Hazard Configurations

Certain fence and mulch combinations were found to result in rapid fire spread and large flames. In a region subject to WUI fires it's advisable to remove these fuel sources if possible. A standard test should be developed to evaluate the fire characteristics of fences.

F6. Rapid fire growth and large flames were found for parallel fences and one type of wood-plastic composite fence. (FH)

– *Parallel wood privacy fences* and *double wood lattice fences* were engulfed in flames within a few minutes of ignition. Radiative exchange between the parallel burning surfaces and convective uplift (buoyancy) of the hot gases trapped in the bounded space caused rapid intensification of combustion and eruptive fire behavior. A large fire occurred even when wood privacy fences were separated by 91 cm (3 ft). A parallel fence configuration can arise when neighbors erect fences along both sides of a property line.

– For a *western redcedar privacy fence next to a pine lattice fence*, the fire behavior depended on spacing. Rapid fire growth and intense flames were found for a spacing of 31 cm (12 in). The char patterns on each fence were similar to those for the fences individually when the spacing between them was 46 cm (18 in).

– Limited testing indicates that ignition of certain *wood-plastic composite fences* can result in high intensity fire behavior. For one of the two types tested, the fence burned intensely, with large flames extending above the fence. The warped frame allowed vertical boards 1.8 m (6 ft) tall to fall to both sides, creating a 3.7 m (12 ft) wide zone of flames that could block egress and threaten property.

F7. Good neighbor fences serve as a ladder fuel to carry flames from the ground to the top of the fence. (FH)

– For *good neighbor fences* at low wind speed, the flames reached the top of the fence downwind from the ignition point. This is due to radiative and convective heat transfer between the boards connected to alternating sides of the stringer, the same mechanisms that caused rapid flame growth between parallel fences. At higher wind speeds the maximum height of the fire stayed below the center stringer of the fence.

F8. Rubber mulch generates large flames initially and when disturbed. (FH)

– *Rubber mulch* burned with black smoke and large initial flames, followed by a long period of sporadic flaming as a top layer of crumbly solid residue slowed the flow of oxygen to the unburned fuel beneath. Disturbing the mulch bed renewed the flaming as the unburned fuel was exposed to air.

6.1.3. High Hazard Configurations

Many fence and mulch combinations exhibited fire behavior in the high hazard range, supporting fire spread and generating firebrands but not progressing to full involvement with large flames. This section describes the behavior of some configurations that fall into this category.

F9. A fence with mulch at its base transports fire through the community and provides a steady source of firebrands to ignite combustible material downwind. (FH)

– *Wood privacy or lattice fences combined with mulch* were more hazardous than either the fence or the mulch bed separately. Adding fine combustible materials to the base of a fence promoted fire spread along the base of the fence, allowing the combination of fence and mulch to act as a wick transporting fire along the entire length of the fence. With ignition at the base of the fence, flames remained below half of the fence height. In every case, firebrands ignited spot fires in the target mulch bed.

– Stringers slowed the upward fire spread in these experiments by limiting the flame height on one side of the fence. In a WUI fire, however, they could provide locations for firebrands to lodge and ignite new fires on the fence.

- The flame spread rate in the horizontal direction was similar for all wood fences, including privacy, lattice, and good neighbor fences. Away from the wind field near the structure, the fire spread from the ignition point to the end of the single fence panel was 2 min to 5 min for high and medium wind speeds and 7 min to 12 min for low wind speeds.
- For one type of *wood-composite fence*, the fire remained below the halfway point of the fence height. Horizontal boards fell out of the frame and burned in line with the fence.
- Lifting a fence 15 cm (6 in) above shredded hardwood mulch decoupled the burning behavior of the fence from the mulch between posts. This conclusion may not hold for mulches that burn with higher flames, such as pine straw or rubber mulch. The benefits of raising the fence above the mulch may not be realized if a barrier is placed between them to keep wildlife out or pets in. Combustible debris such as leaves or needles that collect along the barrier will reduce the advantages of this design in a fire.

F10. Fire spreads easily across the fine overlapping particulates of a mulch bed. The fire intensity, rate of fire spread, and production and size of firebrands depend on the material properties and physical characteristics of the mulch. (FH)

- *Rubber mulch* burned with black smoke and large flame initially and when disturbed. See description under Very High Hazard.
- By itself, the *pine straw mulch* was consumed without igniting spot fires. However, embedded combustible objects were easily ignited by the intense flames. When combined with a western redcedar privacy fence, the fire in the pine straw mulch ignited the fence quickly and spread to the end of the panel within one minute. The burning wood fence then generated firebrands capable of igniting spot fires.
- The fire spread behavior in a *shredded hardwood mulch* bed was affected by the flow field, ignition of spot fires downwind, and the geometry of the mulch bed and structure. Fire progressed in hardwood mulch beds through both continuous flame spread and firebrand spotting. Spot fires allowed the fire to jump in the direction of the wind.
- Fire spread more slowly over the *mini pine bark mulch* than over the shredded hardwood mulch, often taking at least twice as long to reach the end of the mulch bed. This likely results from the difference in texture – the chunks of mini pine bark mulch do not ignite as easily as the long, thin particles that characterize the shredded hardwood mulch.

F11. More information is needed on the fire behavior of a combustible fence next to an auxiliary structure. (IC)

- A *WRC privacy fence separated from a noncombustible cement board* by 31 cm (12 in) resulted in a char pattern similar to that of a single panel WRC privacy fence, with flame spread about three times faster. For a spacing of 46 cm (18 in), the fire behavior was less intense for a WRC privacy fence in combination with either a cement board or a vinyl privacy fence, as compared to a single panel WRC fence. The char pattern remained below the bottom stringer, and the flame spread was at the same rate or slower.

6.1.4. Medium Hazard Configurations

Some fences and mulch experiments demonstrated very slow fire spread without flaming and little or no generation of firebrands.

F12. Without nearby fine combustible materials, the fire spread over a single combustible fence is slow and dominated by glowing combustion. (HR)

The fire spread over wood fences in the absence of fine combustibles was generally slow and dominated by glowing combustion with occasional small flames. Wood fences produced large firebrands from pieces of the fence breaking off and small firebrands from glowing combustion. However, spotting in the target mulch bed was rare in these experiments. It should be noted that it may be difficult to keep a wood fence sufficiently clear of fine combustible materials to achieve the slow-growth fire behavior. Windblown debris such as leaves and pine needles may accumulate during a WUI event.

F13. Fence and ground coverings with added or inherent fire resistance reduce the flame spread rate and the hazard due to flames and firebrands. (HR)

- *Vinyl privacy fences* did not support significant burning under the tested wind conditions. With mulch at its base, vinyl privacy fences, including panel, bottom frame, and fence post, blackened and distorted along the entire length of the fence. Distortion allowed the boards to fall out of the bottom frame. No firebrands were generated.
- The single type of *artificial turf* tested in this study was difficult to ignite and exhibited slow flame spread.

6.1.5. Low Hazard Configurations

Although fences made of noncombustible materials such as stone, brick, or steel were not included in this study, they can be classified as low fire hazard. They do not burn on their own and have been shown provide protection against radiant heat [17]. However, any fence in contact with the ground can trap and accumulate windblown debris along their length. If not removed, combustible materials at the base of even noncombustible fences can allow fire to spread.

F14. Noncombustible fences free of leaf litter and other combustible debris will not spread fire. (HR)

Maintenance is required to reduce the accumulation of fine combustible materials along a fence. This minimizes the amount of windblown debris such as leaves and pine needles that can ignite during a WUI event.

6.2. Primary Recommendations

The following recommendations for members of a residential community are intended to address both ember and fire (radiation/convection) exposure hazards generated by combustible fences. Although the recommendations are intended primarily for moderate to very high hazard WUI locations, they are expected to reduce local fire hazards in any community.

For more detailed recommendations on spacings of combustible elements and hardening of structures and parcels, refer to the WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology report [16].

R1. Avoid parallel fences, to reduce exposure to large flames. Parallel fences can result in highly hazardous fuel accumulation corridors that are difficult to access and maintain. Spacing of 0.9 m (3 ft) between fences is not sufficient.

R2. Avoid combustible fences where they can impact egress, to protect life safety.

R3. Avoid proximity to other combustible fuels, to reduce fire intensity and limit fire spread. This includes fuels above the fence and fuels across parcel boundaries. Avoid mulch at base of fence.

R4. Avoid proximity of combustible fences to residence, including neighboring residence, to prevent direct ignition. The relationship between spacing and structure to prevent structure ignition is a function of structure construction materials/assembly and fence materials/design.

R5. Replace combustible landscape features with noncombustible or low fire hazard features when possible. Fire spread is more likely with wood and wood-plastic composite fences than with fences made of vinyl or noncombustible materials such as stone, brick, or steel.

R6. Keep fence and yard clear of debris, to reduce the amount of fuel and potential pathways for fire.

R7. Harden structures against firebrands, to prevent structure ignition from embers produced by fences or other combustible sources.

6.3. Recommendations for Future Work

More research is needed to determine the vulnerabilities of structures to fence fires relative to fence types and materials, the proximity and connection of the fence to the structure, and the design and exterior materials of the structure itself. Once the vulnerabilities are better understood, mitigation techniques such as material treatments and coatings can be explored beyond the simple solutions of increased separation and replacement of materials with noncombustible options.

S1. Study the effects on fire behavior of closely spaced parallel wall surfaces in communities.

The same radiation exchange and convective transport of hot gases between burning parallel surfaces that led to eruptive behavior for parallel wood fences can potentially result in highly hazardous situations for other closely spaced parallel surfaces. As one approach, the Structure Separation Experiments project at NIST [63, 64] is addressing the question of how far apart residences should be from other nearby structures.

S2. Continue to study the fire behavior of landscape features and potential mitigation methods.

There are many combustible landscape features that may contribute to fire hazards in a parcel or community. Work is ongoing at NIST to understand the interactions of fires on woodpiles, landscape timbers, creosote-treated timber, and sheds. The work will include strategies for mitigation. Together, these studies will inform existing and new codes and standards with quantitative fire spread mitigation and structure protection strategies based on experimental data.

S3. Improve data collection methods.

The range of fire behaviors found for a variety of materials, designs, and configurations suggests improvements in data collection methods that would be useful for future targeted studies. For fence and mulch configurations resulting in large flames and very high hazard conditions, the radiative and convective heat flux received at vulnerable locations could be evaluated by heat flux sensors and/or infrared (IR) imaging. Firebrand fluxes, sizes, and energy content could be assessed in future studies by new measurement technology, including a three-dimensional firebrand tracking system under development at NIST [66].

S4. Use fire modeling to better understand the physics behind the fire behavior.

Modeling can be used to extend the understanding from this study to other configurations of fences, mulch beds, structures, and other fuels, in order to identify other high hazard configurations. The results in this report may be helpful in validating a physics-based fire model, including:

- Fire behavior of fences as a function of material properties and design.
- Fire behavior of parallel fences compared to single fences.
- Dependence on parallel fence spacing for time at which flames engulf the fences.
- Dependence of fire behavior on parallel fence length, including the spacing for which a second panel length results in explosive fire growth, and the time for fire to spread down a long fence.
- Char patterns for wood privacy fences, both individually and in parallel with combustible and noncombustible fences and walls.

S5. Revisit fire tests for evaluating fences and fence materials to ensure that they represent the actual fire hazard.

A standard test method is needed to assess the fire performance of fences. The method should consider not only materials but assemblies and be carried out in a vertical orientation. It should be able to distinguish the fire behavior of various materials, including wood-plastic composites, wood, and vinyl, and designs, including privacy, lattice, and good neighbor. The need for such a test method is highlighted within this report by the significant difference in energy release between the two wood-plastic composite fences included in the study. A fence test method will inform AHJs and the public about implementation options with fences and allow AHJs not only to assess the performance/hazard of composite fences but to compare and assess all combustible fencing options under identical conditions.

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Appendix A. Uncertainties

Each measurement of wind speed, distance, time, or other variable discussed in this report is associated with an uncertainty. Uncertainties generally consist of several components that are grouped into two categories according to the method used to estimate their value [67]. Type A uncertainties are quantified by statistical methods, including the calculation of standard deviation, curve fitting using the method of least squares, or analysis of variance (ANOVA). Type B uncertainties are evaluated by other means, usually using scientific judgment based on all available relevant information. This may include previous measurement data, experience with relevant materials and instruments, manufacturer's specifications, or data from literature sources and handbooks.

For an output quantity Y that is not measured directly but is determined from N input quantities $X_1, X_2, \dots, X_N$ through a functional relation f:

$$Y = f(X_1, X_2, \dots, X_N) \ , \tag{A-1}$$

the estimate y of the output quantity is given by applying the same function to estimates $x_1, x, \dots, x_N$ of the input quantities:

$$y = f(x_1, x_2, \dots, x_N) \ . \tag{A-2}$$

For Type A evaluation of uncertainties, in which n repeated independent observations are made under the same conditions, the input quantity x_i can be estimated by the sample mean,

$$x_i = \bar{X}_i = \frac{1}{n}\sum_{k=1}^{n} X_{i,k} \tag{A-3}$$

and the standard uncertainty $u(x_i)$ associated with x_i is the estimated standard deviation of the mean,

$$u(x_i) = s(\bar{X}_i) = \left(\frac{1}{n(n-1)}\sum_{k=1}^{n}\left(X_{i,k} - \bar{X}_i\right)^2\right)^{1/2} \tag{A-4}$$

This is equivalent to the estimated standard deviation of the input quantity s_i divided by the square root of the size of the sample:

$$s(\bar{X}_i) = \frac{s_i}{\sqrt{n}} \tag{A-5}$$

For Type B evaluations, estimates of the input quantity x_i and standard uncertainty $u(x_i)$ depend on the assumed form of the probability distribution and the range of values. If the quantity is modeled by a normal distribution with essentially all (approximately 99.73 %) of its values contained within a lower limit a_- and an upper limit a_+, and with a mean value

$$x_i = \frac{(a_+ + a_-)}{2} \tag{A-6}$$

then the standard uncertainty is given by

$$u(x_i) = \frac{a}{3} \tag{A-7}$$

where $a = (a_+ - a_-)/2$. In this case, a is equivalent to the 3σ value.

Another alternative is to assume a rectangular probability distribution., with a lower limit a_- and upper limit a_+ and a value that is equally probable to lie anywhere within the interval. In this case, the input quantity can be estimated by Equation (A-6) and the standard uncertainty is

$$u(x_i) = \frac{a}{\sqrt{3}} \tag{A-8}$$

The combined standard uncertainty of the measurement result y, representing its estimated standard deviation, is the positive square root of the variance obtained from the law of propagation of uncertainty:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2\,(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} u(x_i, x_j) \tag{A-9}$$

where $u(x_i)$ is the standard uncertainty associated with the estimate of input quantity x_i and $u(x_i, x_j)$ is the estimated covariance associated with x_i and x_j. When the input quantities are uncorrelated, the equation reduces to the RSS (root sum square) method of combining uncertainties,

$$u_c(y) = \sqrt{\sum_{i=1}^{N} [c_i u(x_i)]^2} \tag{A-10}$$

where $c_i = \partial f / \partial x_i$.

Finally, an expanded uncertainty U is determined by multiplying the combined standard uncertainty u_c by a coverage factor k,

$$U = k u_c\,. \tag{A-11}$$

This provides an interval $y - U$ to $y + U$ within which the value of Y can be asserted to lie with a high level of confidence. A coverage factor of $k = 2$ defines a level of confidence of approximately 95 %.

Relative standard uncertainty $u_r(x_i)$, relative combined standard uncertainty $u_{c,r}(y)$, and relative expanded uncertainty U_r are calculated by dividing the uncertainty measure by the absolute value of the associated quantity, as in:

$$u_r(x_i) = \frac{u(x_i)}{|x_i|} \qquad u_{c,r}(y) = \frac{u_c(y)}{|y|} \qquad U_r = \frac{U}{|y|}$$

Equation (A-10) can be written in terms of relative standard uncertainties as

$$\frac{u_c(y)}{y} = \sqrt{\sum_{i=1}^{N} s_i^2 \left(\frac{u(x_i)}{x_i}\right)^2} \tag{A-12}$$

where s_i is the nondimensional sensitivity coefficient for input quantity x_i,

$$s_i = \frac{\partial y}{\partial x_i}\frac{x_i}{y} \tag{A-13}$$

This appendix does not address the matter of reproducibility of the measurement results in this study; that is, the closeness of the agreement of measurements under different conditions. Most experiments in the study were unique; those that were repeated were performed on different days under different ambient conditions and in the presence of other uncontrolled variables.

The uncertainties examined in this section are associated with four categories of variables. Section A.1 looks at the uncertainties for the experimental setup, including dimensions of test objects, setup distances, and material preparation. Section A.2 discusses the Type A uncertainties in the wind data measured by bidirectional probes. Section A.3 looks at the uncertainties inherent in assessing the timing of events, and Section A.4 considers the uncertainties in the flame spread analyses.

A.1. Experimental Setup

Setting up the experiments included preparing the materials for testing, assembling the mulch beds and fences, and arranging the test setup. The setup and procedures were described in Section 2 of this report. The uncertainties associated with the experimental setup are Type B, either estimated through scientific judgment or obtained from source literature. Table A.1 provides a list of the variable types and their uncertainties. All of the uncertainties listed in this table are Type B, determined from sources in the literature or by scientific judgment.

The moisture content (MC) of the wood mulch and fences at the beginning of each experiment was controlled by allowing the materials to come to equilibrium in conditioned spaces, as described in Section 2.4.3. The relative humidity for these spaces was suitable for bringing the wood to a nominal MC of 6.5 %, a value that is reasonable for the summertime in the American Southwest [35, 36]. The variability of MC for wood over the expected range of ambient temperature and relative humidity is ± 0.8 %. This was consistent with measurements of mulch samples as described in Section 2.4.3.

Estimates of uncertainties for the dimensions of wood components used to construct the fences cam be derived from the American Softwood Lumber Standard [68]. This voluntary standard includes the western redcedar, pine, and redwood fences tested in this study, as well as the pressure treated pine posts and stringers. Nominal sizes for lumber are larger than the minimum dressed sizes (e.g., a 2×4 rail corresponds to 3.8 cm by 8.9 cm (1 ½ in by 3 ½ in)). For thicknesses of 1 in or more, the actual dressed size must exceed the specified minimum value by at least 3.2 mm (1/8 in). Uncertainties can be extracted from the voluntary standard by assuming that the lumber used in this study satisfied the definition of slight variation in sawing. This is defined as variations not exceeding 1.6 mm (1/16 in) over or under for nominal 1-inch lumber, 3.2 mm (1/8 in) for nominal 2-inch, 5 mm (3/16 in) for nominal 3-inch to 7-inch, and 6 mm (1/4 in) for nominal 8-inch or greater. The dimensions for boards used in constructing fences is specifically called out in the standard as satisfying the 1.6 mm (1/16 in) tolerance for thickness.

Sizes may shrink or expand with moisture. Tolerance allowances are 0.7 % shrinkage or expansion for each four percentage points of MC change below 30 % for redwood and western redcedar, and 1 % for other wood types [68]. As discussed in Section 2.4.3, the fences in this experiment are held to MC of 6.5 % ± 1 %. The standard relative uncertainty (standard uncertainty divided by the mean value) of dimensions due to shrinkage and expansion for fences in this study is therefore 0.2 %, or 0.002. These tolerances are for transverse shrinkage, in directions tangential to or across the tree growth rings. Longitudinal shrinkage, parallel to the grain, is much smaller [36], and can be neglected relative to the variations due to sawing.

The calculation of uncertainty for fence dimensions includes the components of variation in sawing the lumber and in shrinking and expansion due to changes in moisture content. Since the American Softwood Lumber Standard does not translate the variability due to sawing to a normal distribution, we will assume that the range defines the 3σ value of a normal distribution. For nominal 4-inch lumber, for example, the standard deviation from sawing is taken as $u_1 = (5\text{ mm})/3 = 1.7$ mm. The standard deviation from shrinkage/expansion is $u_2 = 0.002 \times 89\text{ mm} \cong 0.2$ mm. An additional uncertainty of 2 mm is added to the calculation for the height of the lattice fence to account for variations in the assembly process.

As stated in Section 2.5.1, spacing between the vertical boards varied from 1 mm (0.04 in) to 6 mm (0.24 in) and averaged 3.5 mm (0.14 in).

To calculate the uncertainty for the length of both privacy and lattice fences, the standard uncertainties for the length of the stringer and the widths of two posts were combined using the RSS method. The result was then multiplied by 2 to calculate the total expanded uncertainty (95 % confidence level).

Table A.1. Uncertainty in wood fence dimensions

Measurement	**Component Standard Uncertainty, u_i**	**Combined Standard Uncertainty u_c**	**Expanded Uncertainty $2u_c$**
Board thickness (19 mm):		0.5 mm	1.0 mm
Sawing	0.5 mm		
Expansion/shrinkage	0.04 mm		
Board width (140 mm):		1.7 mm	3.4 mm
Sawing	1.7 mm		
Expansion/shrinkage	0.3 mm		
Board/Fence height (1.83 m):		2.0 mm	4.0 mm
Sawing	2.0 mm		
Expansion/shrinkage	< 0.1 mm		
Spacing between boards (3.5 mm)	1.0 mm	1.0 mm	2.0 mm
Post width (89 mm):		1.7 mm	3.4 mm
Sawing	1.7 mm		
Expansion/shrinkage	0.2 mm		
Stringer height (89 mm):		1.7 mm	3.3 mm
Sawing	1.7 mm		
Expansion/shrinkage	0.1 mm		
Stringer thickness (38 mm):		1.1 m	2.1 mm
Sawing	1.1 mm		
Expansion/shrinkage	0.08 mm		
Stringer length (2.44 m):		2.0 mm	4.0 mm
Sawing	2.0 mm		
Expansion/shrinkage	< 0.1 mm		
Lattice fence height (1.22 m):		2.8 mm	5.7 mm
Assembly	2.0 mm		
Sawing	2.0 mm		
Expansion/shrinkage	< 0.1 mm		
Privacy fence length (2.62 m):		3.1 mm	6.2 mm
Post width	1.7 mm		
Stringer length	2.0 mm		
Post width	1.7 mm		
Lattice fence length (2.51 m):		3.1 mm	6.2 mm
Post width	1.7 mm		
Stringer length	2.0 mm		
Post width	1.7 mm		

The uncertainties for mulch pan dimensions and the locations relative to the shed and centerline of mulch pan, bidirectional probe array, and wind machine are presented in Table A.2. All uncertainties listed in this table are Type B, determined by scientific judgment.

The mulch pan is described in Section 2.4.1 and the target mulch bed at the base of the shed is described in Section 2.4.4. The mulch pans were 87.6 cm (34.5 in) wide with 2.5 cm (1 in) high side walls, and two pans were overlapped and clamped for a total length of 3.35 m (11 ft). A few sets of pans were made during the study, and the pan walls tended to warp over time. The expanded uncertainties for both pan width and length are estimated as ±1 cm. The target mulch pans along the shed were 46 cm (18 in) wide and 1.37 m (4.5 ft) long, with two pans overlapped to give a total length matching the shed wall dimension at 2.44 m (8 ft) long. The target mulch bed was not confined by a lip on the outside edge facing the fence, which allowed 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, by an expanded uncertainty of ±2.0 cm.

The mulch to be ignited was prepared by spreading it over the mulch pans and compressing it by foot to a depth of 5 cm, double the height of the walls of the mulch pan, as discussed in Sections 2.4.1 and 2.9.2. The mulch was tapered at the edges of the pan to a depth of 2.5 cm. For cases with a fence, the depth was designed to cover the gap between the pan top surface and the bottom of the fence, which was set (with a pair of measured shims) at 5 cm. 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 also depended on the evenness of the spreading over the mulch bed and the uniformity of the compaction. The expanded uncertainty of the mulch bed depth was ±1 cm. The same uncertainty was estimated for the depth of the mulch at half thickness and for the target mulch bed, both of which were compressed at a nominal height of 2.5 cm

After the shed and wind machine were placed into position, they usually remained there over multiple test days and several tests. For every setup, a long tape measure that covered the full 10.7 m (35 ft) distance between them was used to adjust the equipment to the desired position. This procedure was estimated to result in an expanded uncertainty (95 % confidence level) of ±3 cm. In the transverse direction, the center of the fan hub was within ±1 cm of the centerline of the experiment.

The separation distance, from the shed to the mulch pan, was measured by tape measure for each experiment. The expanded uncertainty for a confidence level of 95 % was estimated as ±1 cm. A longer tape measure used for distances greater than 11 m (36 ft) had an expanded uncertainty of ±2.5 cm (±1 in).

The bidirectional probe array was typically placed 4 ft from the end of the fence. For cases without a fence, the measurement was made from the shed to the probe array, with the distance based on the separation distance of each experiment. The expanded uncertainty was estimated for the distance of the array from the shed as ±2 cm and for the distance of the centerline probes to the actual centerline as ±1 cm. There was an additional uncertainty for the position of each probe within the array, which was estimated as ±1 cm in the vertical direction and ±0.5 cm perpendicular to the plane of the probe array.

Table A.2. Uncertainty in dimensions for experimental setup

Measurement	Component Standard Uncertainty u_i	Combined Standard Uncertainty u_c	Expanded Uncertainty $2u_c$
Mulch bed width (0.88 m)	5 mm	5 mm	10 mm
Mulch bed length (3.35 m)	5 mm	5 mm	10 mm
Target mulch bed width (0.46 m)	10 mm	10 mm	20 mm
Mulch thickness (50 mm or 25 mm)	5 mm	5 mm	10 mm
Wind machine to shed (10.67 m)	15 mm	15 mm	30 mm
Wind machine to centerline	5 mm	5 mm	10 mm
Mulch pan to shed: Separation distance (0-1.83 m)	5 mm	5 mm	10 mm
Bidirectional probe array to shed	10 mm	10 mm	20 mm
Bidirectional probe array to centerline	5 mm	5 mm	10 mm
Probe position, x (toward shed) Probe array Position within array	 10 mm 2.5 mm	10.3 mm	20.6 mm
Probe position, y (toward center) Probe array	5 mm	5 mm	10 mm
Probe position, z (vertical) Position within array	5 mm	5 mm	10 mm
Distances > 11 m (36 ft)	25 mm	25 mm	51 mm

A.2. Wind Data

Wind speed uncertainties involve the bidirectional probe design and the measurement statistics from the wind field. Bidirectional probes are simple tubular devices that calculate velocities from the pressure differential between front and back openings. They are similar to pitot static tubes, with added advantages of robustness in a fire environment and insensitivity to flow angle. Velocity is calculated using the equation:

$$V = \frac{1}{C}\sqrt{\frac{2R_u}{P_s M_{air}}\Delta P\, T} \tag{A-14}$$

where C is the probe constant, R_u is the universal gas constant, P_s is standard atmospheric pressure, M_{air} is the molecular mass of dry air, ΔP is dynamic pressure, and T is absolute temperature.

McCaffrey and Heskestad [37] measured the probe constant for the bidirectional probe as C = 1.08 for Reynolds numbers greater than 1000. A study of the angular sensitivity showed the value remaining within ±10 % for flow directions within 50° of the probe axis. For flows generally parallel to the probe axis and a probe Reynolds number above 500, a relative standard uncertainty of 0.07 can be used for the probe constant [69]. For the fence and mulch study, the Reynolds number was above this limit for all wind velocities.

The dynamic pressure in Equation (A-14) was the difference in pressure between windward and leeward sides of the bidirectional probe. As described in Section 2.7.1, the probe signals were converted to a pressure differential through transducers, which the manufacturer rated with an accuracy of 1 %. Because the probe array was located upwind of the fire and not exposed to its heat, the ambient temperature measurement was used to calculate velocity. The standard limit of error for the Type K thermocouples used in this study was 0.75 % or 2.2 °C, whichever is greater.

Table A.3 lists the relative standard uncertainty for each variable and uses Equation (A-12) to determine the contribution of each variable to the relative standard uncertainty of the wind speed calculated from the bidirectional probe $u_{r,BP} = 0.0703$. In Appendix C, this Type B uncertainty of the calculated wind speed from the probe will be combined with the Type A evaluation of the uncertainty of unsteady wind speed measurements (the standard error of the mean) to determine a total uncertainty of the mean wind speed for each probe.

Table A.3. Uncertainty budget for point velocity measurements

Measurement Component	**Value** x_i	**Relative standard uncertainty** $u_{r,i} = u(x_i)/x_i$	**Nondimensional sensitivity coefficient** s_i	**Percent contribution, %**
Probe constant, C	1.08	0.07	-1.0	99.2 %
Probe differential pressure, ΔP (Pa)	56	0.01	0.5	0.5 %
Ambient temperature, T (K)	293	0.0075 (not less than 2.2 °C)	0.5	0.3 %
Standard atmospheric pressure, P_s (Pa)	101325	0.0003	-0.5	0 %
Molecular weight of dry air, M_{air} (kg/kmol)	28.97	0.0001	-0.5	0 %
Velocity, V	8.93	0.0703 [a] (0.1406 [b])		

[a] Total relative standard uncertainty
[b] Total relative expanded uncertainty (coverage factor $k = 2$ for a confidence level of about 95 %)

A.3. Timing Data

A common system of timing was required in order to synchronize multiple videos recorded during each experiment and relate the experiments to each other. Five events that could be easily identified in the test videos were selected: End of Gas Burner Ignition, Start to Remove Gas Igniters, Fan On, Fan Off, and Water First Applied. The events were defined in Section 3.1.1. Time t = 0 for each experiment was defined as the Fan On event, when the engine of the wind machine engaged after turning over, and the end of the experiment was defined as Fan Off, when the engine was turned off and the audio signal (including the sound pitch and amplitude) started to change.

The Fan On and Fan Off events were detected through the audio signal from the video. The image in Fig. A.1 shows a screen shot from the analysis of the left camera video from Test A-29. One second of audio signal (29 frames) is shown for the two channel feeds. The tracks are displayed in red against a black background, except for the center frame that is highlighted in blue. This is the frame that was selected as the Fan On event. The audio signal to the left and right of this frame illustrates the difference between the engine turning over and engaged. It is not difficult to locate the frame in which the change in signal occurs plus or minus a few frames. Accounting for variations in the signal from one experiment to the next and for differences in the decisions of multiple analysts, the standard uncertainty for Fan On is conservatively estimated as ±0.5 s.

A similar screen shot in Fig. A.2 was taken from the one-second period during which the wind machine was turned off. The dark blue highlight in the center marks the frame that has been selected as Fan Off, and the audio signal is seen to be qualitatively different to the left and the right of this frame. The differences are not as apparent as for the Fan On event, however, and a standard uncertainty estimated at ±1 s reflects this.

The test duration is defined as the time difference between Fan On and Fan Off. As such, the standard uncertainty for this measurement combines the uncertainty from these two events. Using the RSS method gives a combined standard uncertainty for test duration of ±1.1 s. As a check, the differences in test duration measured from the right and left videos for each experiment (which were analyzed independently) were calculated. Considering the entire set of experiments, the mean of this difference was -0.27 s and the standard deviation was 1.01 s, comparable to the estimated combined standard uncertainty of the test duration.

The three timing events that relied on visual evidence were usually easily determined though examination of the video. For the End of Gas Burner Ignition event, the analysis must identify the final application of the ignition torch to the gas burner. If the torch is visible, and the video is carefully examined, the end of the final application can easily be defined within ±1 s. This is estimated as the standard uncertainty. If the torch movement is hidden by the fence, the only way to set this time may be to calculate it using the timing from the video on the other side of the fence.

The Start to Remove Gas Igniters event is easily detected from both sides of the fence as the moment when the gas igniters start to be lifted from the mulch bed after ignition has been established. This event can easily be identified within ±0.5 s.

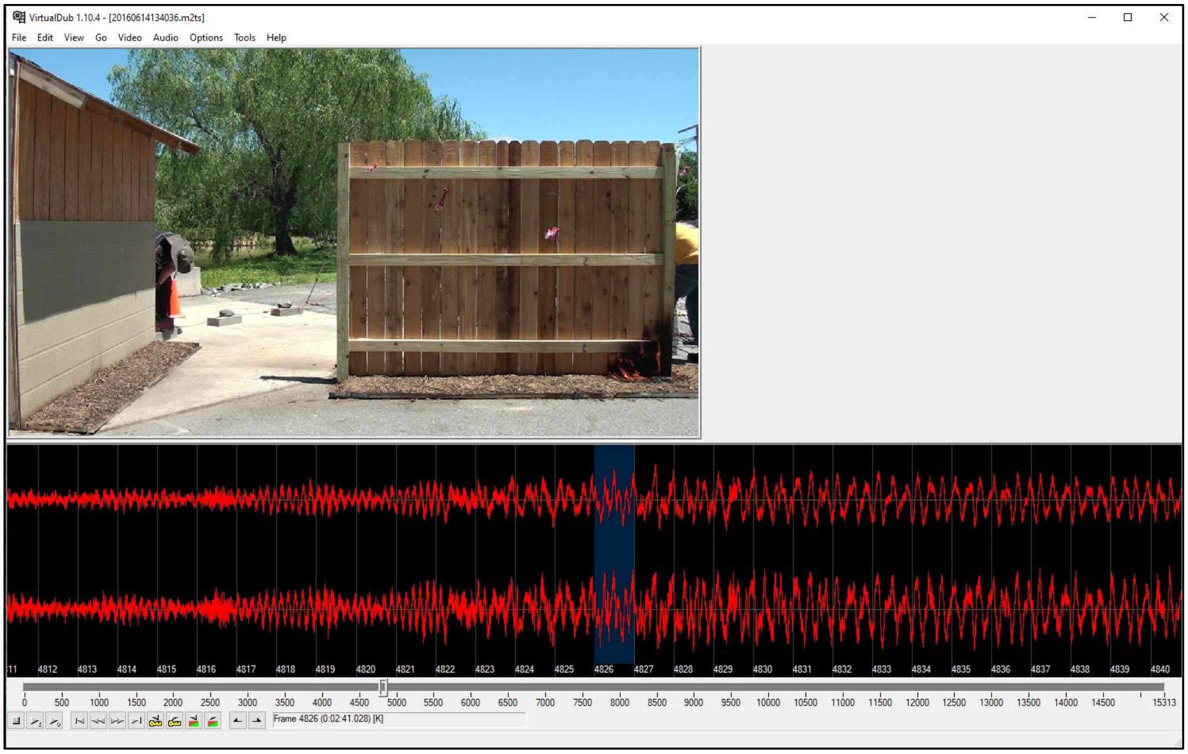


Fig. A.1. Audio feed from left camera showing frame selected for Fan On (centered, in blue). Total time shown is 1 s, or 29.97 frames.

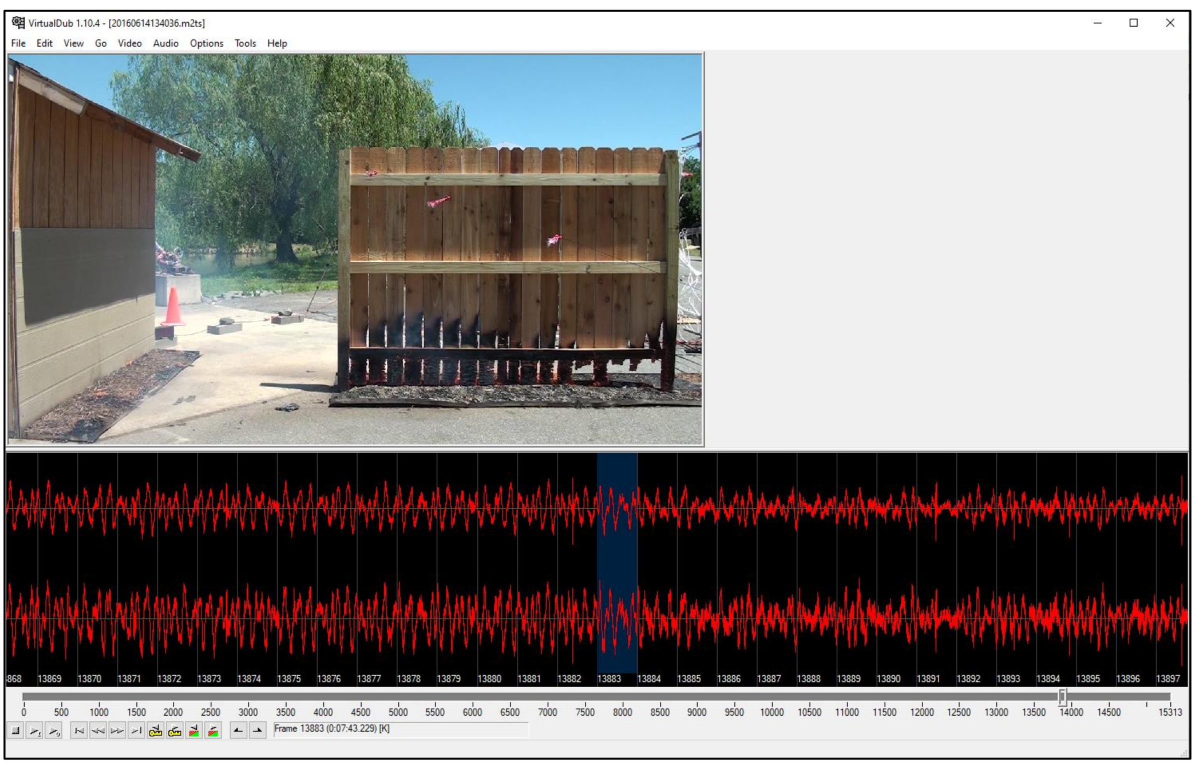


Fig. A.2. Audio feed from left camera showing frame selected for Fan Off (centered, in blue). Total time shown is 1 s, or 29.97 frames.

The Water First Applied event is similar to the End of Gas Burner Ignition event in that the water striking the burning object may be blocked by the fence. Judgment is involved in deciding when the water first reaches its target. When the water application is visible, the standard uncertainty is estimated as ±1 s.

Three time events were identified to evaluate how fast spot fires occurred in the target mulch bed and how quickly they threatened the structure. The first was the time at which the first spot fire ignited. Even if this spot fire did not reach the shed wall, it could threaten other combustible objects, such as vegetation, near the structure. The second event was ignition of the first spot fire to result in flames against the wall. The third was the first time at which flames were observed on the wall. Spot fire ignition times were determined by using video processing software to first identify the spot fire in the mulch bed and then to track it backwards in time to the point at which the first wisp of smoke could be detected. The indication of ignition was often subtle, and there were very few cases in which the deposition of the igniting ember was observed. The timing uncertainty was therefore estimated as ±10 s. The orange color of the flame made it easy to identify flames nearing the wall, but the 3D nature of the flames and their often transient nature added to the uncertainty, estimated at ±3 s.

Table A.4 summarizes the timing uncertainties, which are all Type B and are determined by scientific judgment.

Table A.4. Uncertainty in timing data

Measurement	Component Standard Uncertainty u_j	Combined Standard Uncertainty u_c	Expanded Uncertainty $2u_c$
End of Gas Burner Ignition (s)	1.0	1.0	2.0
Start to Remove Gas Igniters (s)	0.5	0.5	1.0
Fan On (s)	0.5	0.5	1.0
Fan Off (s)	1.0	1.0	2.0
Water First Applied (s)	1.0	1.0	2.0
Test duration (s)		1.1	2.2
Fan on	0.5		
Fan off	1		
Time to spotting (s)		10	20
Fan on	0.5		
Smoke detected	10		
Time to flames on wall (s)		3.0	6.1
Fan on	0.5		
Flame detected	3		

Other approaches to determining timing were considered. A digital timer was visible in most videos recorded from the left side, but variations of a few seconds in when the timer was set by one of the test operators made this a less accurate measure of the test timing. A consistent discrepancy of about 14 frames, or 0.5 s, between two of the video processing software packages resulted in a decision to use a single tool (VirtualDub) for both timing the videos and extracting images from them.

A.4. Flame Spread Analysis

The measurement of the flame front location, described in Section 3.1.3 for mulch experiments and Section 3.1.4 for experiments with fences, was subject to uncertainty from multiple sources. These included the physical uncertainties of the experimental setup as described in Appendix A.1, the process of determining the perspective lines, the uncertainty in setting the physical scale, and the determination of the leading edge of the flame front. Uncertainties in timing, covered in Appendix A.4, also contributed to the uncertainty of the plotting of flame front location as a function of time, but the contribution was small relative to the uncertainties in the location of the flame front.

Sources of uncertainty were Type B, with standard uncertainty based on scientific judgment. An estimate of the component standard uncertainty is given for each source.

A.4.1. Mulch

For mulch experiments, the location of the flame front was expressed as the distance from the shed wall to the closest boundary of the charred mulch. The definition required the charred region to be continuous with the area of ignition; spot fires along the mulch bed were ignored until the main burning region joined them. Section 3.1.3 describes the analysis of video images to track the progress of the flame front over time. Sources of uncertainty included the location of the mulch pan (the separation distance, covered in Appendix A.1), the selection of points to define perspective lines at the shed wall and away from the shed wall, the dimensional scale, and the ability to locate the flame front visually.

The perspective line at mulch height along the wall could be off by ±0.5 cm for zero separation cases, due to uneven piling of mulch against the wall and distortions in the mulch pan, and as much as ±1 cm for experiments with nonzero separation distances, for which the line along the top of the target mulch pan was estimated.

The accuracy of the perspective line away from the shed wall depended on the availability within the camera's field of view of a good physical line parallel to the shed wall. In early experiments up to Test A-50, the far end of the mulch pan could be used when it was available. When it was not, other lines were found, such as the shadow of the probe array on a sunny day or the near end of the mulch pan when the separation distance was large. The standard uncertainty in flame front location due to the far perspective line was estimated as ±3 cm for these experiments. Painted lines added to mark the pavement at 0.30 m (1 ft) intervals starting with Test A-51 decreased the uncertainty by providing a series of lines parallel to the shed wall that could be used to identify perspective lines. The standard uncertainty for experiments with markers was estimated as ±1 cm.

Distances from the shed wall were calibrated by selecting a point at a known distance. Up to Test A-50, distances were usually calibrated using a mark on the pavement at 1.0 m (39 in) from the shed wall. For later experiments, a distance marker near the ignition area was selected. Setting the dimensional scale was estimated to contribute ±0.5 cm to the uncertainty.

For the video image analysis, the surface of the mulch was assumed to be in a plane along the top of the mulch pan. Perspective lines at and far from the shed wall were projected to the top of the mulch pan at 2.5 cm. In actuality, the depth of the mulch varied from 2.5 cm along the sides to 5 cm at the center. The warping of the mulch pans over time could increase the level of the mulch by as much as 1 cm in affected areas. The effect of the mulch depth uncertainty and bias on flame front location was minimal for straight line-of-sight from the camera but could be ±0.5 cm near the ignition area.

After identifying points to define the perspective lines, the selection of each point using the mouse was dependent on the patience and care of the analyst. An additional uncertainty of ±0.5 cm was included for this factor.

Camera lens distortions were neglected in the assessment of uncertainty for perspective lines.

An accurate visual determination of the flame front location was inherently challenging. The inhomogeneity of the various mulch types, with gaps and shadows between overlapping particles, made it difficult to mark the boundary of the char with precision. The contrast between burned and unburned areas in the mulch depended on the lighting on sunny or cloudy days and on the presence of smoke and flames in the image. Frames in which the smoke, flames, or an obstruction completely obscured the flame front were skipped. This source of uncertainty was estimated as ±3 cm.

The combined standard uncertainty for the flame front location for mulch experiments, calculated as the square root of the sum of squares from all of these sources, ranged from ±25 mm to ±39 mm, as listed in Table A.5. The expanded uncertainty with coverage factor $k = 2$, for a confidence level of 95 %, ranges from ±50 mm to ±77 mm (±2.0 in to ±3.0 in).

Table A.5. Mulch experiments: Uncertainty in flame spread analysis

Measurement	**Component Standard Uncertainty** u_j	**Combined Standard Uncertainty** u_c	**Expanded Uncertainty** $2u_c$
Flame front location		34 mm/45 mm	67 mm/89 mm
Separation distance (Sep) (from App. A.1)	5 mm		
Perspective line at wall Zero Sep/Nonzero Sep	5 mm/10 mm		
Perspective line far from wall Markers/No Markers	10 mm/30 mm		
Distance scale	5 mm		
Mulch depth	5 mm		
Point selection	5 mm		
Visual char boundary	30 mm		
Timing		0.5 s	1.0 s
Fan On (from App. A.3)	0.5 s		

A.4.2. Fences

For fence experiments, the location of the flame front was expressed in two dimensions extending over the surface of the fence and including the posts at both ends. Section 3.1.4 describes the analysis of video images to track the progress of the flame front over time. The horizontal location of the flame front was considered to be the furthest point the char had reached downwind, and the vertical location was the highest point reached by the char. The height of the char was measured both in the ignition region and in the area downwind from ignition. In addition to flame front location as a function of time, 2-D profiles of the char region were captured at specific times.

Sources of uncertainty in defining the boundaries of the char front in horizontal and vertical directions included the dimensions and setup of the fence, the selection of points identifying fence corners, and the ability to locate the flame front visually.

Uncertainties for the lengths and heights of the two types of fences most commonly used in the study (western redcedar privacy and redwood or pine lattice) were calculated in Appendix A.1. The maximum standard uncertainty values for these measures are repeated in Table A.6.

Identification of the corners of the fence in the video images was subject to some imprecision. For the two lower corners, the mulch may obscure the exact location, introducing an uncertainty estimated as ±5 mm in both directions. For the upper corners, the height of the post sometimes differed slightly from that of the fence panel, introducing an uncertainty of ±3 mm in the vertical direction. The uncertainty of the position of each upper point in the horizontal direction was also estimated as ±3 mm. Combining these values separately in vertical and horizontal directions resulted in a standard uncertainty of ±8 mm for this factor.

The selection of each point using the mouse was dependent on the accuracy of the pointer and the patience and care of the analyst. An uncertainty of ±2 cm was included for this factor.

Camera lens distortions were neglected in the assessment of uncertainty.

The visual determination of the char boundary provided some challenges. Although easier to distinguish than for the mulch bed, dark spots in the boards and shadows sometimes masked the location of the char front, as did the presence of flames and smoke. The char front was not sharp – the wood color changed from light to dark over a distance of a few millimeters. Error was introduced when selecting points on the surfaces of the stringers and posts because they were not in the plane of the fence panel. This source of uncertainty was estimated as ±1 cm.

The combined standard uncertainty for the flame front location for fence experiments, calculated as the square root of the sum of squares from all of these sources, was 1.4 cm in both horizontal and vertical directions, as listed in Table A.6. The expanded uncertainty with coverage factor $k = 2$, for a confidence level of 95 %, was ±2.8 cm (±1.1 in).

Table A.6. Fence experiments: Uncertainty in flame spread analysis

Measurement	**Component Standard Uncertainty** u_j	**Combined Standard Uncertainty** u_c	**Expanded Uncertainty** $2u_c$
Horizontal flame front		24 mm	48 mm
Fence length (from App. A.1)	3.1 mm		
Four corner points	8 mm		
Point selection	20 mm		
Visual char boundary	10 mm		
Vertical flame front		24 mm	48 mm
Fence height (from App. A.1)	2.8 mm		
Four corner points	8 mm		
Point selection	20 mm		
Visual char boundary	10 mm		
Timing		0.5 s	1.0 s
Fan On (from App. A.3)	0.5 s		

As a final note, some situations required judgment calls. One of these was the discontinuity of the flame front at some fence board edges due to the spread of fire in the thin space between the boards. In these cases, following every detail with a large number of selected points would result in a 2-D char with many sharp spikes. Instead, selecting a midpoint between char boundaries on adjacent boards emphasized the general shape of the char profile.

In some experiments, including many with parallel fences, smoke emerged from under the fence ahead of the char, making it difficult to decide on the flame front location. Fortunately, the fire spread in these experiments was rapid, making the precision of each point less important.

Appendix B. Flammability Comparison of Fence Materials

Flammability measurements to compare three types of fence materials used in this study, rigid polyvinyl chloride (PVC), western redcedar (WRC) wood, and wood-plastic composite #1 (WPC1), were obtained using the cone calorimeter. While the flammability performance of bulk PVC and wood materials is well known, the knowledge about the burning behavior of wood-plastic composites is limited. The intent of this materials study was to compare flammability performance of samples taken from the actual fence panels tested in this study. The flammability performance of fence materials was tested using standard cone calorimetry protocols as described in ASTM E-1354. The cone calorimeter test results reported here include ignitability, heat release rate, and mass loss of samples at specified external heat flux. The comparison did not include measures of smoke toxicity.

B.1. Test Sample

Specimens with nominal dimensions of 100 mm × 100 mm were cut from PVC, WRC, and WPC1 fence panels. Cross-sectional and top views of the specimens are shown in Fig. B.1. The WRC and WPC1 samples were solid, with nominal thicknesses of 20 mm and 6 mm respectively. The PVC sample consisted of two sheets 1.23 mm (0.048 in) thick separated by a gap of 18 mm that was supported by three 1.23 mm thick braces. Although PVC and WRC samples were nominally the same total thickness, the geometry was very different. The PVC samples can be characterized as hollow structures with thin elements separated by large gaps and studs as seen in Fig. B.1 (a). Previous studies [70] have shown that hollow-shaped geometries remove combustible material and reduce the fire load but simultaneously increase fire propagation. Nominal masses for PVC, WRC, and WPC1 samples were 44.3 g ± 0.1 g, 66.7 g ± 2.0 g, and 59.1 g ± 1.1 g, respectively.

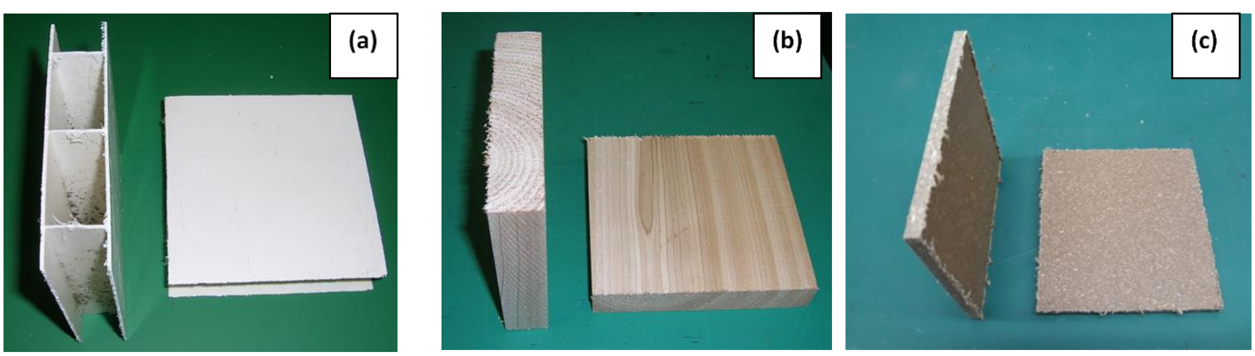


Fig. B.1. Specimens of a) PVC, b) WRC, and c) WPC1 fence boards showing cross-sectional and top views.

Samples were conditioned for 48 hours in the laboratory, with nominal temperatures of 20 °C and variable relative humidity not exceeding 50 %. The samples were allowed to come to equilibrium under laboratory conditions. Although moisture content in cellulosic fuels is known to have a significant effect on burning behavior, no attempt was made to control the moisture content of wood samples. The influence of moisture on the average mass loss rate and hence the heat release rate can be ignored when moisture content in wood is lower than 11 % [71]. The thermal conductivity, however, is known to increase with increasing moisture content. Thermal conductivity increases approximately 1.3 times when moisture content increases from 10 % to 30 % [72].

B.2. Experimental Procedure

Cone calorimeter measurements were performed using the protocols described in ASTM E-1354. Three samples of each fence material were tested in a horizontal configuration at an incident heat flux of 50 kW/m². Uncertainties in heat release rate measurements are typically within 5 % and 10 % for HRRs larger than 50 kW/m² [73, 74].

Cone calorimeter samples were placed in an aluminum foil pan with nominal thickness of 0.035 mm ± 0.01 mm (specified by ASTM E-1474), as shown in Fig. B.2. The sample surface was placed at a distance of 25 mm from the cone heater base. A spark igniter was used to ignite pyrolysis gases generated by heating the sample. Digital still images were taken from various locations to provide additional visual characterization of test samples.

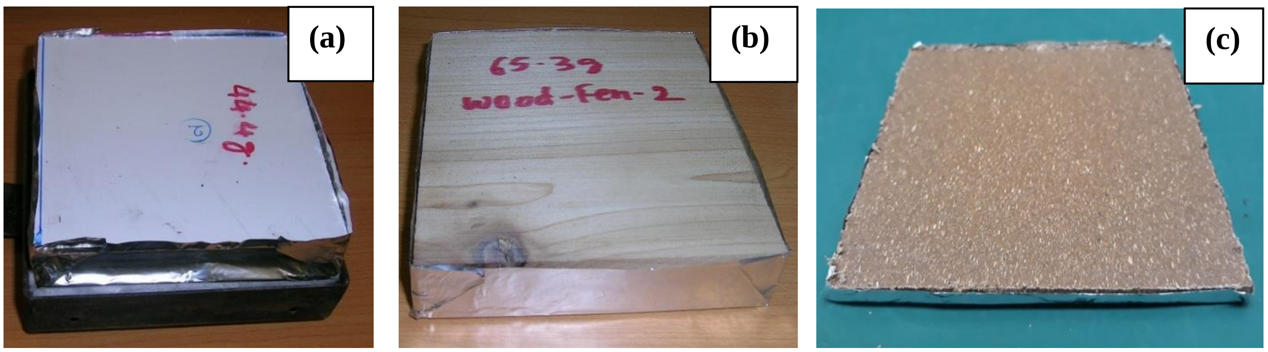


Fig. B.2. Cone calorimeter samples of a) PVC, b) WRC, and c) WPC1 fence materials.

B.3. Test Results

Cone calorimetry data for PVC, WRC, and WPC1 fence materials are given in Table B.1, Table B.2, and Table B.3, respectively. Data include the original sample mass, time to ignition (TTI), flame out (FO) time, peak heat release rate (PHRR), average HRR integrated over 600 s, total heat release (THR) obtained by integrating HRR over duration of flaming combustion, effective heats of combustion (EHOC), and percentage of original sample mass lost over the experiment.

Table B.1. Cone calorimetry data for PVC fence material at 50 kW/m².

Sample	Mass, g	TTI, s	FO, s	PHRR, kW/m²	Avg. HRR_600s, kW/m²	THR, MJ/m²	EHOC, MJ/m²	Mass lost, %
1	44.2	37	443	153	51	29	8.7	74.9
2	44.4	37	449	157	54	29	8.9	74.5
3	44.2	39	430	168	52	30	9.1	75.1
Avg.	**44.3 ± 0.1**	**38 ± 1**	**441 ± 10**	**159 ± 8**	**52 ± 2**	**29 ± 1**	**8.9 ± 0.2**	**74.8 ± 0.3**

Table B.2. Cone calorimetry data for WRC fence material at 50 kW/m².

Sample	Mass, g	TTI, s	FO, s	PHRR, kW/m²	Avg. HRR_600s, kW/m²	THR, MJ/m²	EHOC, MJ/m²	Mass lost, %
1	65.8	18	864	184	81	67	12.3	82.5
2	65.3	15	885	197	84	69	12.4	84.6
3	69.0	18	929	190	81	72	12.6	82.2
Avg.	**66.7 ± 2.0**	**17 ± 2**	**893 ± 33**	**190 ± 7**	**82 ± 2**	**69 ± 2**	**12.5 ± 0.1**	**83.1 ± 1.3**

Table B.3. Cone calorimetry data for WPC1 fence material at 50 kW/m².

Sample	Mass, g	TTI, s	FO, s	PHRR, kW/m²	Avg. HRR_600s, kW/m²	THR, MJ/m²	EHOC, MJ/m²	Mass lost, %
1	59.8	24	1004	417	234	169	28.0	88.6
2	57.9	23	1040	421	229	173	29.4	89.7
3	59.7	31	1060	429	239	174	29.7	82.4
Avg.	**59.1 ± 1.1**	**26 ± 4**	**1035 ± 28**	**422 ± 6**	**234 ±5**	**172 ± 3**	**29.0 ± 0.8**	**86.9 ± 4.0**

Heat release rate measured using the cone calorimeter is the most important property, since the fire hazard is dominated by the rate of heat released as the material is consumed in a fire. A burning material will spread fire to nearby products only if it gives off enough heat to ignite them. Heat release rate is largely influenced by the chemical stability of a material. Several parameters are derived from heat release rate data, including the peak value in the HRR curve (termed as the peak heat release rate), the average heat release rate over time, the total heat release rate, and the effective heat of combustion (defined as the instantaneous HRR divided by the instantaneous mass loss rate). The EHOC is used to provide time-resolved insights into the materials undergoing combustion and the completeness of the combustion process.

The values for WRC and WPC1 samples are in good general agreement with cone calorimeter results for similar materials published in previous studies [75, 76].

The temporal profiles of HRR for PVC, WRC, and WPC1 samples are shown in Fig. B.3. The WRC samples exhibit two characteristic peaks of wood burning, PVC samples exhibit a single peak, and the WPC1 samples have three distinct peaks in their respective temporal profiles.

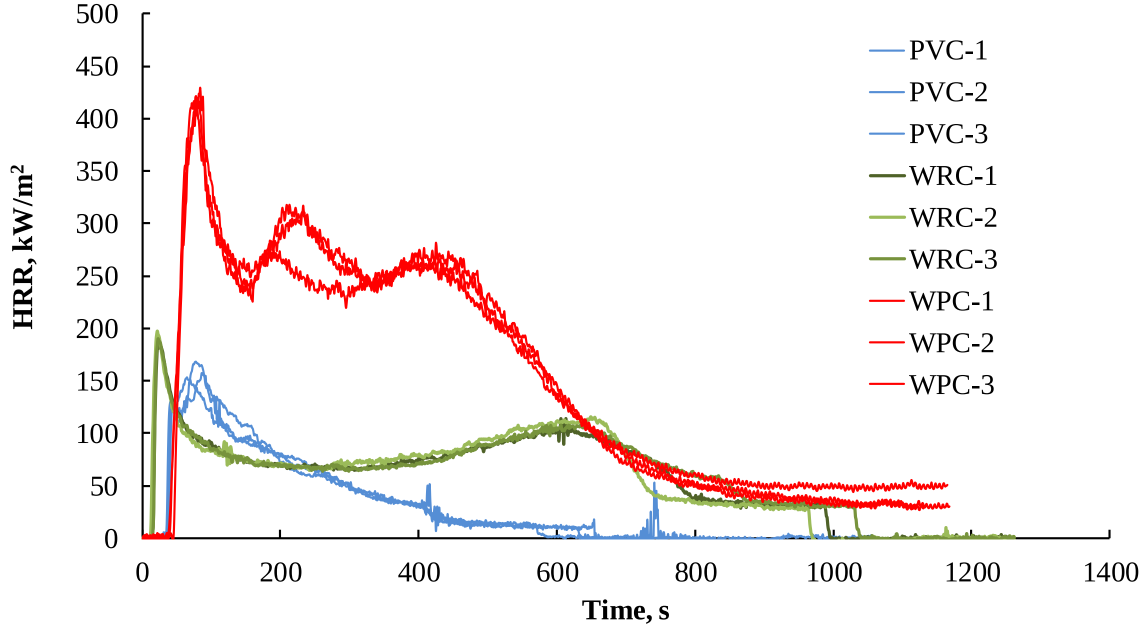


Fig. B.3. Heat release data for PVC, WRC, and WPC1 fence materials exposed to 50 kW/m^2 heat flux.

B.4. Ignitability and Extinction

Ignitability of materials has great importance in fire safety research, since it is associated with the initiation and subsequent growth of fire. Sample orientation has a significant effect on the ignitability of the samples. Earlier studies have shown that ignition times for horizontal orientation are shorter than for vertical orientation for plastic and wood samples [77]. This is primarily due to lower convective cooling in the horizontal orientation compared to the vertical orientation [78].

At an external heat flux of 50 kW/m^2, the times for sustained flaming ignition were significantly less for wood (17 s ± 2 s) as compared to the PVC samples (38 s ± 1 s), and ignition times for WPC1 samples (26 s ± 4 s) were intermediate between WRC and PVC samples. This indicates that WRC wood samples were easiest to ignite. The flame out (FO) times for PVC samples were lower than those for WRC samples by nearly a factor of two. Once ignited, WRC exhibited flaming combustion for 893 s ± 33 s, as compared to 441 s ± 10 s for PVC samples. Longer ignition times and shorter duration of flaming for PVC samples suggest that the risk of contributing to the fire hazard is lower for PVC than for WRC wood. The WPC1 samples continued to burn for a longer duration (1035 s ± 28 s), indicating greater fire hazard compared to WRC and PVC samples.

B.5. Heat Release Rate

Many studies report PHRR values and use this value for screening materials. However, the PHRR value may not always be an appropriate indicator of fire hazard, depending on the end use application of the products tested. For example, in this study, the PHRRs for WRC and PVC samples vary by only 20 %. However, the average HRR over 600 s and the total heat released during the flaming combustion of these two samples vary by 60 % and 135 % respectively. The PHRR value (422 kW/m^2 ± 6 kW/m^2) and the average HRR over 600 s (234 kW/m^2 ± 5 kW/m^2) for the WPC1 samples are significantly higher than for WRC and PVC samples.

The THR is related to the total amount of fuel present and the fraction consumed. Hence, the THR is an indicator of the fire load and fire hazard associated with the material. Higher THR (172 MJ/m^2 ± 3 MJ/m^2) and higher average HRR (234 kW/m^2 ± 5 kW/m^2**)** for WPC1 samples reveal that this material has greater flammability compared to PVC and WRC samples, whose corresponding values are significantly lower.

Another derived parameter that can be used for comparing burning intensities of samples is the effective heat of combustion. The lower EHOC for PVC samples (8.9 MJ/m^2 ± 0.2 MJ/m^2) suggests incomplete combustion of fuel and corroborates the lower burning intensity of these materials compared to wood (12.5 MJ/m^2 ± 0.1 MJ/m^2) and wood-plastic composites (29.10 MJ/m^2 ± 0.8 MJ/m^2).

B.6. Firebrand Generation and Char Residue

Significantly different burning behavior related to firebrand generation was visually observed and digitally recorded for PVC, WRC, and WPC1 samples. Images of PVC, WRC, and WPC1 samples after 800 s of exposure to 50 kW/m^2 heat flux are shown in Fig. B.4.

Formation of firebrands in the wood sample is clearly shown in Fig. B.4 (a). Firebrands were observed following sustained flaming combustion in the wood specimen. Small glowing firebrands separated from the test specimen and flew away from the sample holder, suggesting generation of potential secondary ignition sources. Flaky ash residue remained after glowing combustion ceased, as shown in image (b).

After the same exposure period of 800 s, Fig. B.4 (c) shows that the PVC sample has formed a dome-shape hard carbonaceous residue with a layer of white particles. The white particles are understood to be the residue of metal elements incorporated to improve the flame retardancy and smoke suppression of the polymer [79].

The WPC1 sample burned intensely. However, no evidence of firebrand generation was noted. The residue of the WPC1 sample was woody dust that exhibited no glowing combustion after the flaming combustion ceased, as seen in Fig. B.4 (d).

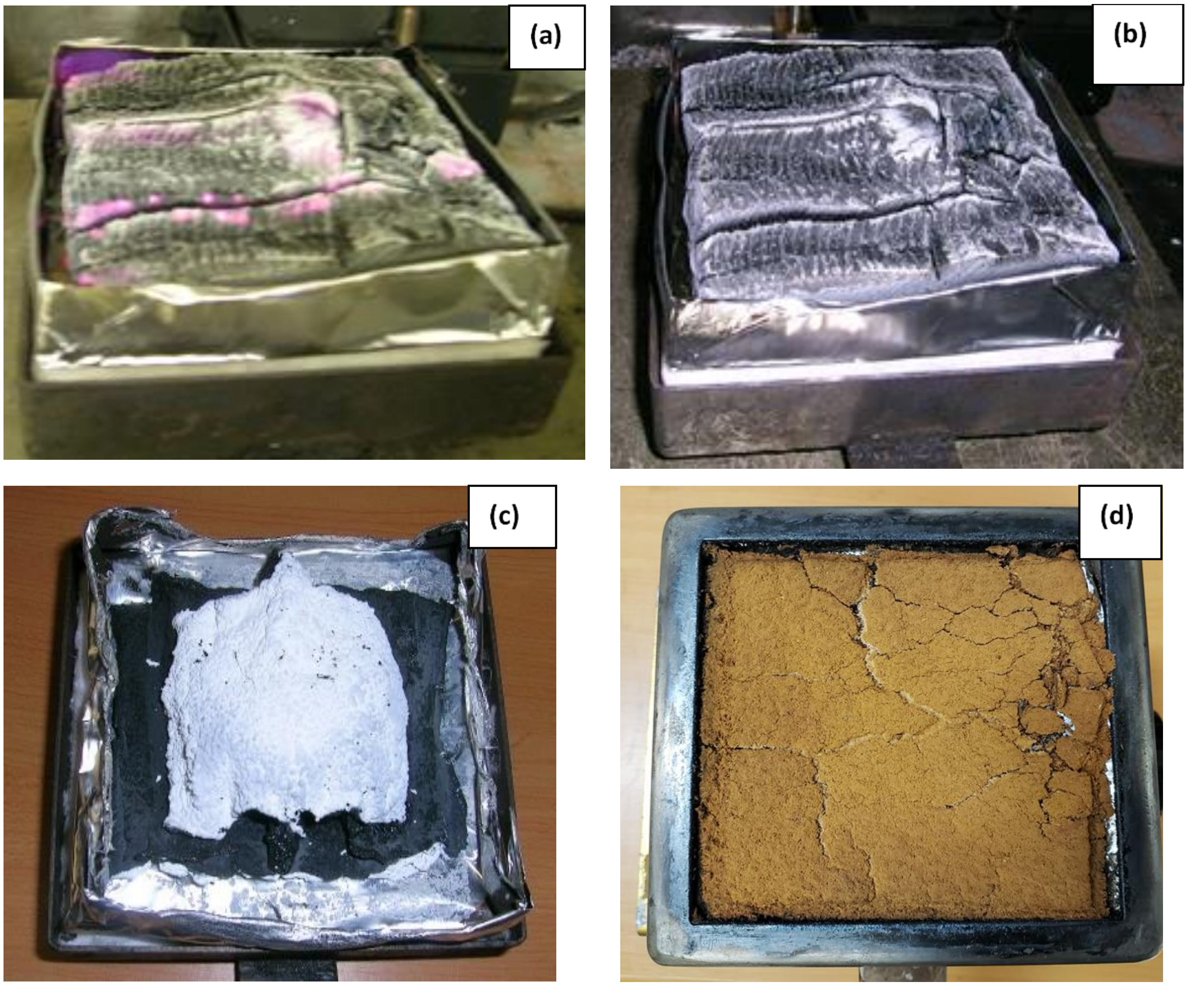


Fig. B.4. Digital images of (a) firebrand formation in WRC wood sample after flame extinction, (b) flaky, ash residue of wood, (c) hard char residue of PVC sample, and d) flaky, woody residue of WPC1 sample after 800 s of exposure to 50 kW/m^2 heat flux.

B.7. Concluding Remarks

In this limited experimental test series, the burning behaviors of selected WRC, PVC, and WPC1 fence materials have been characterized and compared using cone calorimetry data. Cone samples 100 mm × 100 mm in size were cut from fence boards. The WRC and WPC1 samples were solid, with thicknesses of 20 mm and 6 mm respectively. The PVC sample consisted of two thin sheets separated by 20 mm with three thin sheets serving as braces. Because of differences in the densities of these materials, the mass of the WRC wood sample was 50 % greater than the PVC sample, and the total masses of WRC and WPC1 samples were comparable.

Cone testing revealed distinct differences in both quantitative and qualitative burning behaviors of WRC, PVC, and WPC1 fence materials. Wood-containing samples (WRC and WPC1) ignited easily, and the duration of flaming was higher compared to PVC by a factor of two. The WPC1 samples burned intensely, with peak and total heat release values greatly exceeding those of the other two materials. While the PHRR value for wood was marginally

(20 %) higher than that for PVC samples, the total heat release and the average heat release rates for wood were significantly higher, indicating that wood has higher flammability than PVC samples.

Visual observations suggested that WRC samples continued to smolder for a longer duration after the flames extinguished. Firebrand generation was observed in wood samples during flaming and after flame extinction. No smoldering combustion or firebrand generation was observed for PVC and WPC1 samples.

With this limited data set, this study has demonstrated that WPC1 fence materials are highly flammable and can contribute significantly towards the development and growth of the fire hazard, particularly in the WUI fire environment. The WRC wood fence material burns less intensely compared to WPC1 samples; however, WRC has a tendency to smolder and form firebrands that can serve as potential secondary ignition sources. The burning behavior of PVC materials suggests that they have little or no tendency to form firebrands. From a flammability viewpoint, their contribution to the fire hazard is significantly less than that of materials used for WRC or WPC1 fences. However, it is important to note here that PVC is not completely benign in a fire environment, and smoke toxicity effects should be weighed against limited burning and flame spread in a WUI fire.

Appendix C. Wind Characterization

Measurements from the bidirectional probe array described in Sections 2.7.1 and 2.8.1 provided wind speed data in a plane orthogonal to the direction of the wind flow from the fan. For each individual experiment, the data collected from each probe were averaged over time to observe the wind speed as a function of horizontal distance from the centerline and height above the ground. This appendix describes how the data from multiple experiments were combined to provide insights into wind speed contours as a function of nominal applied wind speed and probe array location between the fan and the shed. The uniformity of the wind field in the region of the burning fence and/or mulch bed was of particular interest.

C.1. Measurement Distance from Wind Machine

The first step to organizing the wind data was to identify the distance of the measurement probe array from the wind machine for each experiment. Since the position of the probe array moved with that of the burning fence and/or mulch bed, this distance varied as a function of the separation distance.

The geometry of the experimental setup is shown in Fig. C.1. This diagram focuses on the location of the probe array relative to the wind machine, fence, and target shed. The horizontal distance d_{wp} from the wind machine to the bidirectional probe array is equal to the distance d_{ws} from the wind machine to the shed minus the distance d_{ps} from the probe array to the shed, $d_{wp} = d_{ws} - d_{ps}$. The distance of the probe array from the target shed is equal to the distance d_{pf} of the probe array from the fence plus the total length d_{fence} of a privacy fence plus the separation distance d_{sep} of the fence from the target shed, or $d_{ps} = d_{pf} + d_{fence} + d_{sep}$. Combining these equations results in d_{wp} as a function of separation distance, $d_{wp} = \left[d_{ws} - \left(d_{pf} + d_{fence}\right)\right] - d_{sep}$.

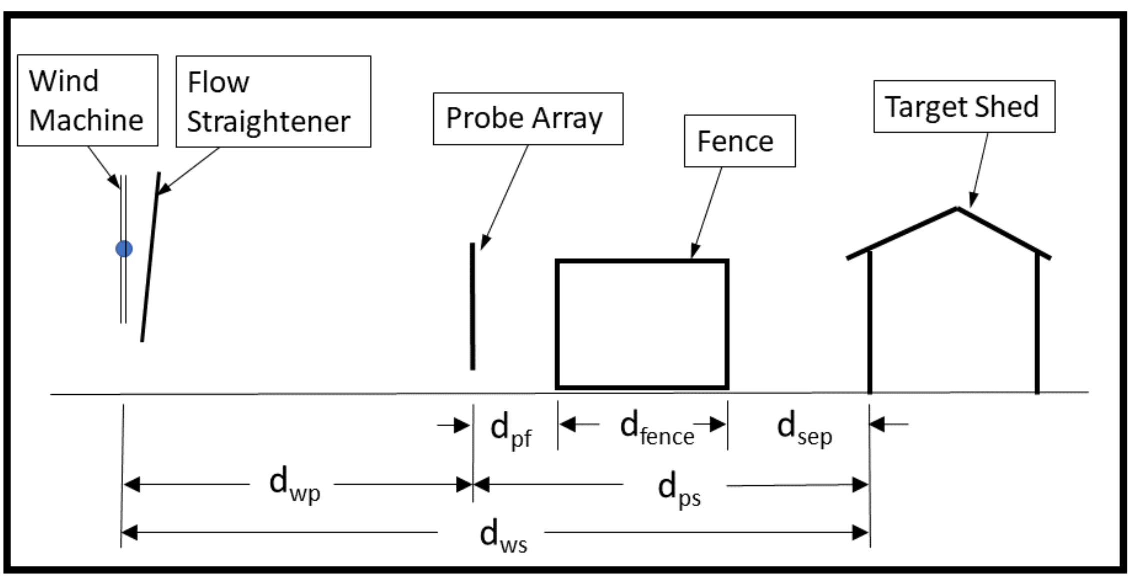


Fig. C.1. Distances between experimental elements. Distances to scale.

For all experiments, d_{ws} = 10.67 m (35 ft) and d_{pf} = 1.22 m (4 ft). The length of privacy fences was equal to the panel length plus the width of the two posts at each end of the panel, for a total length of 2.62 m (8 ft 7 in). (For lattice fences, the panel overlapped each post by 5 cm (2 in), for a total length of 2.51 m (8 ft 3 in). This difference in length will not be considered in this analysis.) The distance from the wind machine to the probe array as a function of separation distance is therefore $d_{wp} = 6.83 \text{ m} - d_{sep}$, with all measurements in meters.

In Fig. C.2, the locations of the probe array are highlighted for the four separation distances between fence/mulch and target shed used in this study. The position of the fence that corresponds to the longest separation distance, $d_{sep,A}$ = 1.83 m (6 ft), is shown in gray. For cases at this separation distance, the fence and/or mulch bed overlaps probe array locations C and D. The velocity profiles at these locations are therefore directly relevant to the flow field over the test object in these cases. As the location moves closer to the target shed, the flow field is expected to be more diffuse, lower to the ground, and increasingly affected by the target shed.

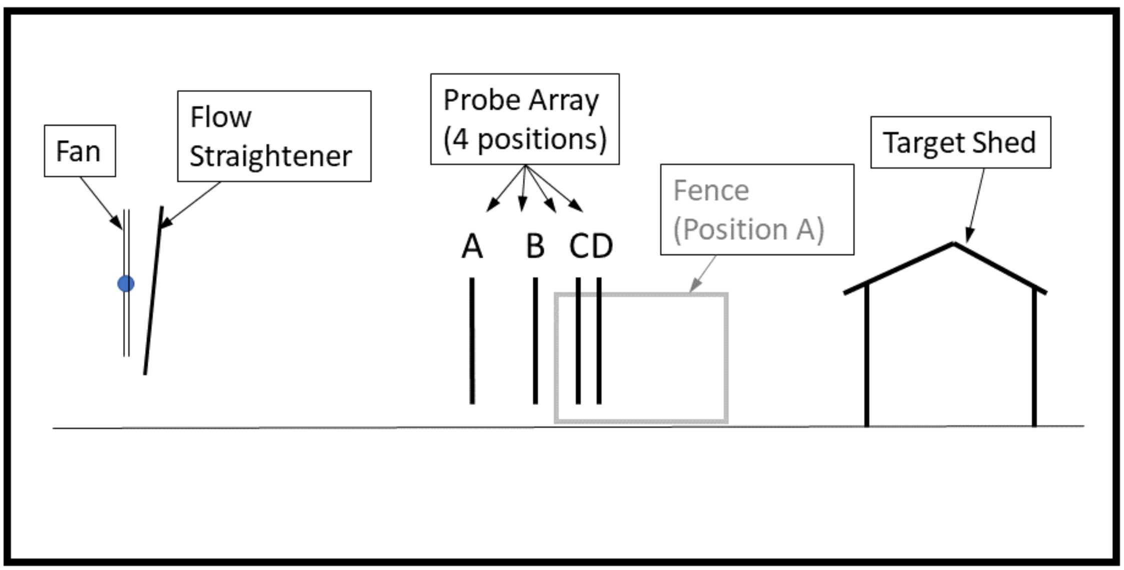


Fig. C.2. Locations of bidirectional probe array for separation distances of (A) 1.83 m, (B) 0.91 m, (C) 0.30 m, and (D) 0 m. Distances to scale.

The distance from the fan to the probe array is listed in Table C.1 for each probe array location. With this information, the wind data from the full set of experiments can be organized to look at how velocity patterns change at increasing distances from the fan.

An expectation can be established for the uniformity of the velocity profiles by referring to the literature on ducted axial fans [32]. As discussed in Section 2.2.3, a uniform air velocity across the duct area of a ducted axial fan is expected to be achieved at a minimum of 2 ½ equivalent duct diameters. The rightmost column of Table C.1 provides the distance from the fan to the probe array divided by the fan diameter D = 2.11 m (83 in) and shows that the 2 ½ diameter threshold is exceeded for every probe array location except for A.

Table C.1. Distances from fan for bidirectional probe array at various separation distances.

Array location	Separation distance d_{sep} (m)	Distance from probe array to shed d_{ps} (m)	Distance from fan to probe array d_{wp} (m)	Distance from fan to probe array / Fan diameter d_{wp}/D
A	1.83	5.67	5.00	2.4
B	0.91	4.75	5.92	2.8
C	0.30	4.14	6.53	3.1
D	0	3.84	6.83	3.2

C.2. Wind Profiles

To calculate mean wind field profiles, the experiments were divided into 12 categories according to the three wind speed levels (Low, Medium, High) and four separation distances (corresponding to array locations A, B, C, D) used in the study. Experiments that were two fence panels long, experiments oriented at an angle of 45° to the wind, and experiments without a shed were not included in the calculations. The number of experiments used for each of these categories is shown in Table C.2.

Table C.2. Number of experiments in each category of wind speed and array location.

Array Location	Low Wind Speed	Medium Wind Speed	High Wind Speed
A	36	22	19
B	9	14	11
C	5	12	12
D	10	17	12

A statistical analysis using standard methods [67, 80, 81] was performed on the dataset collected from the bidirectional probes. Three indices were used to keep track of variables during the calculation: the experiments were indexed by $k = 1, \dots, M$, the probes were indexed by $j = 1, \dots, 13$, using the numbering system from Fig. C.3 (repeated from Fig. 17), and the individual values in a dataset from experiment k were indexed by $i = 1, \dots, N_k$.

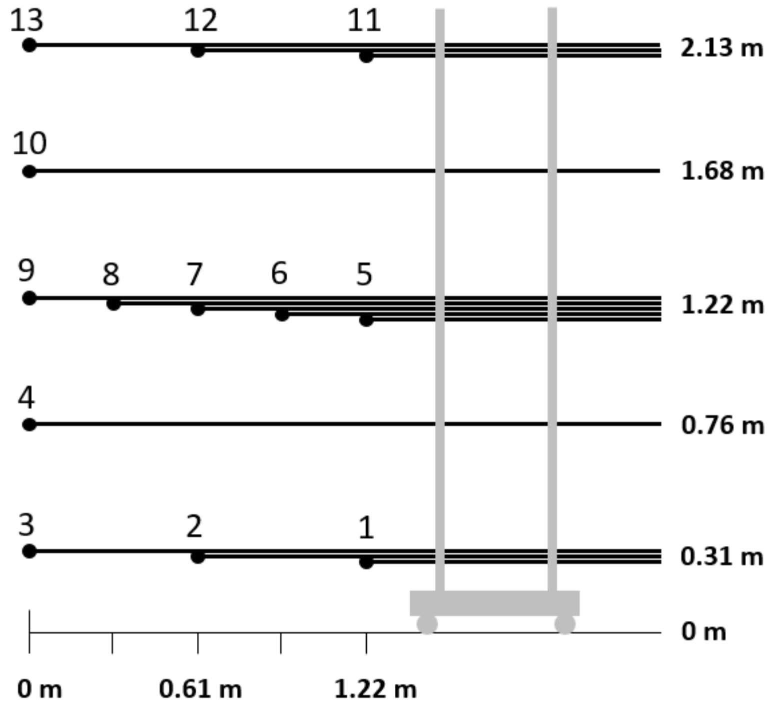


Fig. C.3. Diagram of the bidirectional probe array used to measure the velocity field. (Repeated from Fig. 17).

The calculation for wind speed embedded in the Labview program described in Section 2.8.1 for collecting data from the bidirectional probes is

$$V_{i,j,k} = 0.0698 \frac{1}{C}\sqrt{\Delta P_{i,j,k}\, T_{i,k}} \quad \text{(C-1)}$$

where C is the probe constant, ΔP is the probe differential pressure in Pa, and T is the ambient temperature in K. This equation is derived from Equation A.14, with the universal gas constant R_u, standard atmospheric pressure P_s, and molecular mass of dry air M_{air} incorporated into the value 0.0698. The indices indicate that this is the ith data point from the jth probe in experiment k.

The mean value $\bar{V}_{j,k}$ of the wind speed for each probe j during experiment k is given by

$$\bar{V}_{j,k} = \frac{1}{N_k}\sum_{i=1}^{N_k} V_{i,j,k} \quad \text{(C-2)}$$

with a standard deviation of

$$\sigma_{j,k} = \sqrt{\frac{1}{N_k}\sum_{i=1}^{N_k}\left(V_{i,j,k} - \bar{V}_{j,k}\right)^2} \quad \text{(C-3)}$$

that expresses the variability of the unsteady process under study. This Type A analysis quantifies the variation in wind speed due to fluctuations caused by the fan, ambient wind, and any other influences during an experiment. The uncertainty of the mean value of the wind speed for probe j during experiment k is equal to the standard error of the mean,

$$\sigma_{\bar{V}j,k} = \frac{\sigma_{j,k}}{\sqrt{N_k}} \tag{C-4}$$

The Type A uncertainty of the unsteady wind speed measurements can now be combined with the Type B relative standard uncertainty derived in Table A.3 for the bidirectional probe wind speed calculation. The RSS method is used to arrive at the total standard uncertainty of the wind speed value for probe j during experiment k,

$$u\left(\bar{V}_{j,k}\right) = \sqrt{\sigma_{\bar{V}j,k}^2 + \left(u_{r,BP}\bar{V}_{j,k}\right)^2} \tag{C-5}$$

with $u_{r,BP} = 0.0703$ multipled by the mean wind speed to obtain the absolute contribution of the probe calculation.

With these calculated values, the measurements from experiments that fell into each of the twelve categories of nominal wind speed and separation distance displayed in Table C.2 can be combined to estimate the means and uncertainties of data from each of the 13 bidirectional probes. The calculation requires the assumption that measurements from all experiments in the same category were taken from the same data distribution. This assumption may be weakened by the variability from test to test in wind machine operation and ambient wind conditions, as well as variations in probe array positioning. The measurements were also assumed to be taken from a normal distribution.

Combining the mean values for each probe j over all of the experiments at the same nominal wind speed and separation distance from the shed can be accomplished through a weighted mean. This calculation accounts for the differences in the duration, and thus the number of data points, for each experiment. With N_k equal to the number of data points in experiment k and M the number of experiments in the set being considered, the weighted mean of the wind speed for probe j is

$$V_j = \frac{\sum_{k=1}^{M} N_k \bar{V}_{j,k}}{\sum_{k=1}^{M} N_k} \tag{C-6}$$

for the set of experiments being considered. This calculation was done for each of the twelve cases.

The uncertainty of the weighted mean for each probe can be calculated as

$$u_c\left(V_j\right) = \frac{1}{\sum_{k=1}^{M} N_k} \sqrt{\sum_{k=1}^{M} N_k^2 u^2\left(\bar{V}_{j,k}\right)} \tag{C-7}$$

Multiplying $u_c\left(V_j\right)$ by coverage factor $k = 2$ results in the expanded uncertainty for the weighted mean with a confidence level of 95 %.

A MATLAB program was written to calculate the means and uncertainties for the bidirectional probe velocities from individual experiments and in combination, and to display the results. In Fig. C.4 the weighted mean values of the probe velocities are shown for the three nominal wind speeds and four separation distances in the study. The data are displayed in pseudocolor plots, in which a matrix of colored cells on a gray background represents the wind speed value at each probe. Dots indicate the location of bidirectional probes as shown in Fig. C.3. Velocity scales are identical within each family of nominal wind speeds. To get a clearer look at the variation of the mean wind speeds across the center of the flow field, weighted mean values of probes along the horizontal line 1.22 m (4 ft) above the ground and along the vertical centerline are plotted in Fig. C.5 and Fig. C.6, respectively.

The plots in Fig. C.4 show the spatial extent of the wind field generated by the fan under each condition. The winds from the fan were felt over a region with a diameter of about 1.2 m (4 ft) approximately centered on probe 9, at 1.2 m (4 ft) above the ground. With the probe array at position A, at a distance of 5 m (16.4 ft) from the fan, there was a strong minimum at the center that corresponded to the hub of the fan. As the distance from the fan increased, this minimum washed out, until the velocity profile became reasonably uniform over this entire region at positions C and D. The uniform region extended from the ground to over 1.7 m (5.5 ft) above the ground, spanning both the mulch bed and the fence along essentially its full height. In the streamwise direction, Fig. C.2 shows that positions C and D overlapped with the position of the burning fence or mulch bed at the largest separation distance from the shed. For all of the experiments in the study, therefore, the burning object was subjected to a wind field that is reasonably uniform.

The plots in Fig. C.4 also illustrate the tendency of the wind speed at the centerline point at ground level (at probe #3) to increase with increasing distance from the fan. This is in accordance with the angled flow straightener that tilts the flow field toward the ground.

The maximum Type A relative standard uncertainty value for the weighted mean wind speeds over all probes and all conditions of wind speed and location of the probe array was 0.0067. This is an order of magnitude smaller than the relative standard uncertainty for the bidirectional probe measurement of $u_{r,BP} = 0.0703$ from Table A.3. The uncertainty in the instrument measurement thus dominated the total uncertainty for the measured values of wind speed by the probe array.

The profiles in Fig. C.5 and Fig. C.6 provide a more quantitative look at the wind speed data across the center of the profile horizontally and vertically. For each of the three wind speed categories, high, medium, and low, the plots demonstrate the trend toward a more uniform flow field with increasing distance downwind from the fan. In successive plots from position A (red) to position D (blue), the wind speed increases at 1.22 m (4 ft) above the centerline, near the center of the flow field, and the maximum wind speeds in a ring around this point decrease.

Note that the achievement of a uniform air velocity across the width of the region influenced by the fan at positions C and D is consistent with the guideline from the literature on ducted axial fans [32] discussed in Section 2.2.3. The discussion of Table C.1 points out that the 2 ½ diameter threshold for a uniform flow is easily exceeded at those two locations.

The profiles in Fig. C.6 support the selection of the average of the velocities of the lower four probes along the centerline as a measure of the average wind velocity for a given experiment.

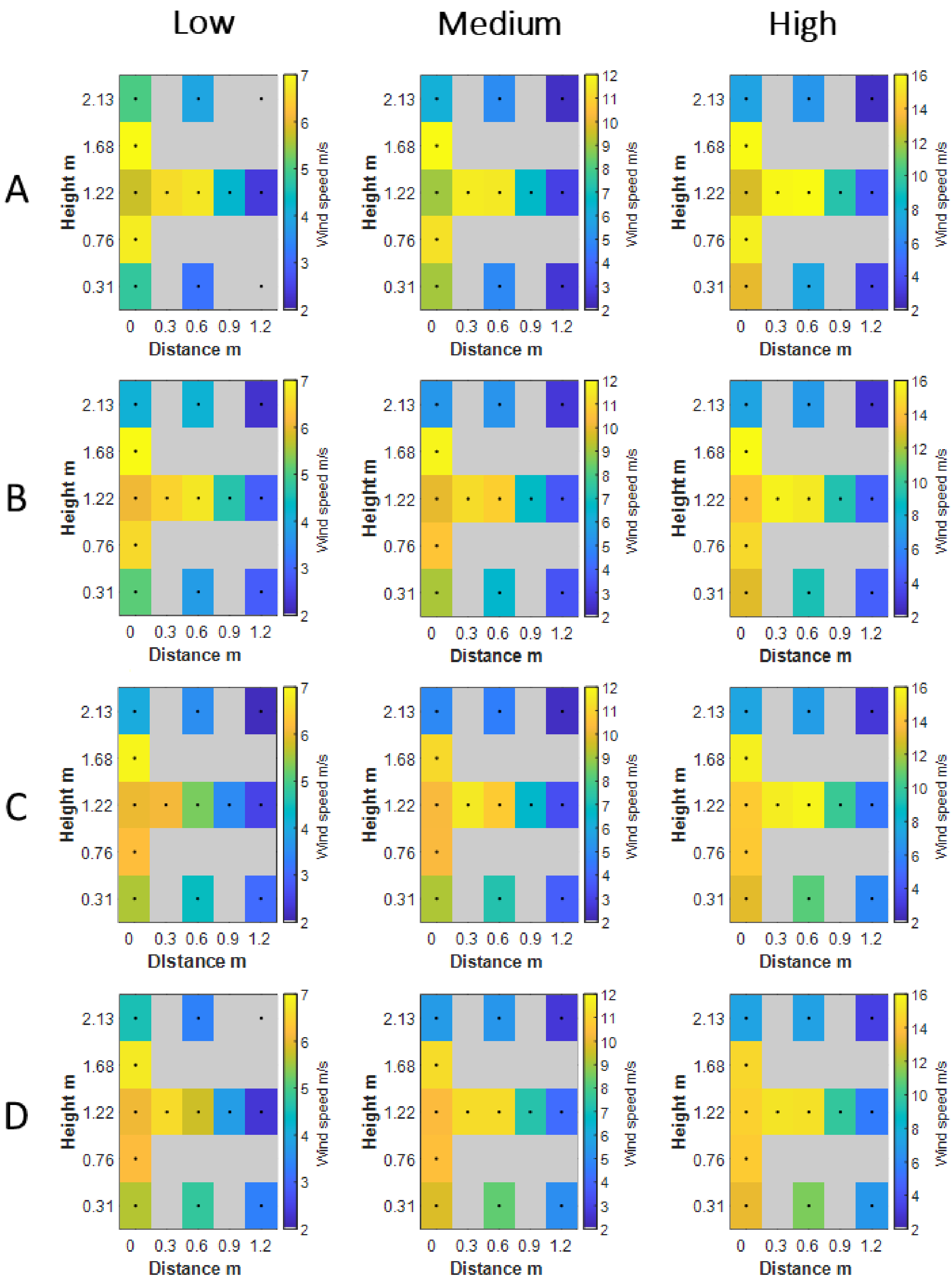


Fig. C.4. Mean wind speed pseudocolor plots by wind speed and probe array location, over all experiments. Dimensions to scale.

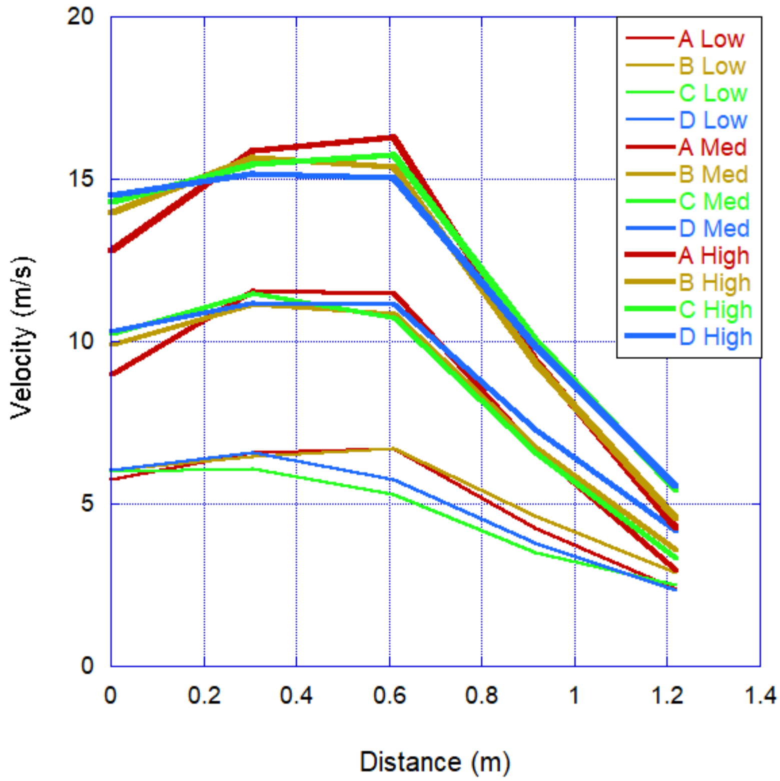


Fig. C.5. Horizontal weighted mean wind speed profiles 1.22 m (4 ft) above the ground.

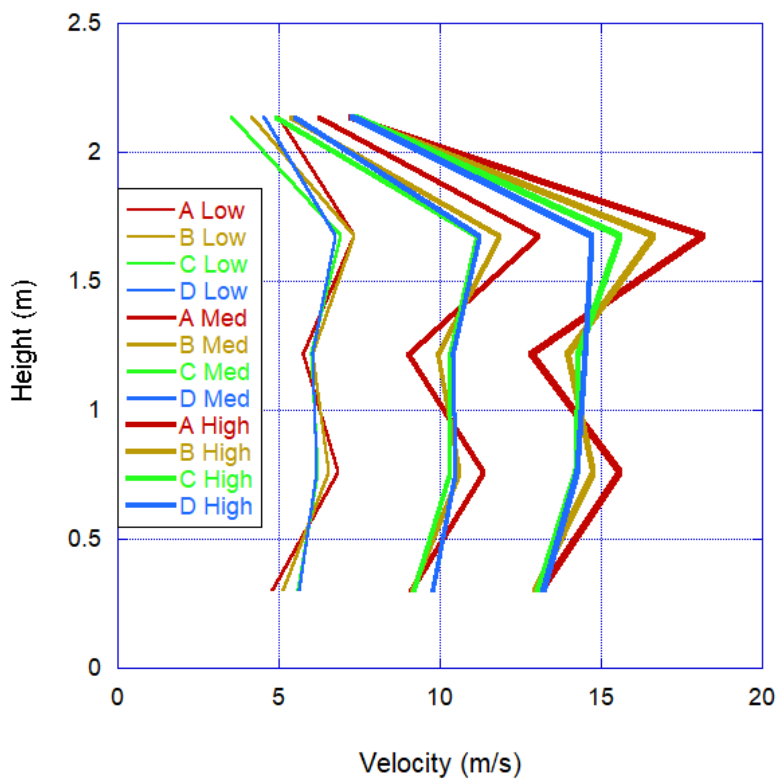


Fig. C.6. Vertical weighted mean wind speed profiles along the centerline.

C.3. Measure of Wind Speed for Each Experiment

In order to compare experimental results, such as the time to ignite a spot fire, a measure was needed to quantify the wind speed for each experiment. The measure needed to be representative of the actual wind speed felt by the burning fence or mulch bed and its immediate surroundings. It also needed to account for bad probes, since not every probe was properly collecting data for every experiment.

The measure that was chosen to represent the wind field for each experiment was the mean wind speed for the lower four probe values along the centerline. Using the probe numbers in Fig. C.3, the characteristic wind speed for a specified experiment k is given by

$$\bar{V}_k = \frac{\left(V_{3,k} + V_{4,k} + V_{9,k} + V_{10,k}\right)}{4} \tag{C-8}$$

This measure uses data from probes that extend from 0.30 m (1 ft) to 1.68 m (5.5 ft) in the vertical direction along the centerline. It measures wind speeds starting a short distance above a mulch bed and encompassing nearly the full height of a fence.

The standard uncertainty for this wind speed measure for experiment k is given by

$$u_{c,k} = \frac{1}{4}\sqrt{u_c^2\left(V_{3,k}\right) + u_c^2\left(V_{4,k}\right) + u_c^2\left(V_{9,k}\right) + u_c^2\left(V_{10,k}\right)} \tag{C-9}$$

Both calculations can account for bad probes by dropping their wind speed or uncertainty values from the equation and averaging over the number of good probes.

The plots of weighted mean wind speeds for probes along the centerline in Fig. C.6 indicate the degree of uniformity of the wind field over the lower four probes for each of the four array locations, A through D. Table C.3 lists the value of $\bar{V}$ using the weighted mean values from this plot.

Table C.3. Weighted mean velocity for lower four probes along centerline in each category of wind speed and array location, in m/s.

Array Location	Low Wind Speed	Medium Wind Speed	High Wind Speed
A	6.18	10.61	14.92
B	6.27	10.37	14.57
C	6.18	10.21	14.28
D	6.16	10.44	14.17

Appendix D. Experimental Matrices

The tables in this appendix show the test numbers for the combinations of fence and mulch, wind speed, and separation distance used in this study. Detailed data for each experiment can be found by type (i.e., fence only, mulch only, fence plus mulch, and parallel fences) and by test number in Appendix F through Appendix I.

Abbreviations used in the tables in this appendix are:

CW	Combustible wall (Series 1 experiments)
MaS	Mulch as Surrogate (Series II experiments)
WRC	Western redcedar
RW	Redwood
WPC	Wood-plastic composite
HWM	Shredded hardwood mulch
½ HWM	Half thickness (2.5 cm) shredded hardwood mulch
PBM	Pine bark mulch
PSM	Pine straw mulch
RM	Rubber (synthetic) mulch
AT	Artificial turf

Wind speed ranges are:

Low	5 m/s to 9 m/s (11 mi/h to 20 mi/h)
Medium	10 m/s to 13 m/s (22 mi/h to 29 mi/h)
High	14 m/s to 18 m/s (30 mi/h to 40 mi/h)

Table D.1. Mulch only.

Wind Speed Level	Separation Distance (m)	Series 1: Combustible Wall		Series 2: Mulch as Surrogate					
		No Fence	No Fence	No Fence	No Fence	No Fence	No Fence	No Fence	No Fence
		HWM	PBM	HWM	½ HWM	PBM	PSM	RM	AT
Low	0			B-72 [b]		B-83 [a], C-4 [a]			
	0.3								
	0.9			A-97 [b] C-9 [a]		C-31 [a]	A-96 [b]		
	1.8			A-104 [a]		B-42 [a]		C-33 [b]	D-22 [c]
Medium	0	A-2 [a], A-8 [a]		A-42 [a]	A-43 [a]				
	0.3	A-50 [b]	A-72 [b]			A-99 [a]	A-98 [b]		
	0.9	A-45 [b]	A-55 [b]	A-83 [a]		A-93 [a]	A-112 [b]		
	1.8	A-44 [b]		A-76 [a]		A-100 [a]	A-87 [b]	C-27 [a]	D-23 [c]
High	0	A-10 [a]		A-27 [a]		A-88 [a]			
	0.3	A-47 [b], A-60 [b]	A-51 [b]						
	0.9	A-46 [b]	A-52 [b]	A-80 [a]		A-85 [a]	A-84 [b]		
	1.8	A-14 [b]	A-62 [b]	A-78 [a]	A-38 [a]	A-86 [a]		C-34 [a]	

[a] Spread to shed (directly or via spotting)
[b] Spread to end of mulch bed, but not to shed
[c] Little spread

Table D.2. Fence only.

Wind Speed Level	Separation Distance (m)	Series 1: Combustible Wall	Series 2: Mulch as Surrogate			
		WRC Privacy Fence	WRC Privacy Fence	RW Lattice Fence	Vinyl Privacy Fence	WPC Fence
		No Mulch	No Mulch	No Mulch	No Mulch	No Mulch
Low	0					
	0.3					
	0.9					
	1.8					E-2 [a]
Medium	0	A-5 [c]	A-18 [c]	A-82 [c]		
	0.3		A-21 [c]	A-113 [c]		
	0.9		A-65 [c]	A-77 [c]		
	1.8		A-30 [c], A-101 [c]	A-75 [b]		
High	0	A-1 [c]	A-28 [b]	A-81 [c]	A-34 [c]	
	0.3		A-32 [c]	A-79 [c]		
	0.9		A-25 [b]			
	1.8		A-26 [b], A-91 [b]			

[a] Flames extend above fence
[b] Spread to shed (via spotting)
[c] Little spread

Table D.3. Fence plus mulch – Western redcedar (WRC) privacy fences.

Wind Speed Level	Separation Distance (m)	Series 1: Combustible Wall	Series 2: Mulch as Surrogate				
		WRC Privacy Fence	WRC Privacy Fence	WRC Privacy Fence	WRC Privacy Fence	WRC Privacy Fence	WRC Privacy Fence
		HWM	HWM	½ HWM	PBM	PSM	HWM
							45 ° Wind Angle
Low	0	A-69 [a]	A-106 [a]	B-70 [a]	B-71 [a]	A-111 [a]	
	0.3		A-105 [a]	B-63 [a]	B-73 [a]		
	0.9		A-95 [a]	B-58 [a]	B-60 [a]	A-94 [a]	
	1.8		A-102 [a], C-19 [a] (two panels long)	B-56 [a]	B-57 [a]	A-108 [a]	
Medium.	0	A-3 [a], A-4 [a], A-7 [a]	A-19 [a]	A-39 [a], A-48 [a]	A-57 [a]	A-114 [a]	
	0.3	A-6 [b]	A-20 [a], A-41 [a]	A-40 [a]	A-73 [a]		
	0.9	A-11 [b]	A-17 [a]	A-54 [a]	A-66 [a]	A-92 [a], A-89 [a]	
	1.8	A-12 [b]	A-29 [a]	A-64 [a]	A-74 [a], A-90 [a]	A-109 [a]	
High	0	A-9 [a]	A-22 [a]	A-49 [a]	A-58 [a]		A-115 [a]
	0.3	A-16 [b], A-61 [b]	A-23 [a], A-33 [a]	A-56 [a]	A-59 [a]		
	0.9	A-15 [b]	A-24 [a]	A-36 [a]	A-53 [a]		A-116 [a]
	1.8	A-13 [b]	A-31 [a]	A-37 [a]	A-63 [a]		

[a] Spread to shed (directly or via spotting)
[b] Spread to end of mulch bed, but not to shed

Table D.4. Fence raised above mulch bed

All experiments with fence raised above mulch bed were performed at a separation distance of 1.83 m (6 m) between the end of the mulch bed under the fences and the wall of the shed.

Wind Speed Level	Height of base of fence panel above surface of mulch (cm)	Series 2: Mulch as Surrogate WRC Privacy Fence HWM
Low	5.1	C-10 [a]
	7.6	C-11 [a]
	10.2	C-14 [a]
	15.4	C-28 [a]
Medium	5.1	C-12 [a]

[a] Spread to shed (directly or via spotting)

Table D.5. Fence plus mulch – Other fences.

Wind Speed Level	Separation Distance (m)	Series 1: Combustible Wall	Series 2: Mulch as Surrogate					
		RW Lattice Fence	RW Lattice Fence	Pine Lattice Fence	Vinyl Privacy Fence	Good Neighbor Fence	WPC Fence	Aged WRC Privacy Fence
		HWM	HWM	HWM	HWM	HWM	HWM	HWM
Low	0	A-70 [b]	B-66 [b]					
	0.3	A-71 [c]	B-74 [b]					
	0.9		B-59 [b]					
	1.8		A-107 [b]	C-21 [b]		C-18 [b]	E-1 [a], F-1 [a]	C-26 [b]
Medium	0		B-64 [b]		A-35 [b]			
	0.3		A-68 [b]					
	0.9		A-67 [b]					
	1.8		B-79 [b]	B-81 [b]		C-22 [b]		C-25 [b]
High	0		B-65 [b]					
	0.3		B-69 [b]					
	0.9		B-61 [b]					
	1.8		B-67 [b], B-85 [b]	B-86 [b]		C-23 [b]		C-24 [b]

[a] Flames extend above fence
[b] Spread to shed (via spotting)
[c] Spread to end of mulch bed, but not to shed

Table D.6. Parallel fences involving western redcedar (WRC) privacy fence.

All parallel fence experiments were performed at a separation distance of 1.83 m (6 m) between the end of the mulch bed under the fences and the wall of the shed.

Wind Speed Level	Fence Spacing (m)	Series 2: Mulch as Surrogate					
		2× WRC Privacy Fence	2× WRC Privacy Fence	2× WRC Privacy Fence – Two panels long	WRC Privacy Fence / Cement Board	WRC Privacy Fence / Vinyl Privacy Fence	WRC Privacy Fence / Pine Lattice Fence
		HWM	No Mulch	HWM	HWM	HWM	HWM
Low	0.152		B-84 [d]				
	0.203	B-82 [a]					
	0.305	C-5 [a], C-32 [a], D-9 [a]			D-7 [b]		D-8 [a]
	0.457	C-6 [a]			C-15 [b]	C-16 [c]	C-17 [b]
	0.610	C-7 [a]					
	0.914	C-8 [a]		C-13 [a]			

[a] Flames extend above fence
[b] Spread to shed (via spotting)
[c] Spread to end of mulch bed, but not to shed
[d] Little spread

Table D.7. Parallel lattice fences.

All parallel fence experiments were performed at a separation distance of 1.83 m (6 ft) between the end of the mulch bed under the fences and the wall of the shed.

Wind Speed Level	Fence Spacing (m)	Series 2: Mulch as Surrogate				
		2× RW Lattice Fence	2× RW Lattice Fence	2× RW Lattice Fence	2× Pine Lattice Fence	2× Pine Lattice Fence
		HWM	PBM	No Mulch	HWM	No Mulch
Low	0.089		A-103 [a]	A-110 [a]	C-29 [a]	C-20 [c]
Medium	0.089	B-75 [a]		B-80 [b]		
High	0.089	B-62 [a]		B-68 [b]		

[a] Flames extend above fence
[b] Spread to shed (via spotting)
[c] Little spread

Appendix E. Reading the Case Descriptions

This appendix explains how to read the data from the experimental cases listed in Appendix F though Appendix I. The data for each experiment includes a brief description, photographs from before and during the experiment, flame spread plots, summary data, and plots showing applied winds and ambient weather conditions. An example of the data provided for each experiment is shown in Fig. E.1, and explanations of data boxes A through F follow.

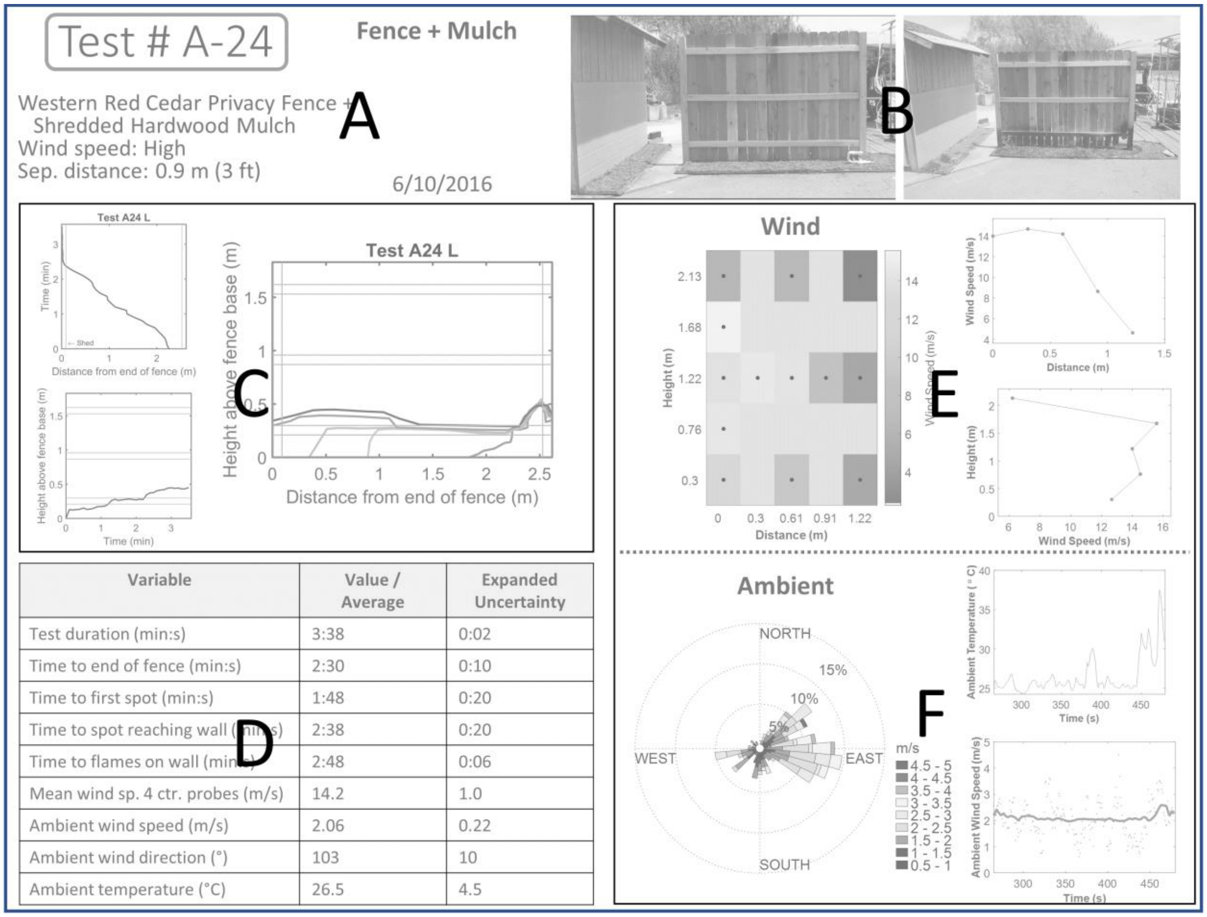


Fig. E.1. Experimental case description.

E.1. Data Box A: Experimental Configuration

The top left corner of each experimental case description, shown in Fig. E.2, provides the basic configuration for the experiment. This includes the test number, the category of the experiment (Fence Only, Mulch Only, Fence + Mulch, Parallel Fence with/without Mulch, or No Shed), and the date on which the experiment was performed. The material and type of fence and/or mulch, the applied wind speed level (Low, Medium, or High), and the separation distance of the end of the fence or mulch bed from the wall of the structure are also listed. Low applied wind speeds indicate a range of 5 m/s to 9 m/s as measured by the bidirectional probes near the centerline of the flow. Medium indicates a range of 10 m/s to 13 m/s, and High indicates 14 m/s to 18 m/s.

Test # A-24

Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

6/10/2016

Fig. E.2. Data Box A – Experimental configuration.

E.2. Data Box B: Photographs Taken Before and During the Experiment

In the top right corner of each case description are two photos, as shown in Fig. E.3. The photo on the left is the initial setup of the experiment as observed by the camera on the left side as viewed from the fan. In this photo, the shed appears to the left of the fence or mulch bed. For cases with single fences, the fence was typically mounted with the stringers facing this side.

The photo on the right was taken during the experiment and may show the testbed from any angle. This photo was selected to show an interesting feature of this experiment. In some cases, this photo shows the pattern of fire damage near the end of the experiment; in other cases, flames are shown from a period when the fence was burning strongly. For experiments in the No Shed category, the right-hand photo shows the target mulch bed (with any ignited spot fires) at a time near the end of the experiment.

Fig. E.3. Data Box B – Photographs taken before and during the experiment.

E.3. Data Box C: Flame Spread as a Function of Time

The center left box in the case description contains plots that illustrate the progress of the flame spread over the fence or mulch bed. The plots used data from the mulch and fence analysis procedures described in Section 3.1.3 and Section 3.1.4, respectively.

E.3.1. Fences

For experiments involving fences, presented in Appendix G through Appendix I, three flame spread plots are shown, as in Fig. E.4. Distance from the shed is always plotted along the horizontal axis and height is plotted along the vertical axis. For plots as a function of time, therefore, the axis representing time will vary.

The upper left plot shows the distance of the char front from the end of the fence nearest the shed as a function of time. Time is plotted on the vertical axis, and the locations of the end posts are marked with vertical lines as a visual aid. The char front begins at t = 0 s close to the outer end post at the lower right of the plot. With time, the front advances toward the end of the fence closest to the shed at the upper left.

The lower left plot shows the maximum height of the char front downwind of the ignition zone as a function of time. To look at the flame spread characteristics independent of the ignition zone, this plot tracks the maximum char height at least two board widths downwind from the ignition zone. In this plot, time is along the horizontal axis, and the locations of the stringers are marked with horizontal lines.

On the right is a plot showing the contours of the burned area of the fence over time. Contours have been obtained at five points in time spaced evenly between the initial and final times. The order of the sequence is displayed using color, with blue indicating the earliest contour and red the contour at the end of the experiment.

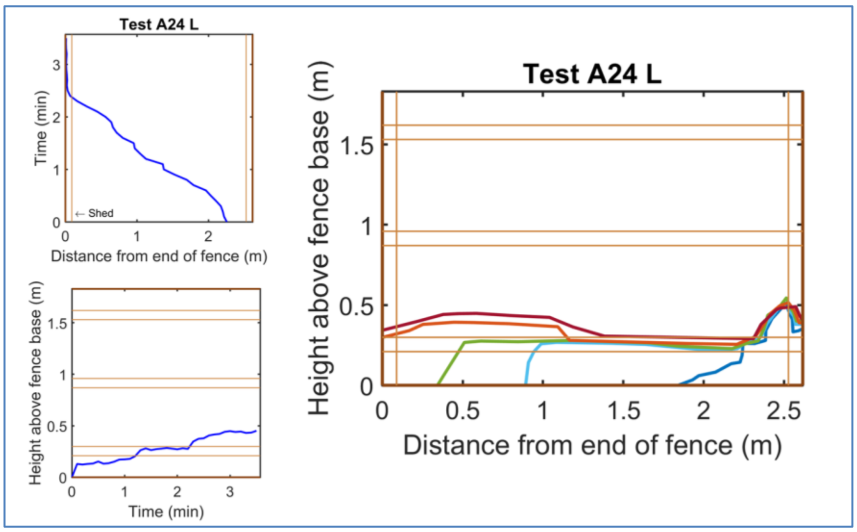


Fig. E.4. Data Box C – Flame spread as a function of time for fence experiments.

E.3.2. Mulch Only

For experiments with mulch only, presented in Appendix F, data box C contains a single plot showing flame spread, as shown in Fig. E.5. In this plot, the distance of the char front from the wall of the structure is plotted as a function of time, with time along the vertical axis. The regions occupied by the ignited mulch bed and the target mulch bed next to the shed are shaded. The gap between the ignited mulch bed and the target mulch bed (in Series 2 experiments) or the wall (in Series 1 experiments) is shown in white. The example to the right shows the gap between mulch beds for a separation distance of 0.91 m (3 ft) between the end of the ignited mulch bed and the shed wall.

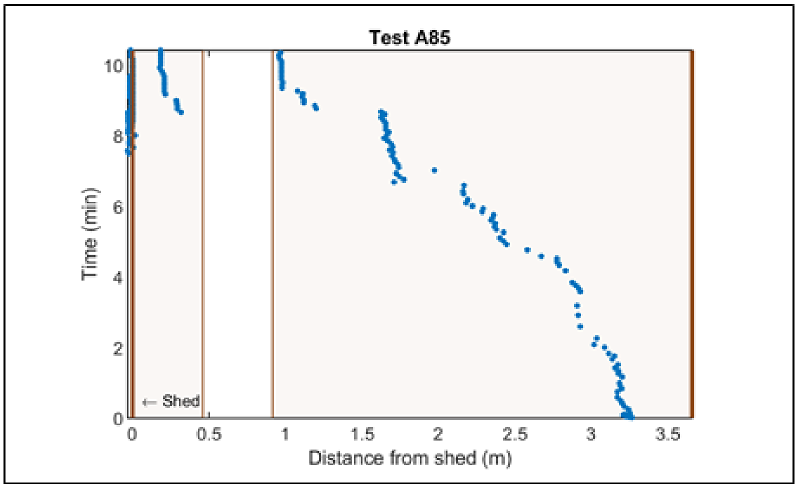


Fig. E.5. Data Box C – Flame spread as a function of time for mulch experiments.

E.4. Data Box D: Table of Timing Values and Environmental Factors

At the lower left of the case description is a table containing average values and standard deviation for timing and environmental variables, as shown in Fig. E.6.

The test duration was obtained from subtraction of the time at which the fan was turned on from the time at which the fan was turned off, as determined from videos recorded from cameras mounted to the right and left of the test object. Other times listed in this table include the time for the flame front to reach the end of the fence or mulch bed, the time for the first firebrand ignition to occur in the target mulch bed, the time for ignition of the spot fire that puts flames on the wall of the shed, and the time for those flames to reach the wall. Expanded uncertainties (at the 95 % confidence level) for these values are estimated from the Type B uncertainties of determining the time from the videos, as explained in Appendix A.

Environmental variables include the average values and expanded uncertainties of applied wind speed, ambient wind speed and direction, and ambient temperature. The value used to characterize the applied wind speed is an average of the mean values for the lower four bidirectional probes along the centerline of the probe array, as discussed in Appendix C. These probes measure the wind field that strikes the edge of the fence facing the fan. Ambient data are collected from probes mounted on a 3.7 m (12 ft) pole about 7.9 m (26 ft) south-southeast of the wind machine propellers and 17.7 m (58 ft) south-southwest of the target shed, as described in Section 2.7.2.

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:38	0:02
Time to end of fence (min:s)	2:30	0:10
Time to first spot (min:s)	1:48	0:20
Time to spot reaching wall (min:s)	2:38	0:20
Time to flames on wall (min:s)	2:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	2.06	0.22
Ambient wind direction (°)	103	10
Ambient temperature (°C)	26.5	4.5

Fig. E.6. Data Box D – Table of timing values and environmental factors.

E.5. Data Box E: Applied Wind

Wind speeds measured by the 13 bidirectional probes and averaged over the duration of the experiment (the time during which the fan is on) are displayed in the three plots in data box E, as shown in Fig. E.7.

The pseudocolor plot on the left displays the mean wind speed value for each probe as a colored cell in a rectangular array. The array represents the probe locations in Fig. 17 or Fig. C.3. The scale along the right of the plot relates color to wind speed. If any of the probes are not operational during the experiment, they appear as white.

The plot at the top right of data box E shows the mean wind speeds for probes #9, #8, #7, #6, and #5, which extend horizontally out from the centerline at a height of 1.22 m (4 ft) above the ground. The probe distance is plotted along the horizontal axis, and the wind speed is along the vertical axis. The plot typically indicates a minimum at the centerline, which is a flow field artifact from the hub region of the wind machine propellers, as described in Section 2.2.3. The wind speed decreases rapidly away from the central flow field.

The plot at the bottom right shows the mean wind speeds for probes #3, #4, #9, #10, and #13, which are arrayed along the centerline of the wind field. For this plot, the height of each probe is plotted along the vertical axis, and the wind speed is along the horizontal axis. The wind speeds are typically highest in the central region and lower at the position of the top probe. The tilt of the wind straightener, described in Section 2.2.2, helped to extend higher wind speeds toward the ground.

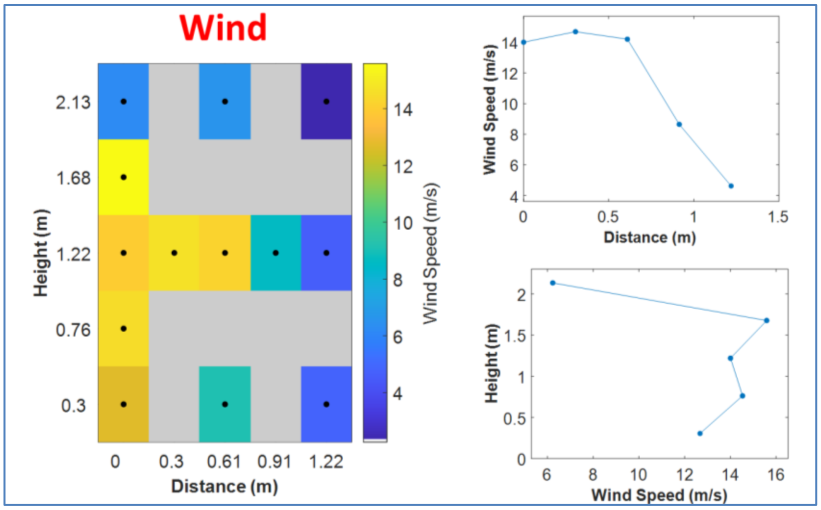


Fig. E.7. Data Box E – Applied wind.

E.6. Data Box F: Ambient Wind

Data box F, located at the lower right of the case description, displays a wind rose and time plots of temperature and wind speed based on data taken over the duration of the experiment, as shown in Fig. E.8. The instruments used to measure ambient temperature and winds have been described in Section 2.7.2.

In the wind rose plot on the left, the wind speed and direction of the ambient winds are binned. The length of each spoke indicates the percentage of time that the wind blew from that direction during the experiment. The concentric rings are labeled to show the frequency. The colored bins within each spoke indicate wind speed ranges, which are listed in the scale to the right of this diagram.

On the upper right of data box F is a plot of ambient temperature as function of time. The time begins when the fan is turned on and ends when it is turned off, which defines the timing for the experiment.

On the lower right is a plot of ambient wind speed as a function of time. The red line applies a moving average filter with a 300 s span to the data, indicating the value and trend of the ambient wind speed over the experiment.

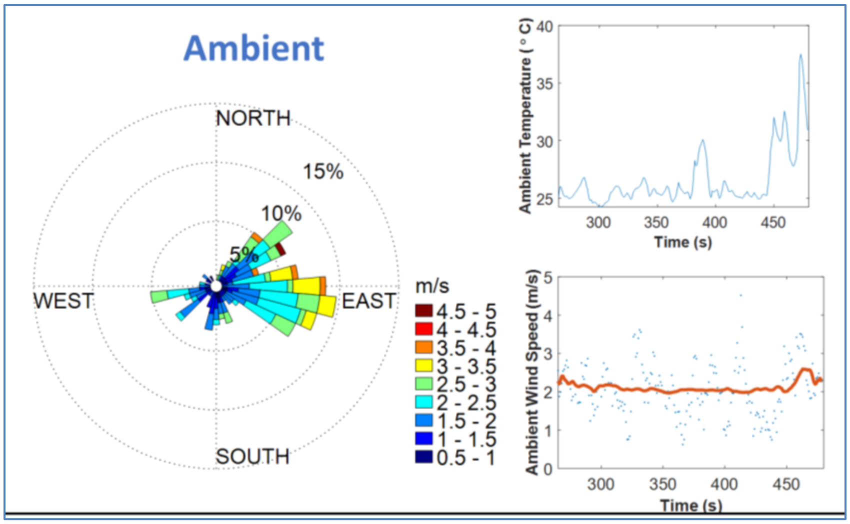


Fig. E.8. Data Box F – Ambient wind.

Appendix F. Case Details: Mulch Only

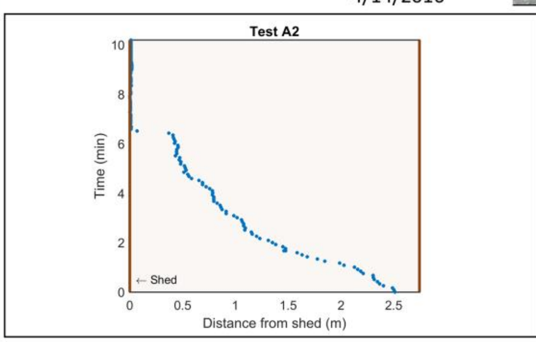
This appendix provides the data from all experimental cases on mulch without a fence present. The data includes a description of the experiment, photographs from before and during, flame spread plots, critical times, and ambient and applied winds. The data for each experiment can be read as described in Appendix E.

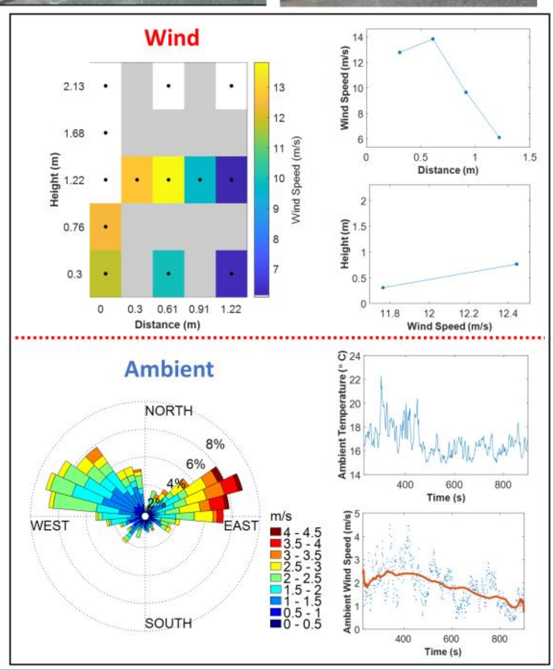
Test # A-2

Mulch only

Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

4/14/2016





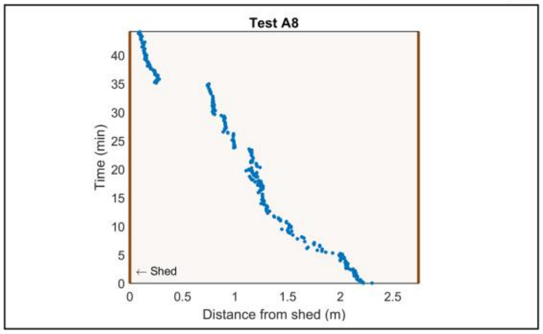
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:42	0:02
Time to end of mulch (min:s)	6:28	0:10
Time to first spot (min:s)	5:20	0:20
Time to spot reaching wall (min:s)	5:20	0:20
Time to flames on wall (min:s)	6:08	0:06
Mean wind sp. 4 ctr. probes (m/s)	12.1	1.2
Ambient wind speed (m/s)	1.88	0.21
Ambient wind direction (°)	345	10
Ambient temperature (°C)	16.7	4.4

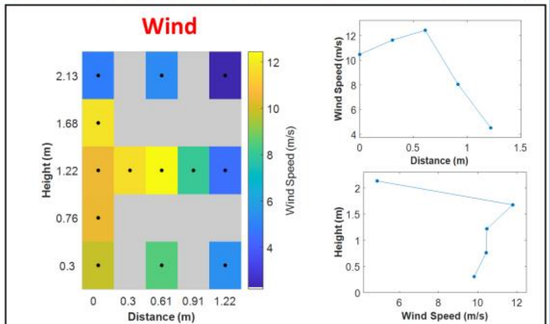
Test # A-8

Mulch only

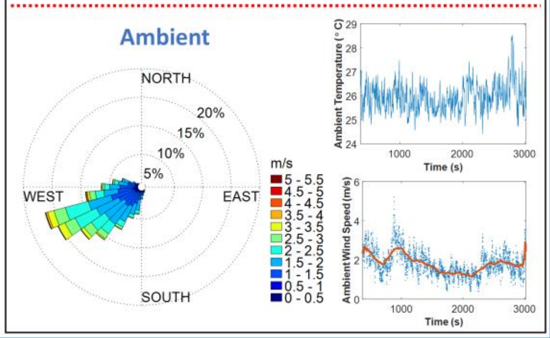
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

4/25/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	44:15	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	41:49	0:20
Time to spot reaching wall (min:s)	41:49	0:20
Time to flames on wall (min:s)	42:01	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.6	0.7
Ambient wind speed (m/s)	1.80	0.20
Ambient wind direction (°)	238	10
Ambient temperature (°C)	25.9	4.5

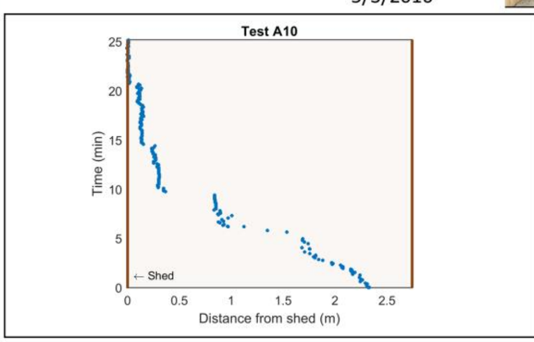


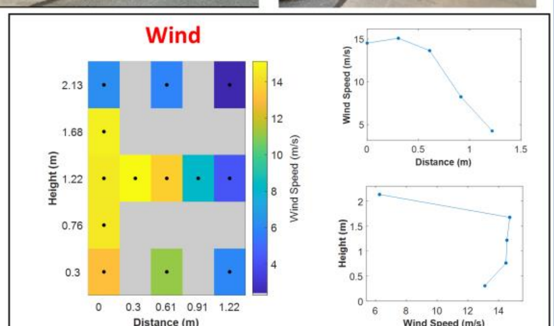
Test # A-10

Mulch only

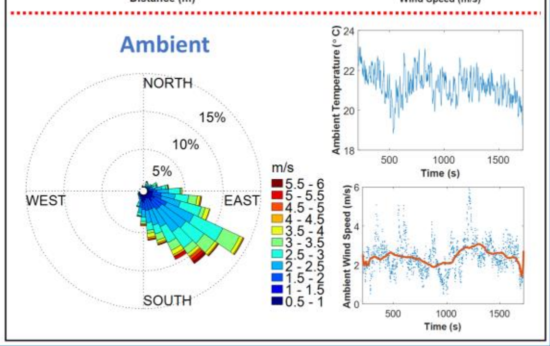
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

5/3/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	25:14	0:02
Time to end of mulch (min:s)	21:43	0:10
Time to first spot (min:s)	24:04	0:20
Time to spot reaching wall (min:s)	24:04	0:20
Time to flames on wall (min:s)	19:30	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	2.44	0.20
Ambient wind direction (°)	131	10
Ambient temperature (°C)	21.2	4.4

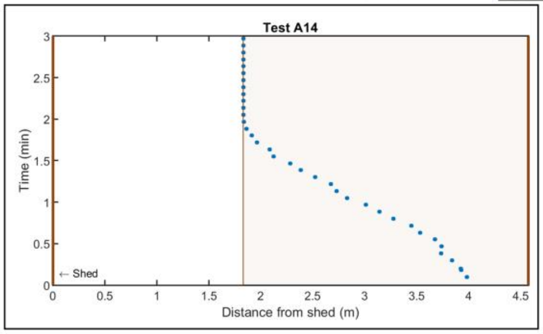


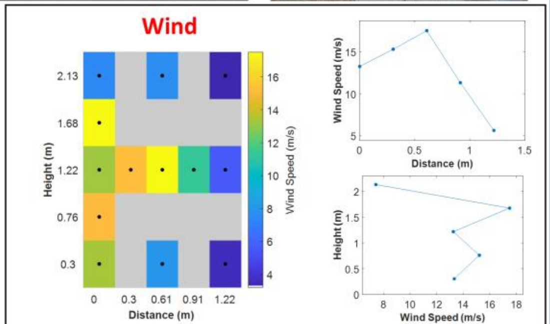
Test # A-14

Mulch only

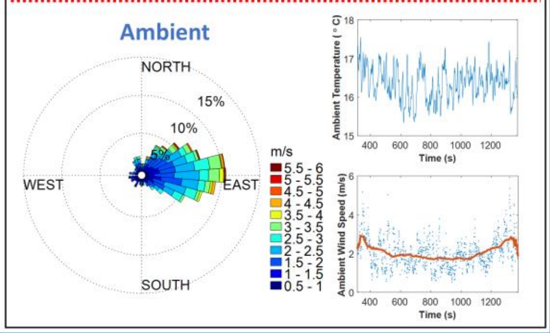
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

5/18/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	17:45	0:02
Time to end of mulch (min:s)	2:00	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.8	1.0
Ambient wind speed (m/s)	2.03	0.21
Ambient wind direction (°)	79	10
Ambient temperature (°C)	16.4	4.4

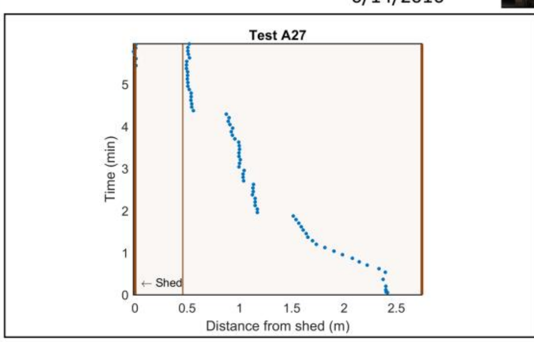


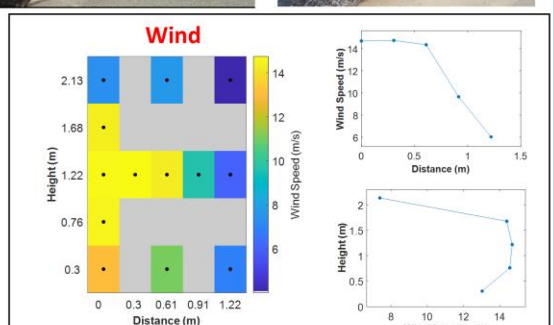
Test # A-27

Mulch only

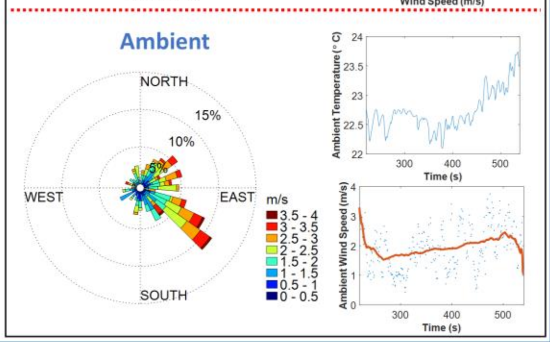
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

6/14/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:48	0:02
Time to end of mulch (min:s)	4:20	0:10
Time to first spot (min:s)	4:13	0:20
Time to spot reaching wall (min:s)	4:43	0:20
Time to flames on wall (min:s)	5:05	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	1.91	0.22
Ambient wind direction (°)	103	10
Ambient temperature (°C)	22.7	4.4

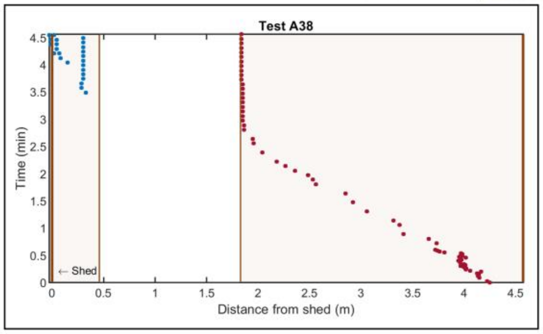


Test # A-38

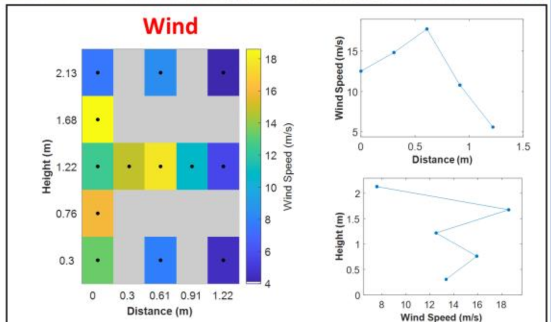
Mulch only

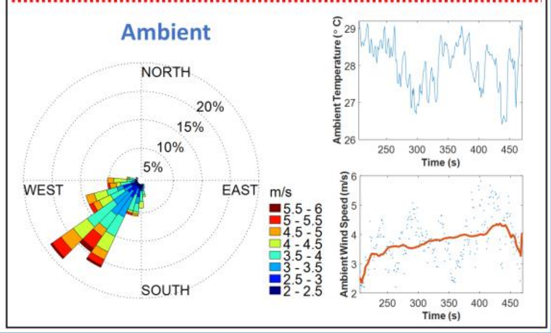
½ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

6/27/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:35	0:02
Time to end of mulch (min:s)	2:43	0:10
Time to first spot (min:s)	2:37	0:20
Time to spot reaching wall (min:s)	3:47	0:20
Time to flames on wall (min:s)	4:04	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.1	1.1
Ambient wind speed (m/s)	3.80	0.22
Ambient wind direction (°)	225	10
Ambient temperature (°C)	28.0	4.5



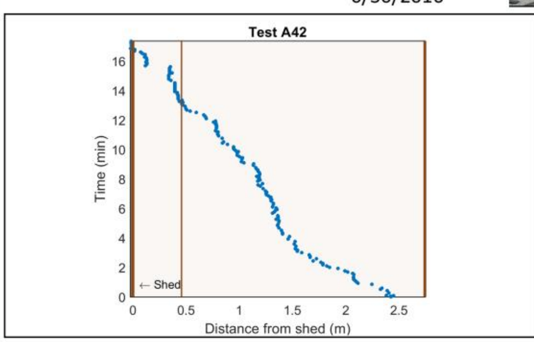


Test # A-42

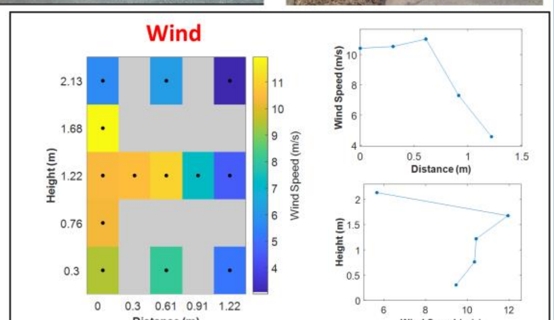
Mulch only

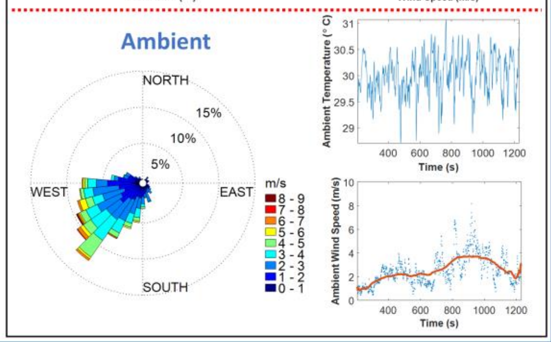
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

6/30/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	17:16	0:02
Time to end of mulch (min:s)	12:40	0:10
Time to first spot (min:s)	12:59	0:20
Time to spot reaching wall (min:s)	14:03	0:20
Time to flames on wall (min:s)	16:38	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.5	0.7
Ambient wind speed (m/s)	2.55	0.22
Ambient wind direction (°)	231	10
Ambient temperature (°C)	30.0	4.5



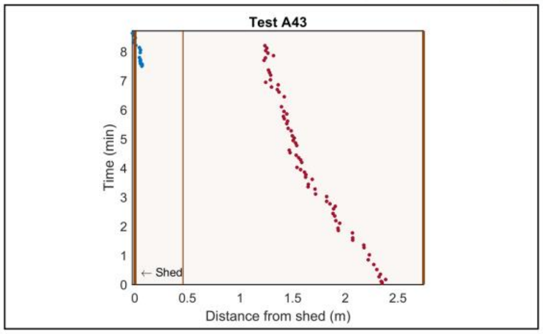


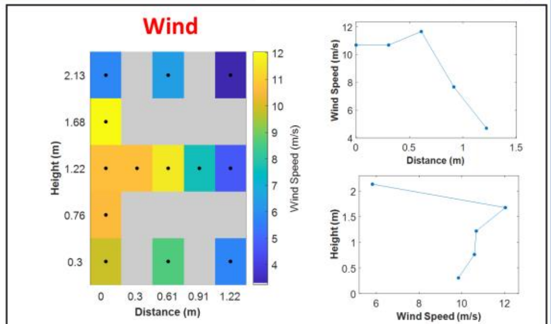
Test # A-43

Mulch only

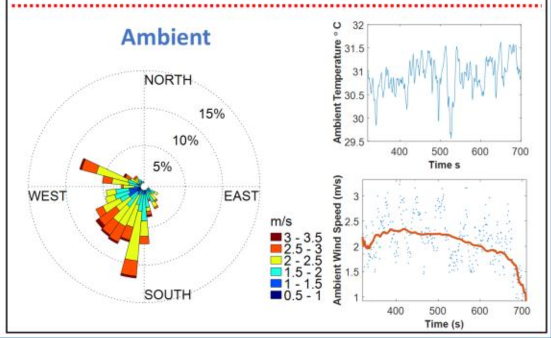
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

6/30/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:34	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	6:32	0:20
Time to spot reaching wall (min:s)	6:32	0:20
Time to flames on wall (min:s)	7:54	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.8	0.8
Ambient wind speed (m/s)	2.13	0.21
Ambient wind direction (°)	223	10
Ambient temperature (°C)	30.9	4.6

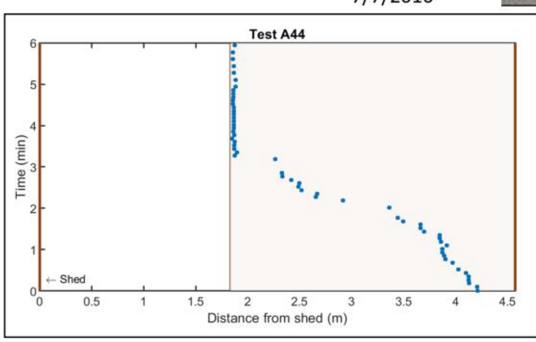


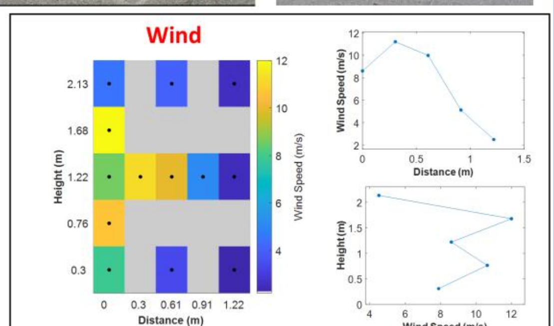
Test # A-44

Mulch only

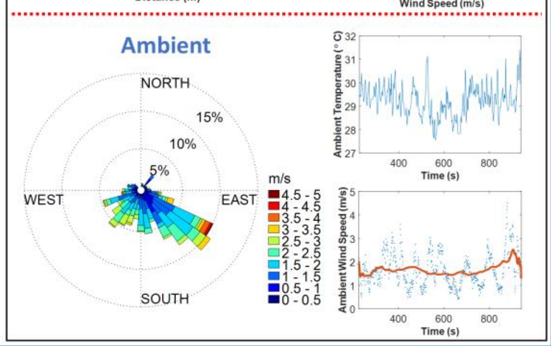
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

7/7/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	12:28	0:02
Time to end of mulch (min:s)	3:14	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	9.8	0.7
Ambient wind speed (m/s)	1.65	0.21
Ambient wind direction (°)	169	10
Ambient temperature (°C)	29.2	4.5

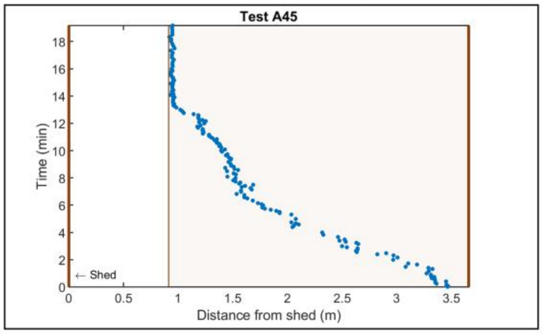


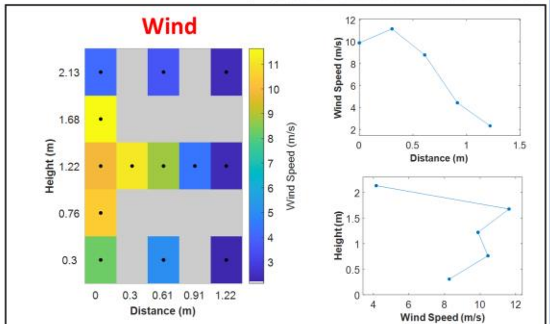
Test # A-45

Mulch only

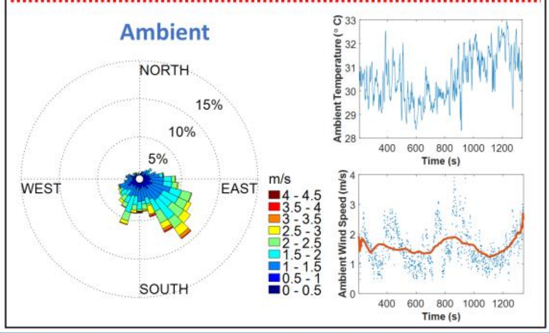
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

7/7/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	19:06	0:02
Time to end of mulch (min:s)	13:20	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.55	0.20
Ambient wind direction (°)	151	10
Ambient temperature (°C)	30.5	4.6

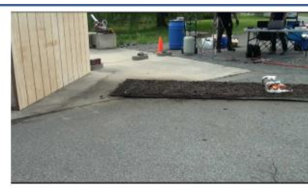


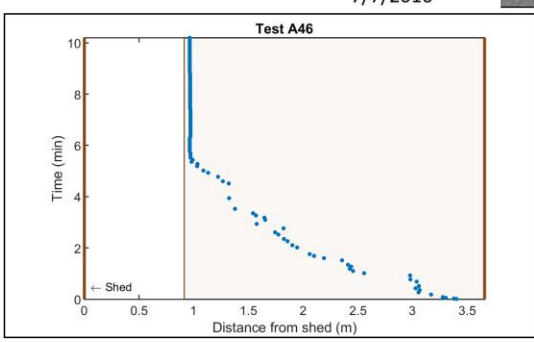
Test # A-46

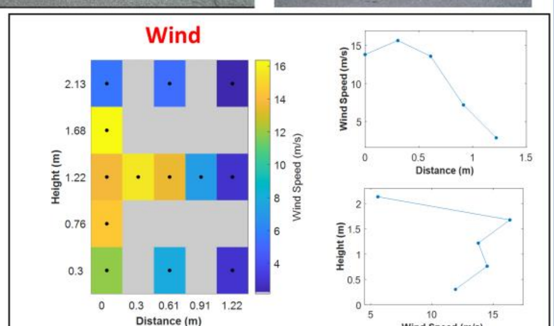
Mulch only

Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

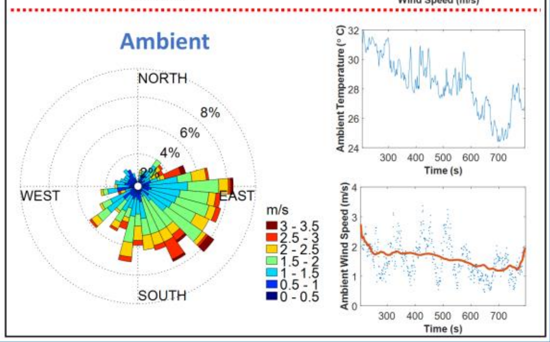
7/7/2016







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:06	0:02
Time to end of mulch (min:s)	5:30	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	1.57	0.21
Ambient wind direction (°)	142	10
Ambient temperature (°C)	28.3	4.5

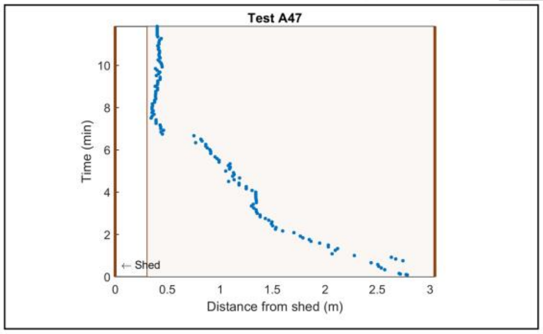


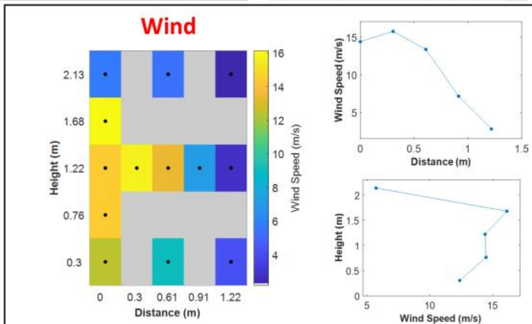
Test # A-47

Mulch only

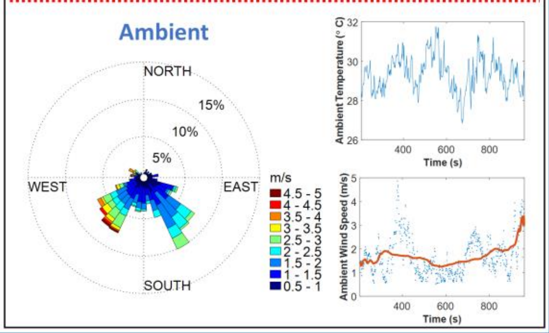
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

7/7/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	12:52	0:02
Time to end of mulch (min:s)	7:15	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.3	1.0
Ambient wind speed (m/s)	1.67	0.21
Ambient wind direction (°)	180	10
Ambient temperature (°C)	29.3	4.5

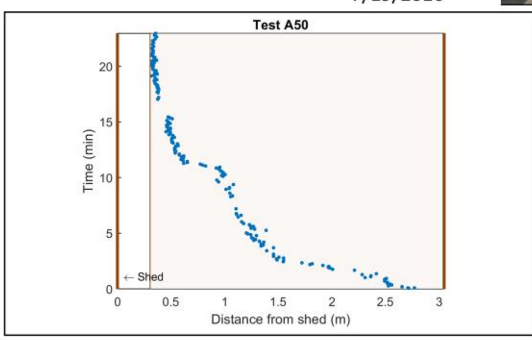


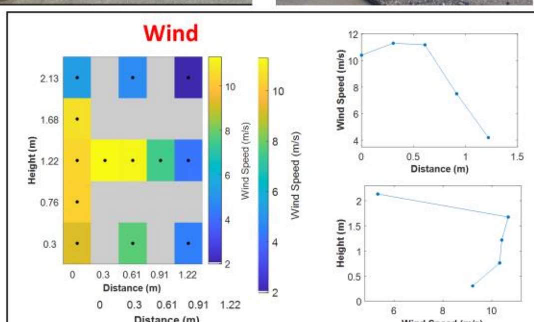
Test # A-50

Mulch only

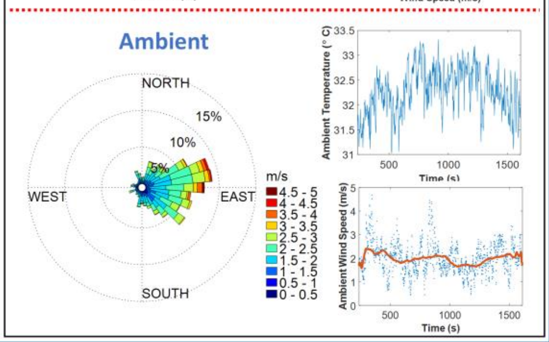
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

7/19/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	23:03	0:02
Time to end of mulch (min:s)	17:10	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.2	0.7
Ambient wind speed (m/s)	1.99	0.20
Ambient wind direction (°)	93	10
Ambient temperature (°C)	32.3	4.6

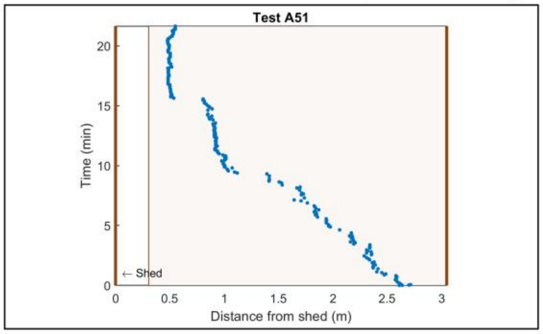


Test # A-51

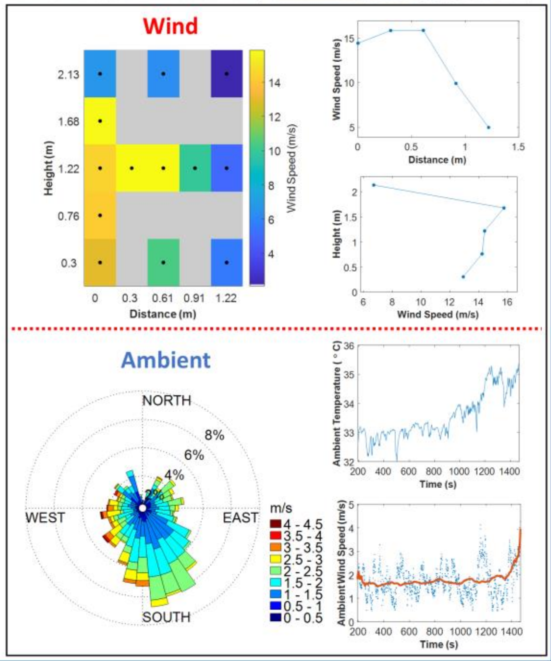
Mulch only

Pine Bark Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

7/19/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	21:20	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.3	1.0
Ambient wind speed (m/s)	1.73	0.20
Ambient wind direction (°)	170	10
Ambient temperature (°C)	33.5	4.6

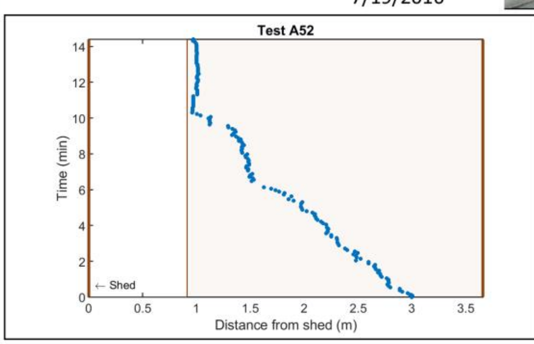


Test # A-52

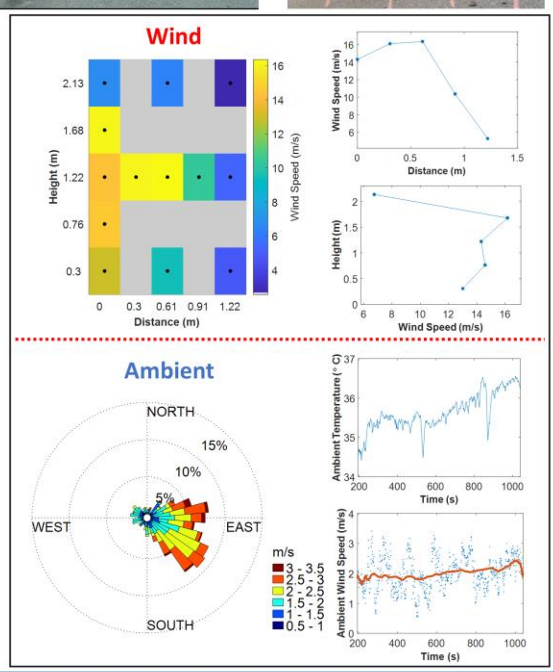
Mulch only

Pine Bark Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

7/19/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:14	0:02
Time to end of mulch (min:s)	10:05	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.5	1.0
Ambient wind speed (m/s)	2.00	0.20
Ambient wind direction (°)	111	10
Ambient temperature (°C)	35.6	4.6

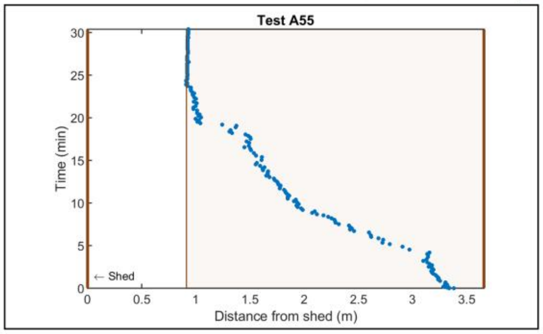


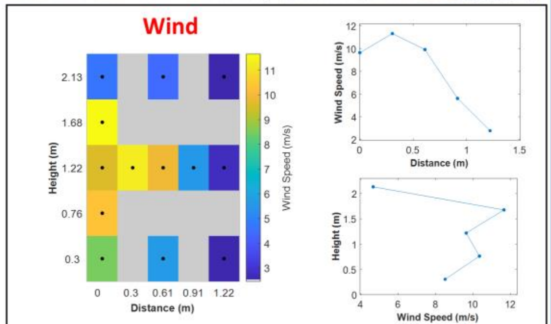
Test # A-55

Mulch only

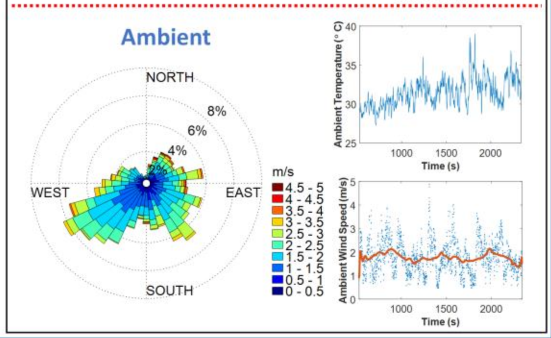
Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

7/20/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	30:23	0:02
Time to end of mulch (min:s)	19:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	1.78	0.20
Ambient wind direction (°)	184	10
Ambient temperature (°C)	31.4	4.6

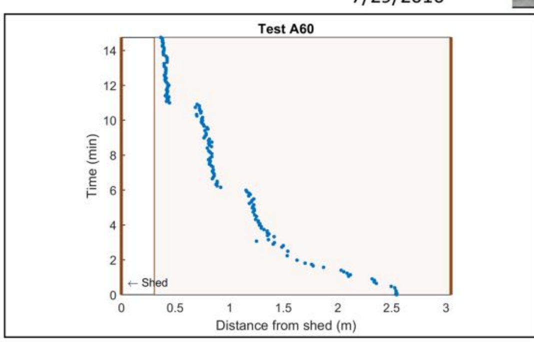


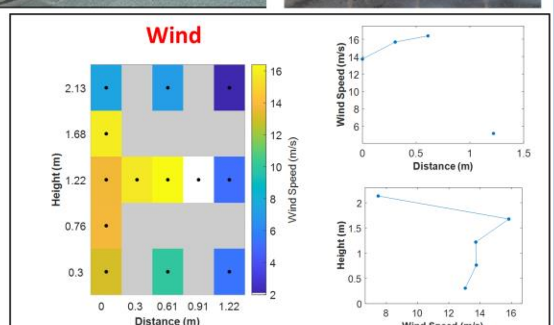
Test # A-60

Mulch only

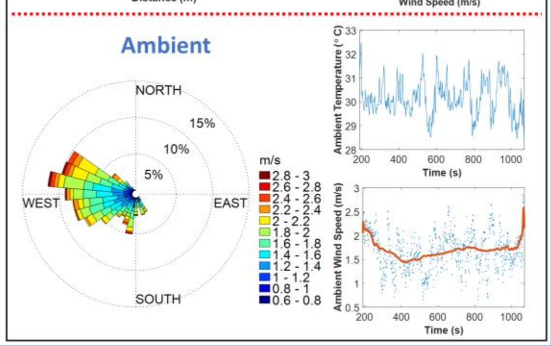
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

7/29/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:42	0:02
Time to end of mulch (min:s)	11:00	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	1.67	0.20
Ambient wind direction (°)	255	10
Ambient temperature (°C)	30.1	4.5

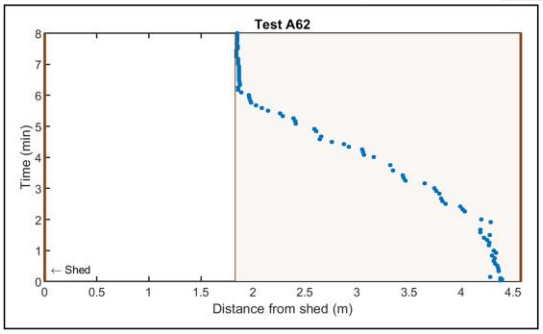


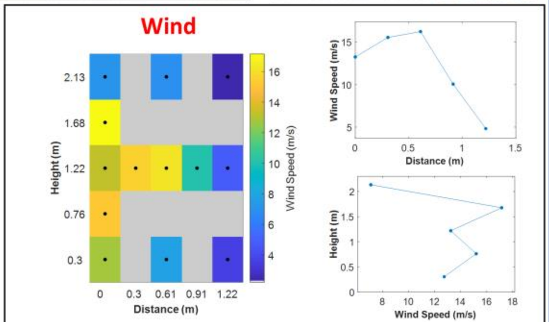
Test # A-62

Mulch only

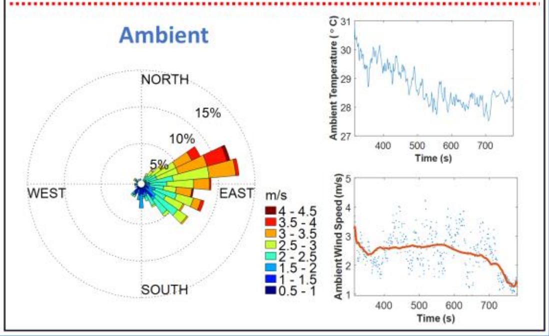
Pine Bark Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

8/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:55	0:02
Time to end of mulch (min:s)	6:05	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.6	1.0
Ambient wind speed (m/s)	2.47	0.21
Ambient wind direction (°)	101	10
Ambient temperature (°C)	28.7	4.5

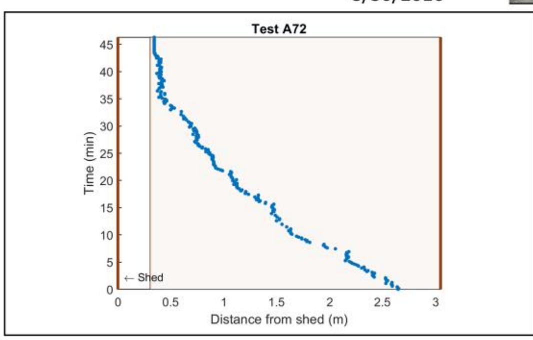


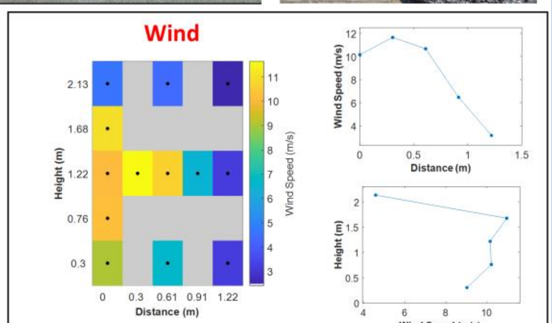
Test # A-72

Mulch only

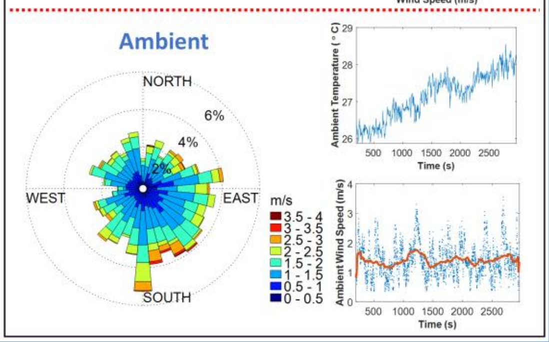
Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

8/30/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	46:04	0:02
Time to end of mulch (min:s)	43:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.40	0.20
Ambient wind direction (°)	141	10
Ambient temperature (°C)	27.2	4.5

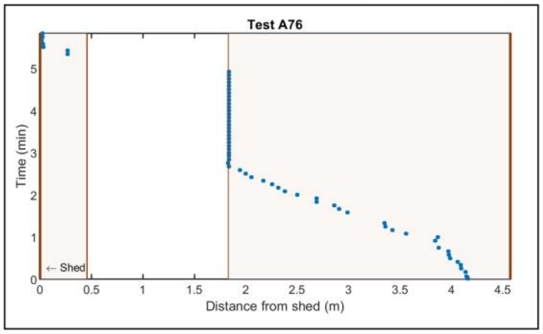


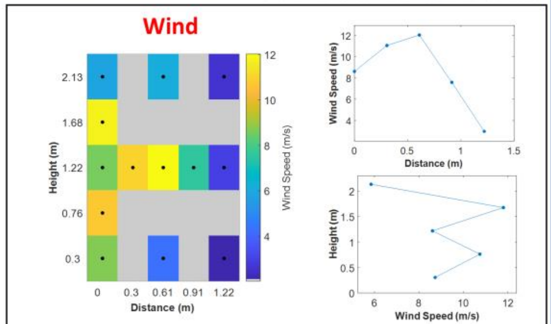
Test # A-76

Mulch only

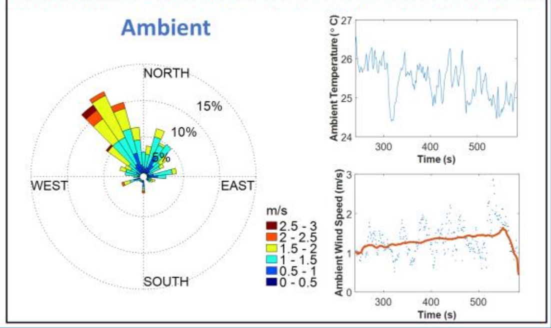
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

9/12/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:51	0:02
Time to end of mulch (min:s)	2:47	0:10
Time to first spot (min:s)	4:34	0:20
Time to spot reaching wall (min:s)	4:34	0:20
Time to flames on wall (min:s)	5:15	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	1.32	0.20
Ambient wind direction (°)	350	10
Ambient temperature (°C)	25.4	4.5

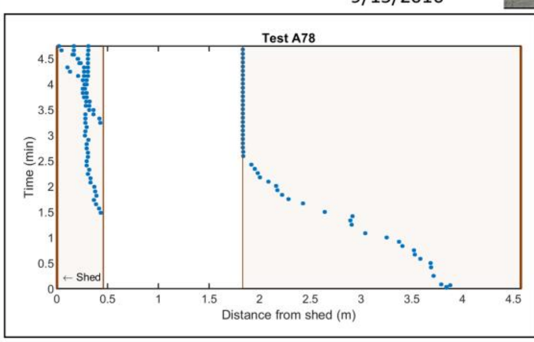


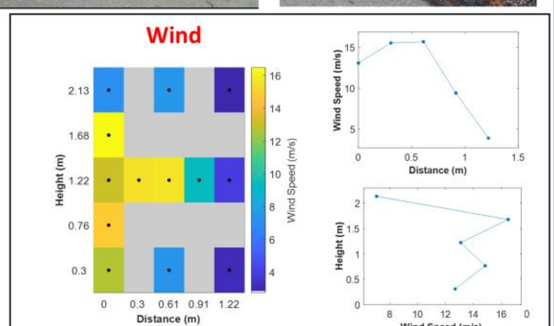
Test # A-78

Mulch only

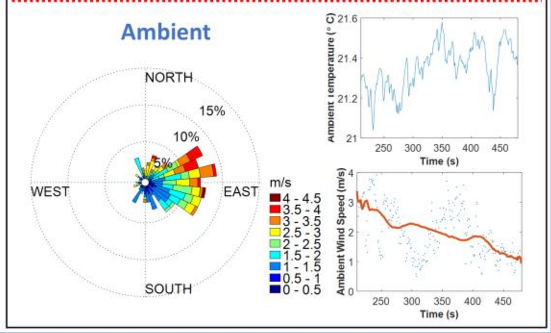
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

9/15/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:40	0:02
Time to end of mulch (min:s)	2:30	0:10
Time to first spot (min:s)	1:17	0:20
Time to spot reaching wall (min:s)	1:17	0:20
Time to flames on wall (min:s)	3:57	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.3	1.0
Ambient wind speed (m/s)	1.99	0.23
Ambient wind direction (°)	93	10
Ambient temperature (°C)	21.4	4.4

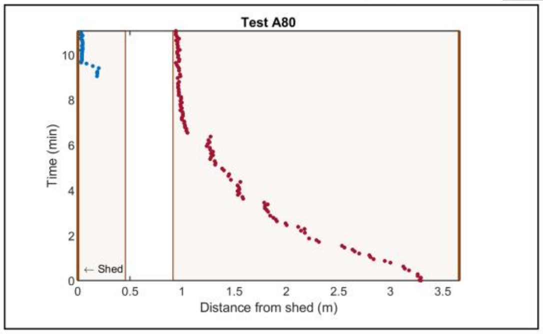


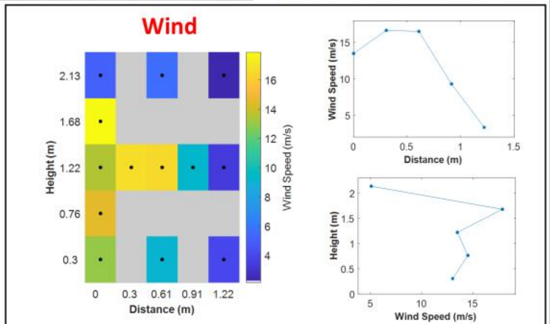
Test # A-80

Mulch only

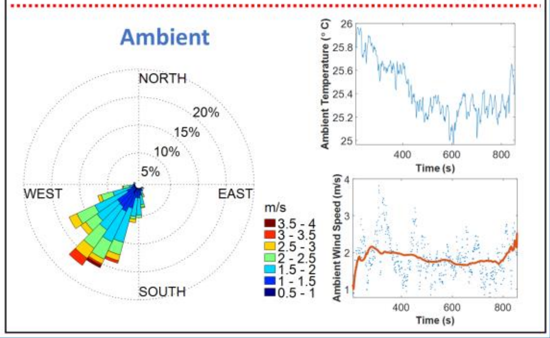
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

9/15/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:53	0:02
Time to end of mulch (min:s)	7:00	0:20
Time to first spot (min:s)	8:41	0:20
Time to spot reaching wall (min:s)	8:41	0:20
Time to flames on wall (min:s)	9:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.7	1.0
Ambient wind speed (m/s)	1.84	0.20
Ambient wind direction (°)	215	10
Ambient temperature (°C)	25.4	4.5

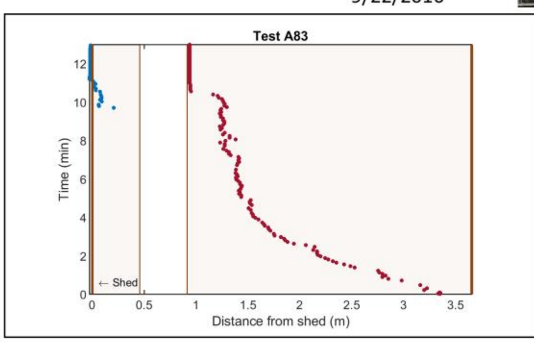


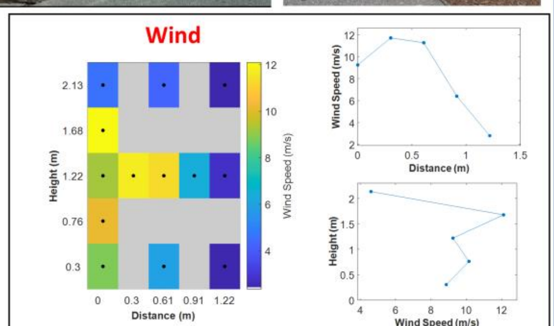
Test # A-83

Mulch only

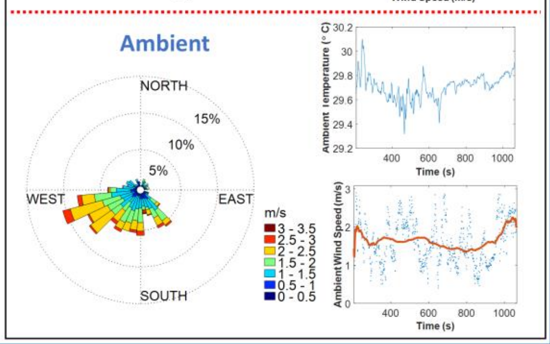
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

9/22/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:25	0:02
Time to end of mulch (min:s)	10:30	0:10
Time to first spot (min:s)	8:15	0:20
Time to spot reaching wall (min:s)	8:15	0:20
Time to flames on wall (min:s)	10:29	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.61	0.20
Ambient wind direction (°)	217	10
Ambient temperature (°C)	29.7	4.5

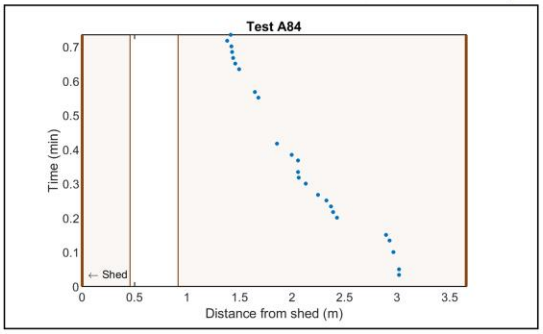


Test # A-84

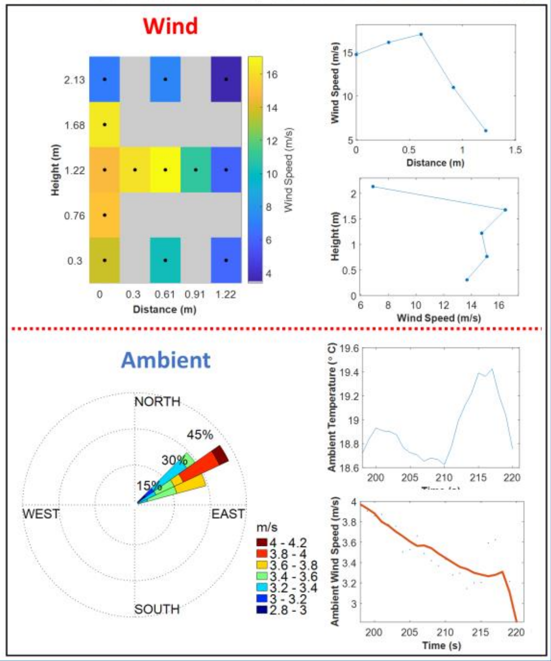
Mulch only

Pine Straw Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

9/28/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	0:35	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	15.0	1.1
Ambient wind speed (m/s)	3.51	0.24
Ambient wind direction (°)	60	10
Ambient temperature (°C)	18.9	4.4

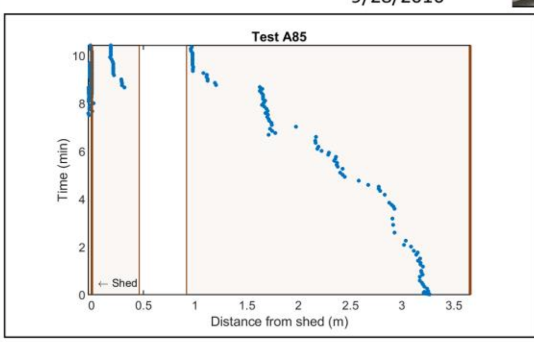


Test # A-85

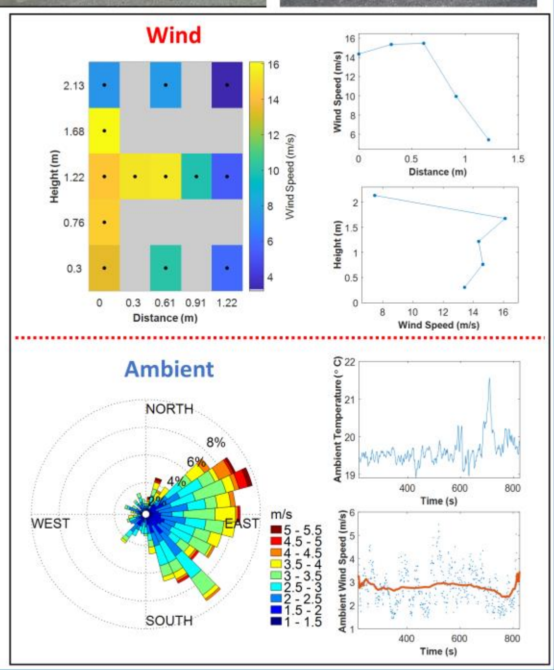
Mulch only

Pine Bark Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

9/28/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:23	0:02
Time to end of mulch (min:s)	9:20	0:10
Time to first spot (min:s)	6:41	0:20
Time to spot reaching wall (min:s)	6:56	0:20
Time to flames on wall (min:s)	7:11	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.6	1.0
Ambient wind speed (m/s)	2.76	0.21
Ambient wind direction (°)	103	10
Ambient temperature (°C)	19.6	4.4

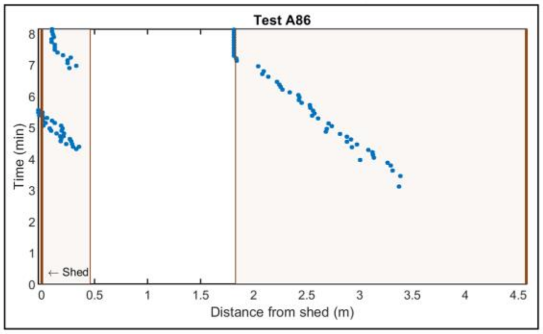


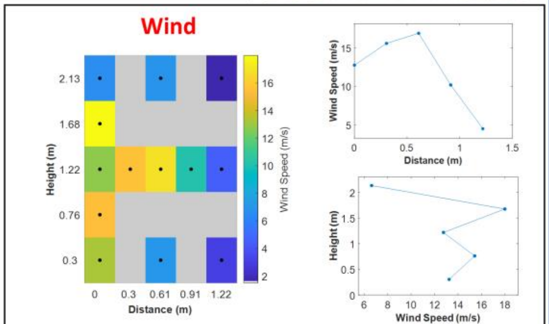
Test # A-86

Mulch only

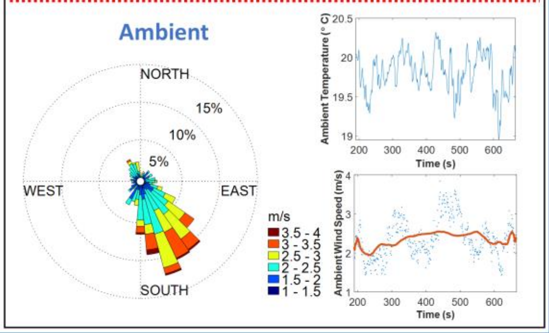
Pine Bark Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

9/28/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:08	0:02
Time to end of mulch (min:s)	7:15	0:02
Time to first spot (min:s)	3:07	0:20
Time to spot reaching wall (min:s)	3:36	0:20
Time to flames on wall (min:s)	4:11	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.9	1.1
Ambient wind speed (m/s)	2.37	0.20
Ambient wind direction (°)	152	10
Ambient temperature (°C)	19.8	4.4

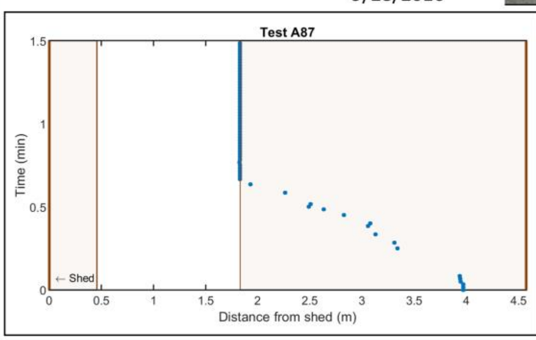


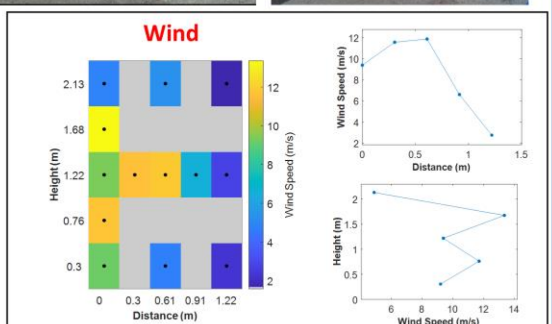
Test # A-87

Mulch only

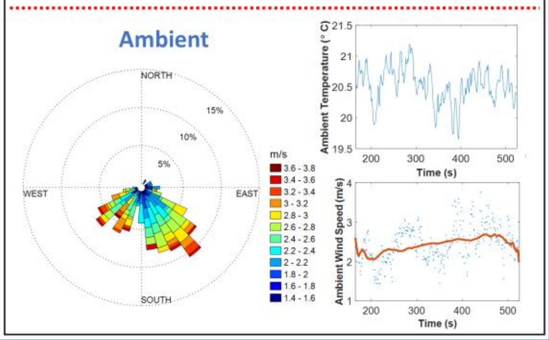
Pine Straw Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

9/28/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:09	0:02
Time to end of mulch (min:s)	0:38	0:04
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	2.44	0.21
Ambient wind direction (°)	170	10
Ambient temperature (°C)	20.5	4.4

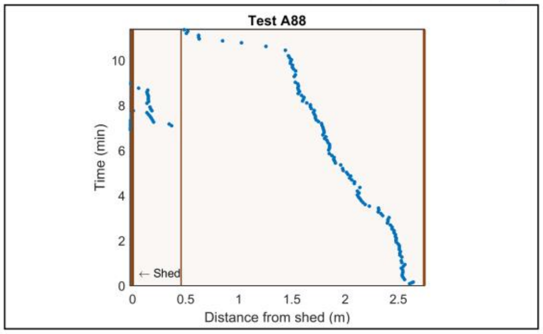


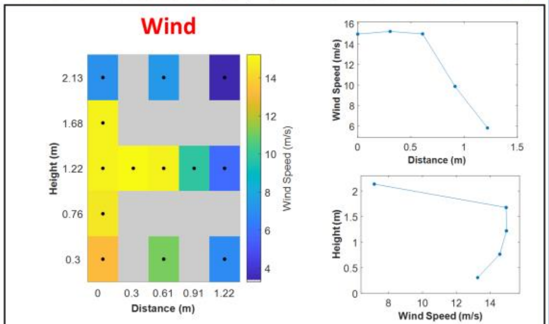
Test # A-88

Mulch only

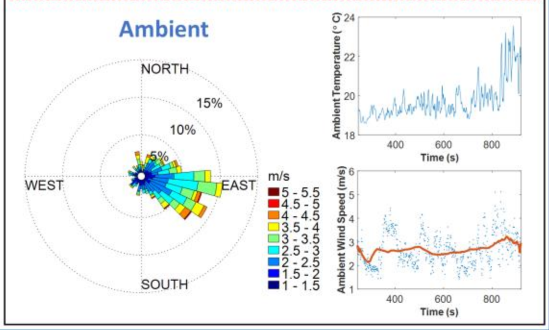
Pine Bark Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

10/4/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:22	0:02
Time to end of mulch (min:s)	11:15	0:10
Time to first spot (min:s)	5:36	0:20
Time to spot reaching wall (min:s)	5:36	0:20
Time to flames on wall (min:s)	7:20	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.4	1.0
Ambient wind speed (m/s)	2.67	0.21
Ambient wind direction (°)	101	10
Ambient temperature (°C)	19.7	4.4

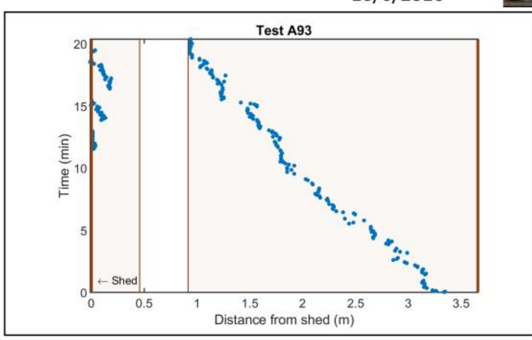


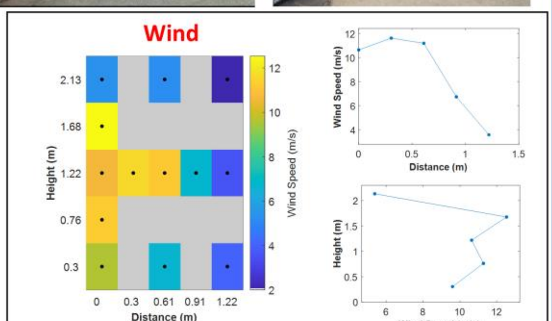
Test # A-93

Mulch only

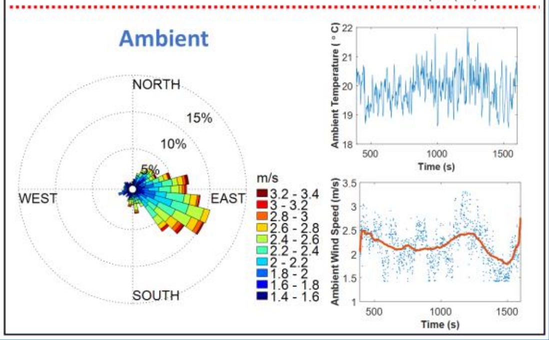
Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

10/6/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	20:20	0:02
Time to end of mulch (min:s)	18:50	0:10
Time to first spot (min:s)	11:25	0:20
Time to spot reaching wall (min:s)	11:25	0:20
Time to flames on wall (min:s)	12:10	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.0	0.8
Ambient wind speed (m/s)	2.16	0.20
Ambient wind direction (°)	106	10
Ambient temperature (°C)	19.9	4.4

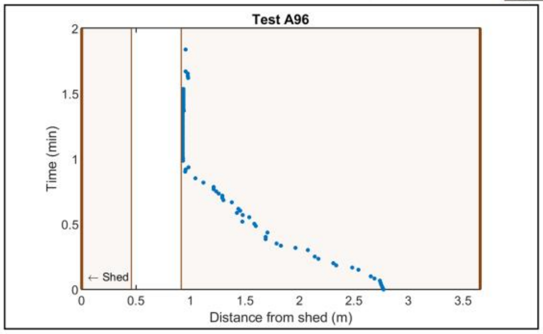


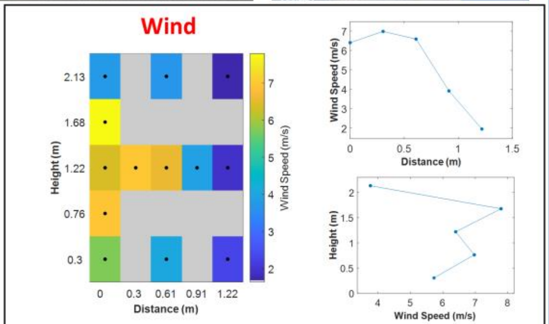
Test # A-96

Mulch only

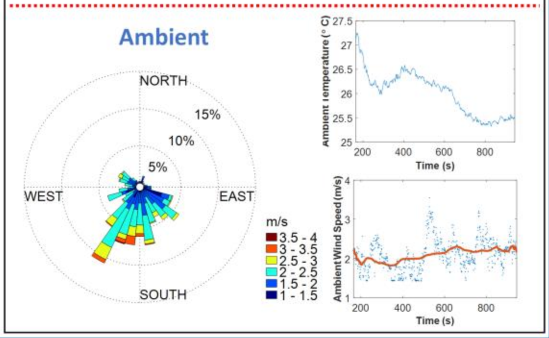
Pine Straw Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

10/20/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	18:38	0:02
Time to end of mulch (min:s)	0:58	0:04
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.7	0.5
Ambient wind speed (m/s)	2.08	0.20
Ambient wind direction (°)	188	10
Ambient temperature (°C)	26.0	4.5

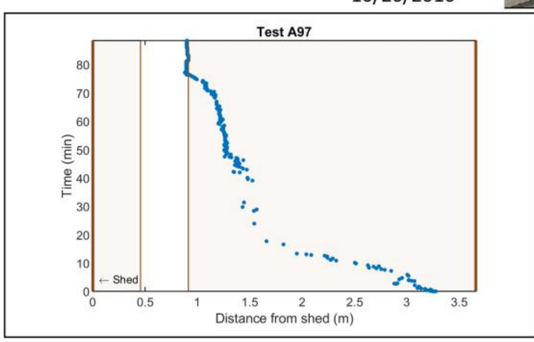


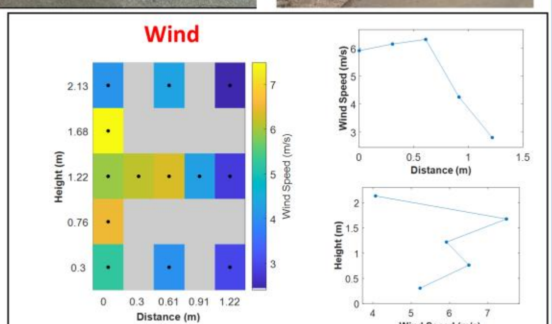
Test # A-97

Mulch only

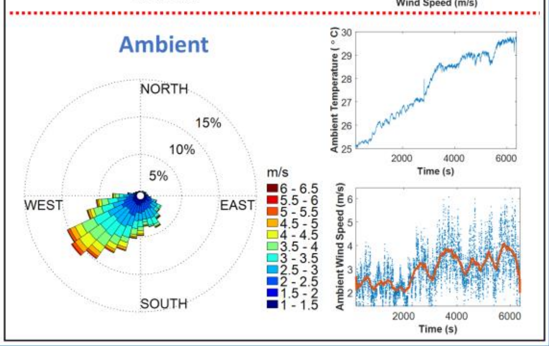
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

10/20/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (h:min:s)	1:42:48	0:02
Time to end of mulch (min:s)	76:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.4
Ambient wind speed (m/s)	2.98	0.20
Ambient wind direction (°)	209	10
Ambient temperature (°C)	27.7	4.5

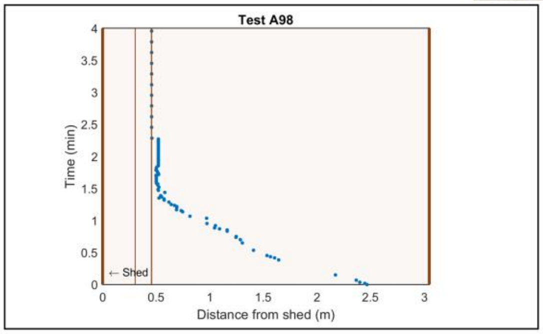


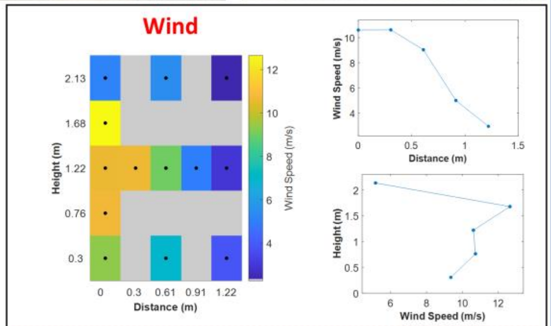
Test # A-98

Mulch only

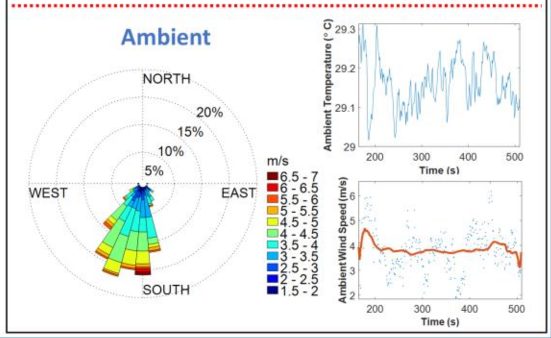
Pine Straw Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

10/20/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:53	0:02
Time to end of mulch (min:s)	1:35	0:04
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.8	0.8
Ambient wind speed (m/s)	3.80	0.22
Ambient wind direction (°)	192	10
Ambient temperature (°C)	29.2	4.5

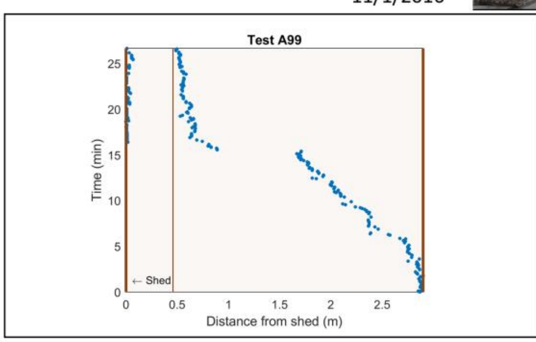


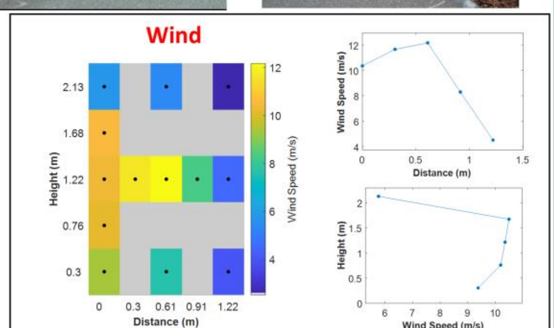
Test # A-99

Mulch only

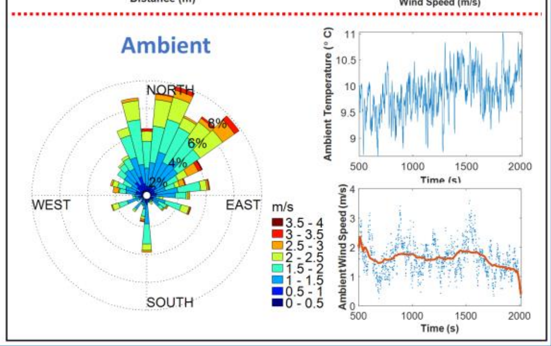
Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

11/1/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	26:30	0:02
Time to end of mulch (min:s)	22:00	0:20
Time to first spot (min:s)	15:53	0:20
Time to spot reaching wall (min:s)	15:53	0:20
Time to flames on wall (min:s)	16:08	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.61	0.20
Ambient wind direction (°)	21	10
Ambient temperature (°C)	9.9	4.4

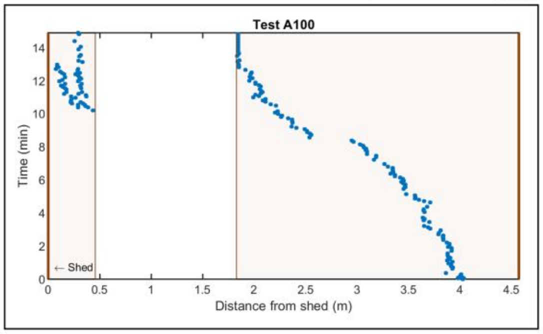


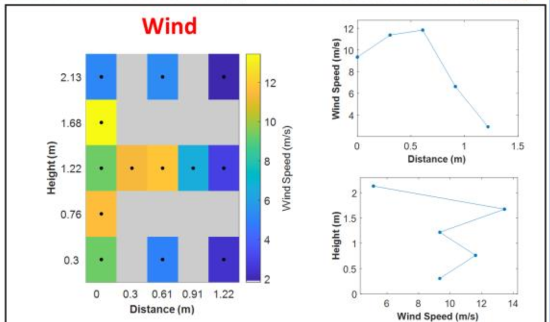
Test # A-100

Mulch only

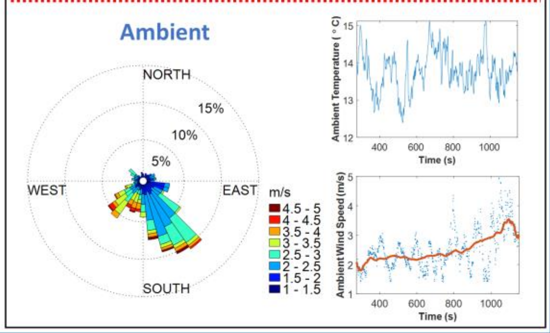
Pine Bark Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

11/1/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:45	0:02
Time to end of mulch (min:s)	12:45	0:02
Time to first spot (min:s)	9:38	0:20
Time to spot reaching wall (min:s)	9:38	0:20
Time to flames on wall (min:s)	12:16	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	2.49	0.21
Ambient wind direction (°)	168	10
Ambient temperature (°C)	13.8	4.4

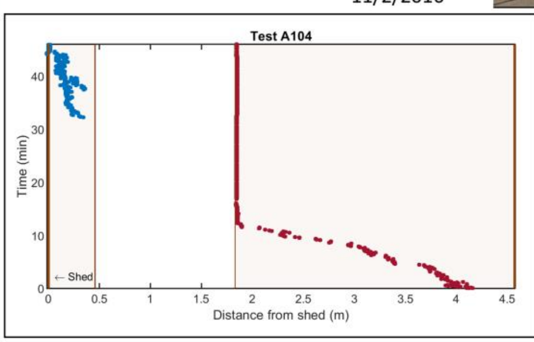


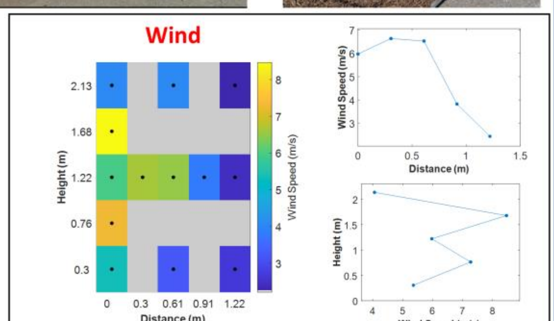
Test # A-104

Mulch only

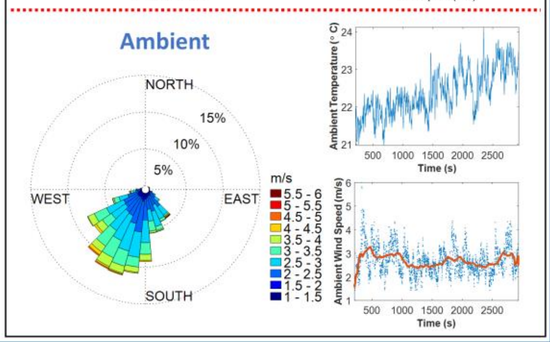
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

11/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	45:47	0:02
Time to end of mulch (min:s)	12:15	0:10
Time to first spot (min:s)	29:39	0:20
Time to spot reaching wall (min:s)	29:39	0:20
Time to flames on wall (min:s)	43:31	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.8	0.5
Ambient wind speed (m/s)	2.70	0.20
Ambient wind direction (°)	199	10
Ambient temperature (°C)	22.4	4.4

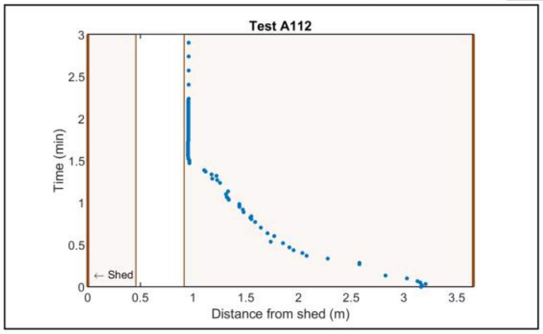


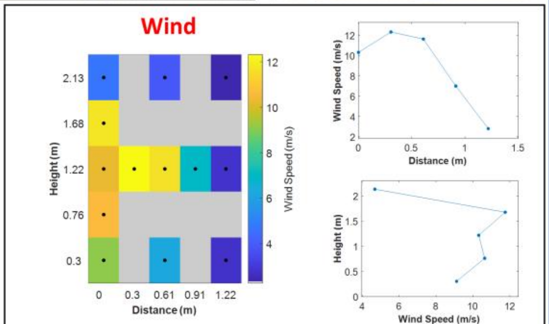
Test # A-112

Mulch only

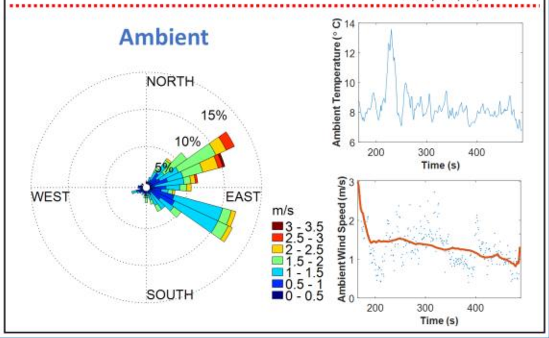
Pine Straw Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

11/23/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:34	0:02
Time to end of mulch (min:s)	1:32	0:04
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.5	0.7
Ambient wind speed (m/s)	1.31	0.21
Ambient wind direction (°)	93	10
Ambient temperature (°C)	8.4	4.4

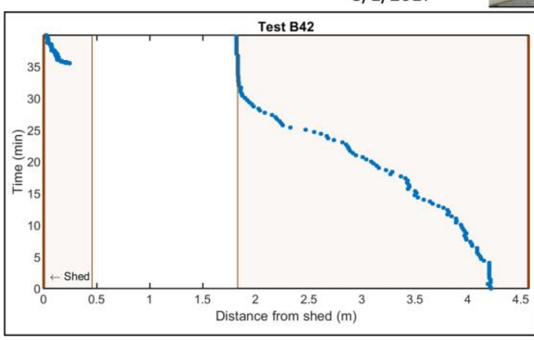


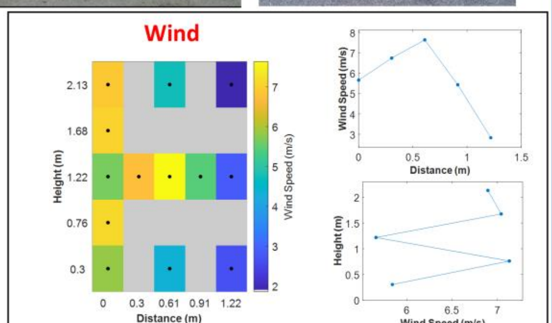
Test # B-42

Mulch only

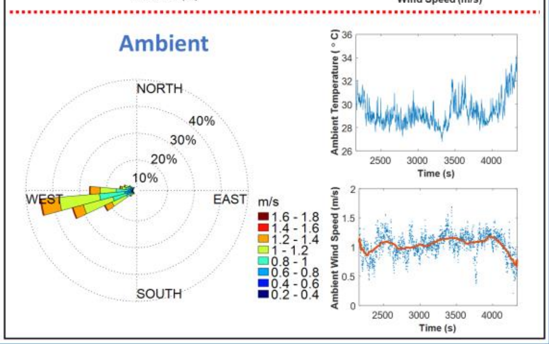
Pine Bark Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

8/1/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	36:31	0:02
Time to end of mulch (min:s)	30:00	0:30
Time to first spot (min:s)	31:55	0:20
Time to spot reaching wall (min:s)	31:55	0:20
Time to flames on wall (min:s)	35:19	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.5
Ambient wind speed (m/s)	1.04	0.20
Ambient wind direction (°)	259	10
Ambient temperature (°C)	29.3	4.5

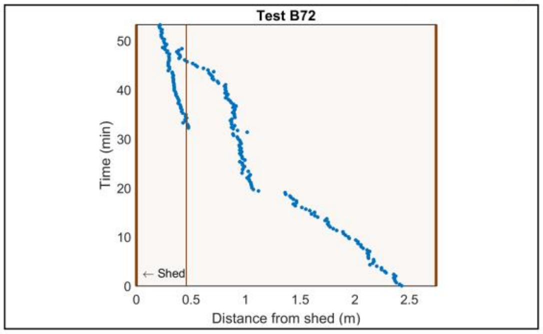


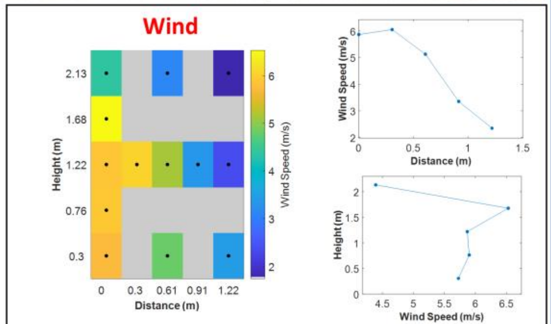
Test # B-72

Mulch only

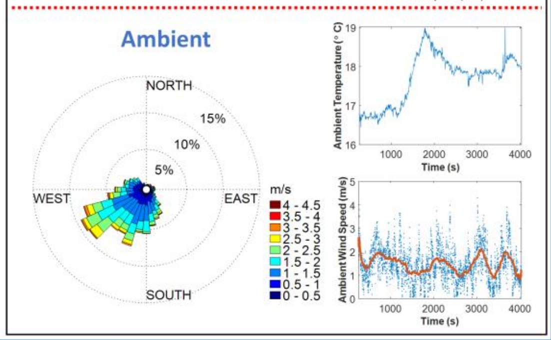
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

10/17/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	62:49	0:02
Time to end of mulch (min:s)	45:50	0:30
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	1.46	0.20
Ambient wind direction (°)	220	10
Ambient temperature (°C)	17.7	4.4

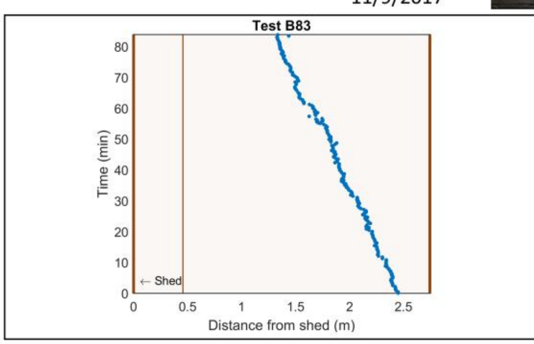


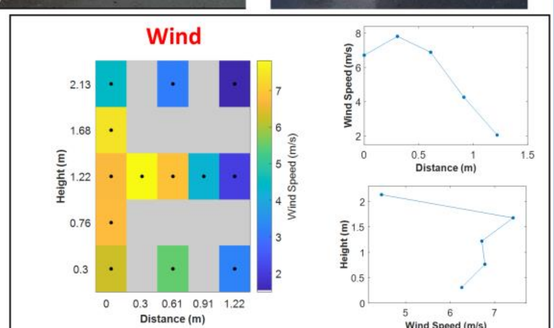
Test # B-83

Mulch only

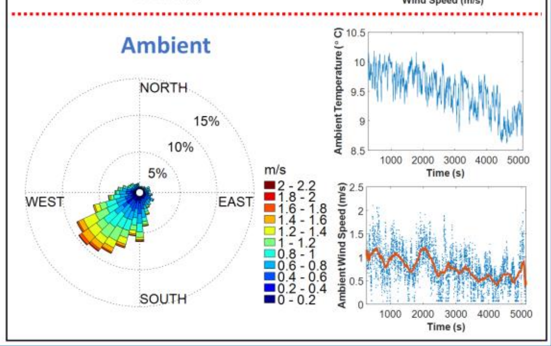
Pine Bark Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

11/9/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	81:16	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.8	0.5
Ambient wind speed (m/s)	0.78	0.20
Ambient wind direction (°)	216	10
Ambient temperature (°C)	9.5	4.4

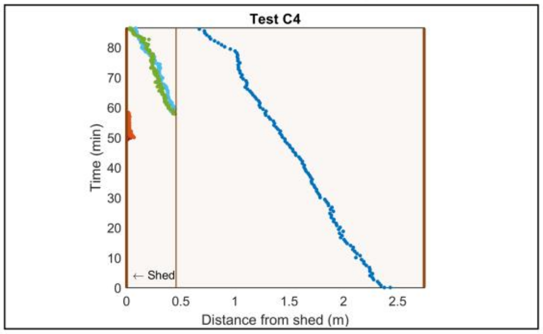


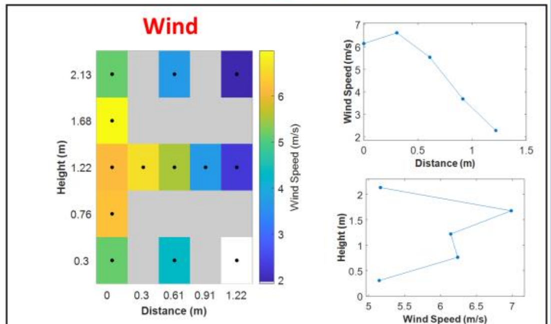
Test # C-4

Mulch only

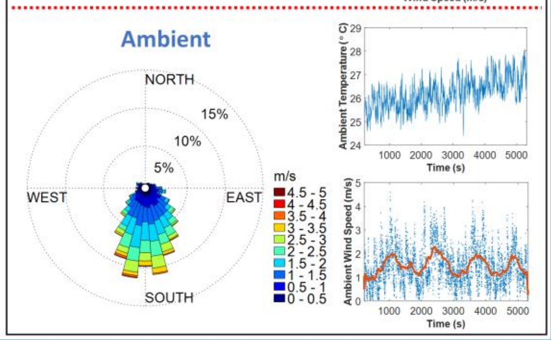
Pine Bark Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

6/7/2018



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	84:58	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	47:41	0:20
Time to spot reaching wall (min:s)	47:50	0:20
Time to flames on wall (min:s)	48:41	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.1	0.4
Ambient wind speed (m/s)	1.48	0.20
Ambient wind direction (°)	174	10
Ambient temperature (°C)	26.2	4.5

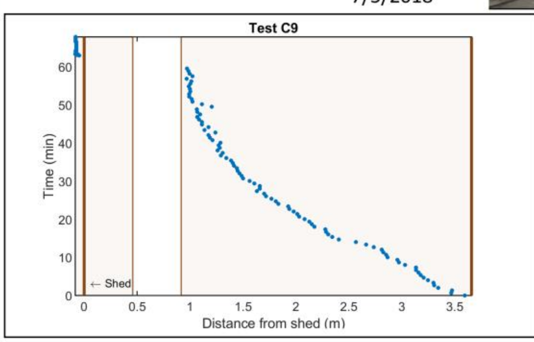


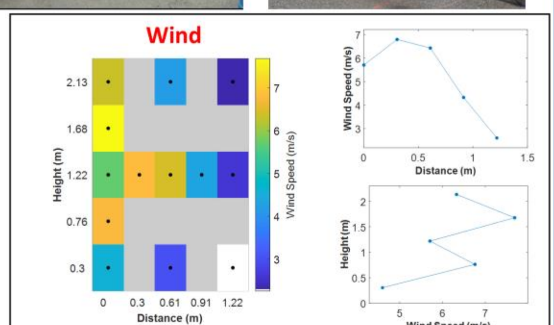
Test # C-9

Mulch only

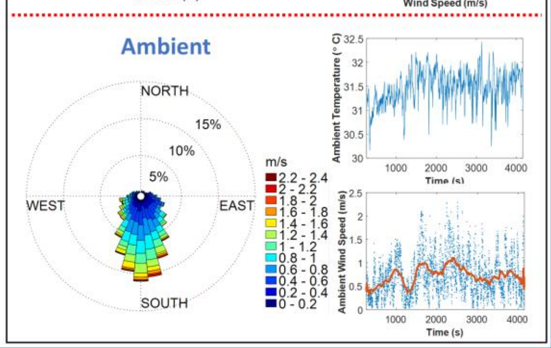
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

7/5/2018



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	66:05	0:02
Time to end of mulch (min:s)	51:00	1:00
Time to first spot (min:s)	59:38	0:20
Time to spot reaching wall (min:s)	59:38	0:20
Time to flames on wall (min:s)	65:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	0.72	0.20
Ambient wind direction (°)	178	10
Ambient temperature (°C)	31.5	4.6



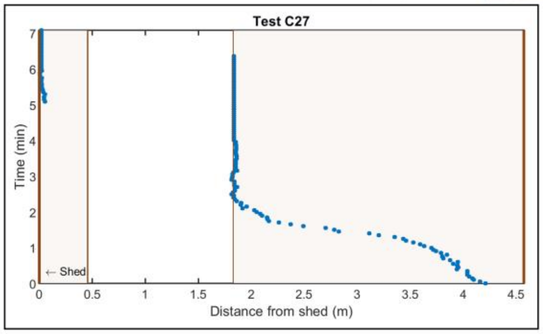
Test # C-27

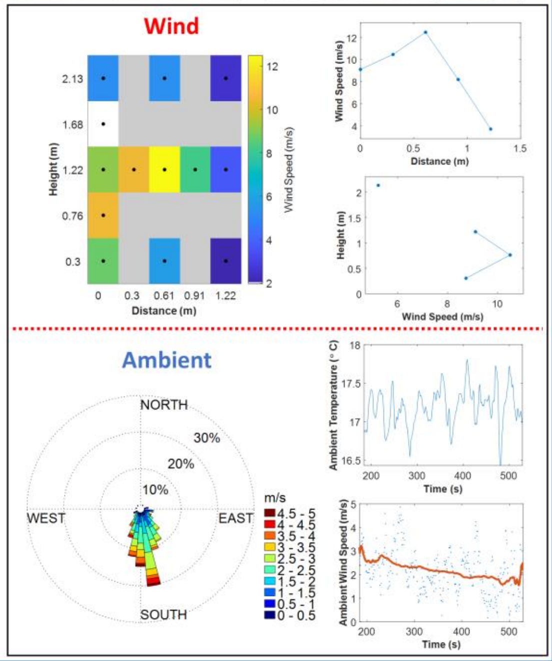
Mulch only

Shredded Rubber Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

10/19/2018







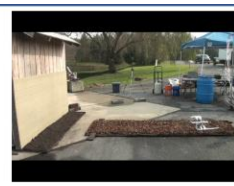
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:52	0:02
Time to end of mulch (min:s)	2:25	0:10
Time to first spot (min:s)	3:40	0:20
Time to spot reaching wall (min:s)	3:40	0:20
Time to flames on wall (min:s)	4:23	0:06
Mean wind sp. 4 ctr. probes (m/s)	9.5	0.8
Ambient wind speed (m/s)	2.15	0.22
Ambient wind direction (°)	170	10
Ambient temperature (°C)	17.2	4.4

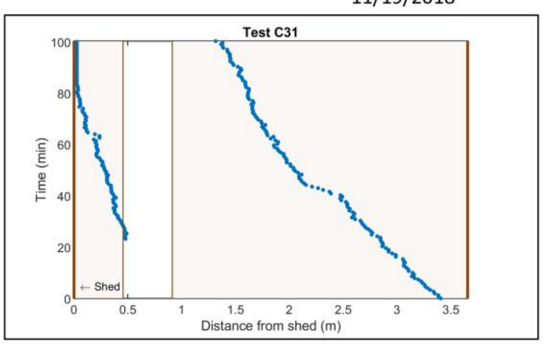
Test # C-31

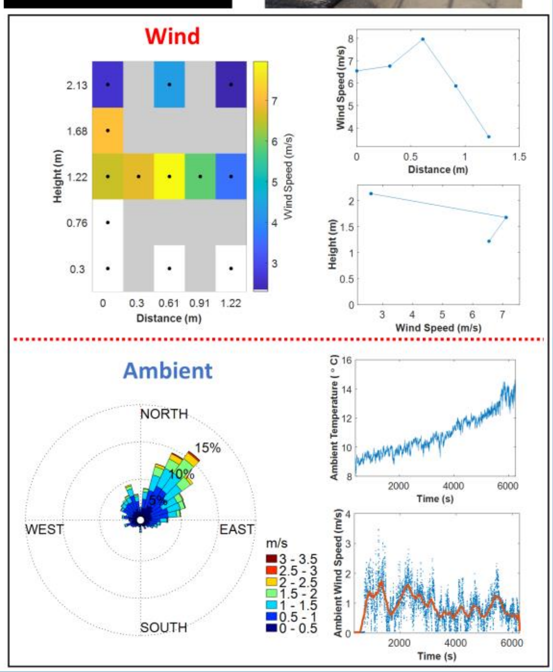
Mulch only

Pine Bark Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

11/19/2018







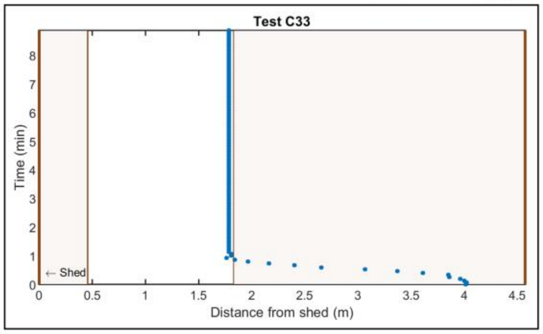
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	97:04	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	19:30	0:20
Time to spot reaching wall (min:s)	56:00	0:20
Time to flames on wall (min:s)	59:54	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.8	0.7
Ambient wind speed (m/s)	0.88	0.20
Ambient wind direction (°)	30	10
Ambient temperature (°C)	10.9	4.4

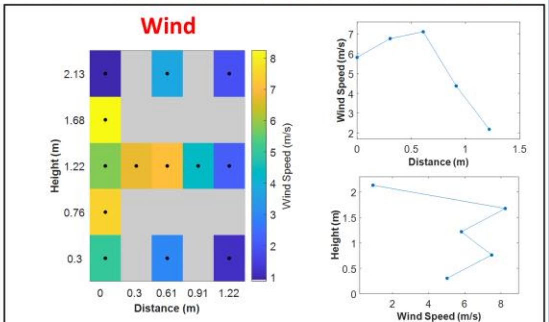
Test # C-33

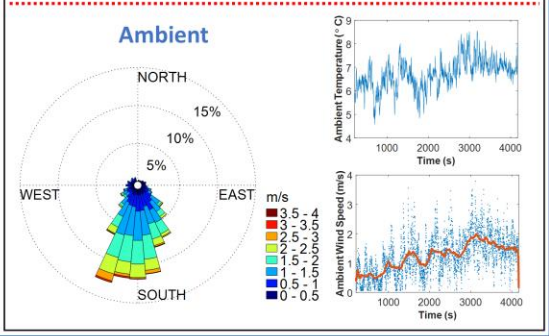
Mulch only

Shredded Rubber Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

12/19/2018







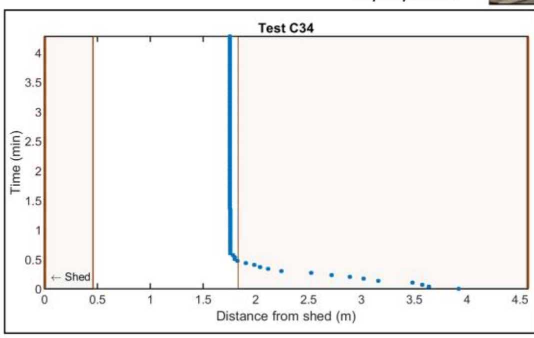
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	70:08	0:02
Time to end of mulch (min:s)	0:55	0:10
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.5
Ambient wind speed (m/s)	1.23	0.20
Ambient wind direction (°)	181	10
Ambient temperature (°C)	6.7	4.4

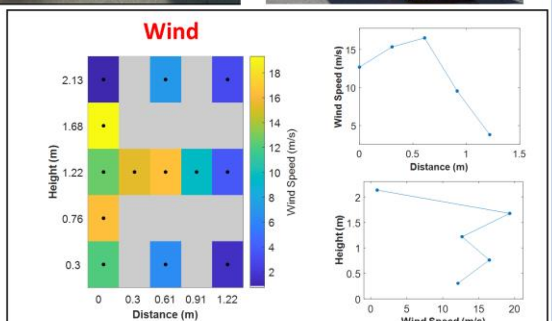
Test # C-34

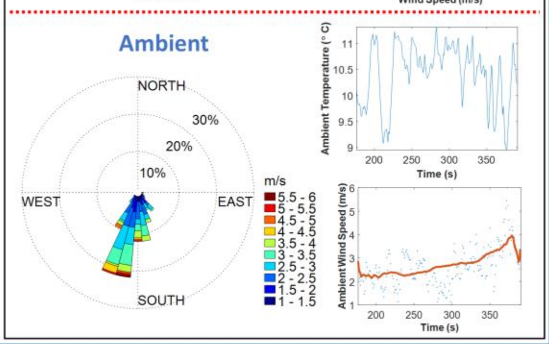
Mulch only

Shredded Rubber Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

12/19/2018







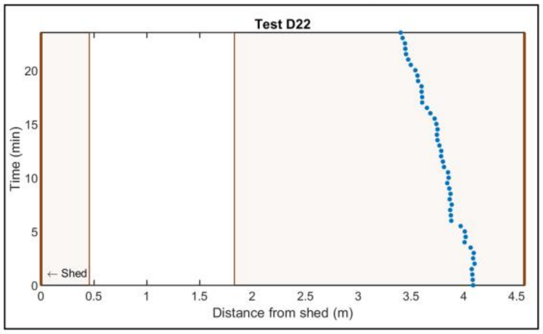
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:52	0:02
Time to end of mulch (min:s)	0:35	0:04
Time to first spot (min:s)	1:31	0:20
Time to spot reaching wall (min:s)	1:31	0:20
Time to flames on wall (min:s)	3:54	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.7	1.2
Ambient wind speed (m/s)	2.63	0.23
Ambient wind direction (°)	183	10
Ambient temperature (°C)	10.4	4.4

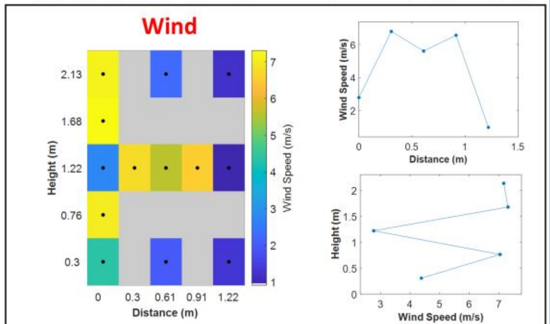
Test # D-22

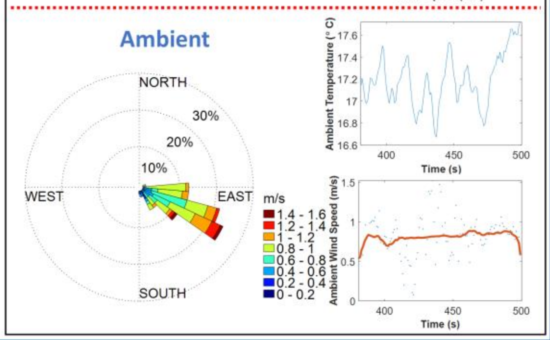
Mulch only

Artificial Turf
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

10/30/2019







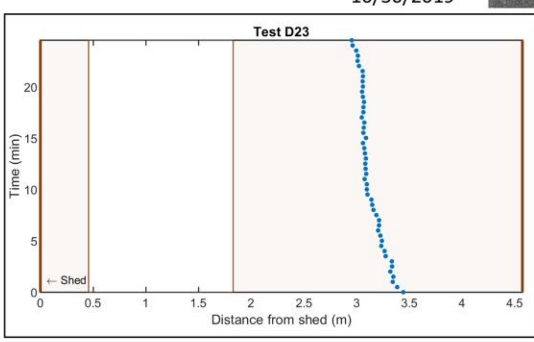
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	24:01	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	5.4	0.4
Ambient wind speed (m/s)	0.81	0.21
Ambient wind direction (°)	117	10
Ambient temperature (°C)	17.2	4.4

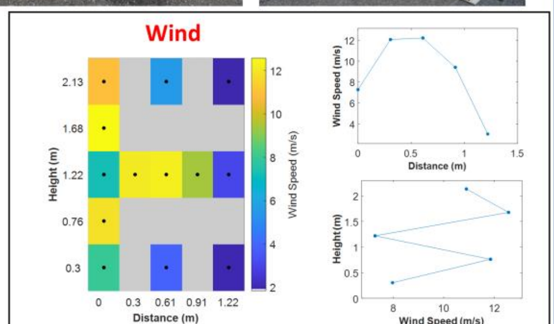
Test # D-23

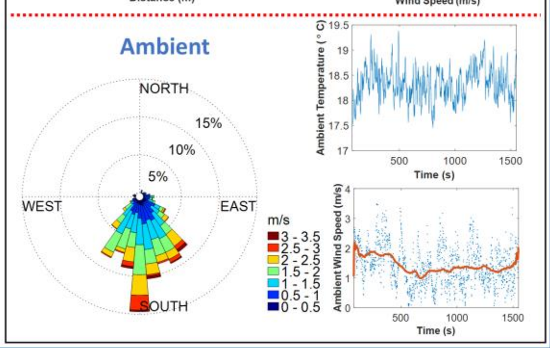
Mulch only

Artificial Turf
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

10/30/2019







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	24:37	0:02
Time to end of mulch (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	9.9	0.7
Ambient wind speed (m/s)	1.41	0.20
Ambient wind direction (°)	171	10
Ambient temperature (°C)	18.3	4.4

Appendix G. Case Details: Fence Only

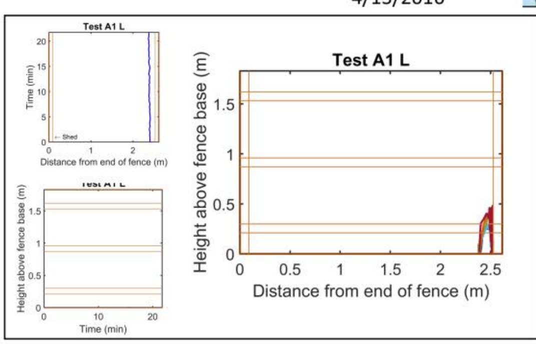
This appendix provides the data from all experimental cases in which the fence was mounted in an empty mulch pan that did not contain mulch. The data includes a description of the experiment, photographs from before and during, flame spread plots, critical times, and ambient and applied winds. The data for each experiment can be read as described in Appendix E.

Test # A-1

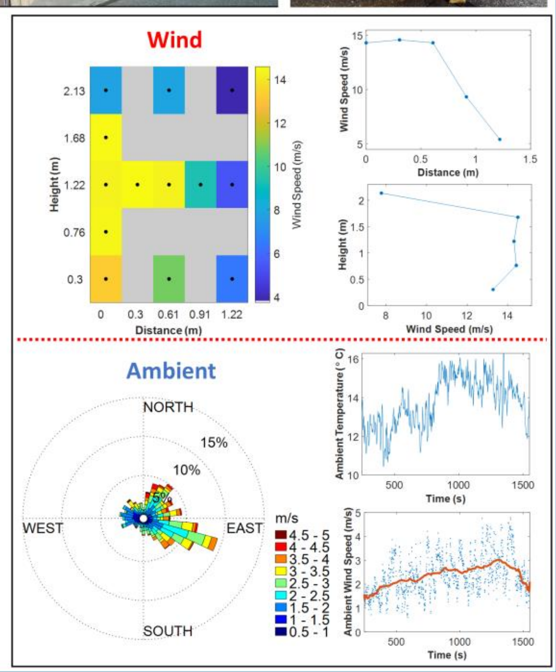
Fence only

Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 0 m (0 ft)

4/13/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	22:01	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	2.39	0.20
Ambient wind direction (°)	82	10
Ambient temperature (°C)	13.7	4.4

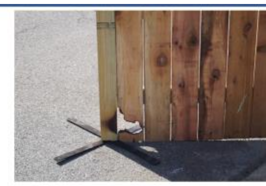
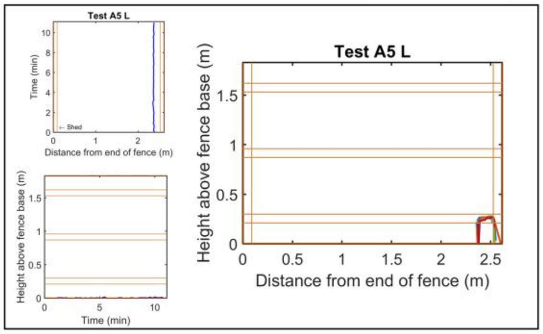


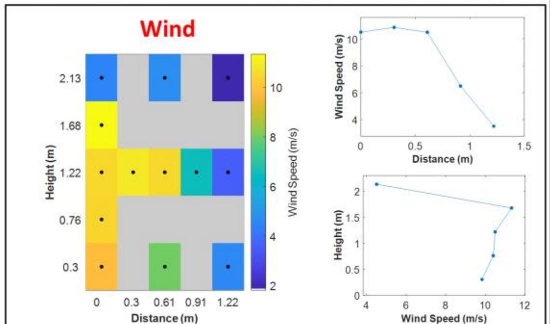
Test # A-5

Fence only

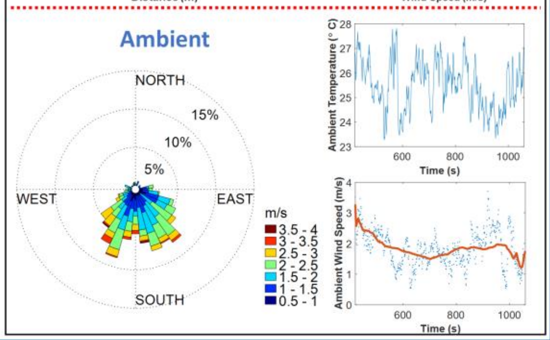
Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 0 m (0 ft)

4/20/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:44	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.5	0.7
Ambient wind speed (m/s)	1.83	0.21
Ambient wind direction (°)	171	10
Ambient temperature (°C)	25.5	4.5



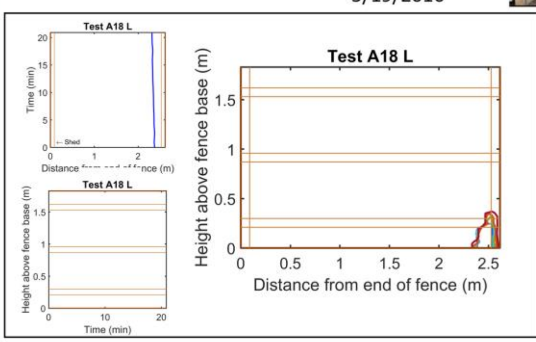
Test # A-18

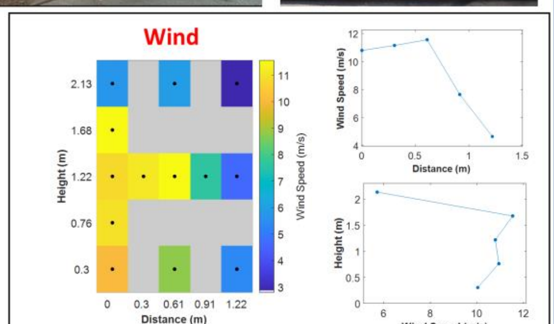
Fence only

Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 0 m (0 ft)

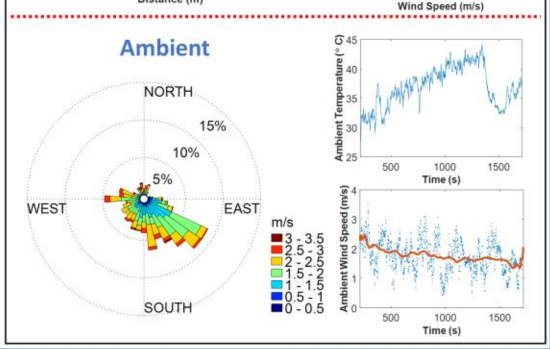
5/19/2016







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	25:05	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.8	0.8
Ambient wind speed (m/s)	1.76	0.20
Ambient wind direction (°)	170	10
Ambient temperature (°C)	36.9	4.7

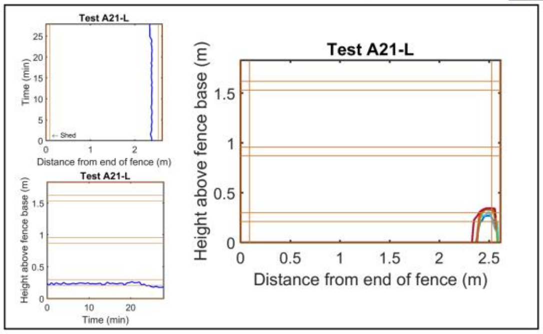


Test # A-21

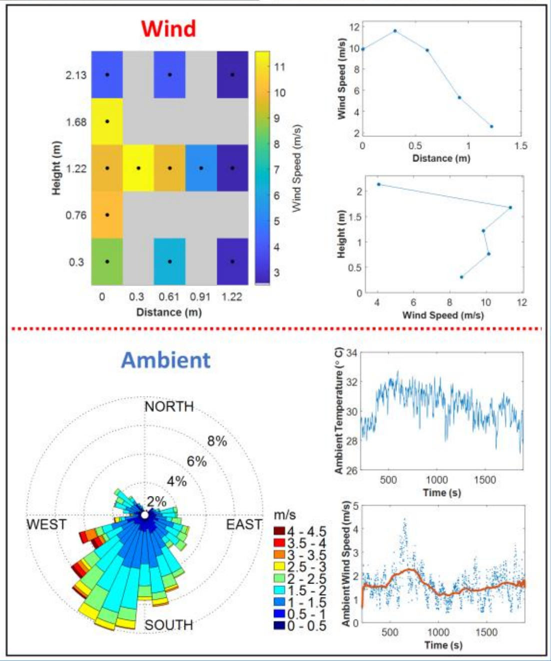
Fence only

Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

6/2/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	28:19	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	1.59	0.20
Ambient wind direction (°)	193	10
Ambient temperature (°C)	30.3	4.6

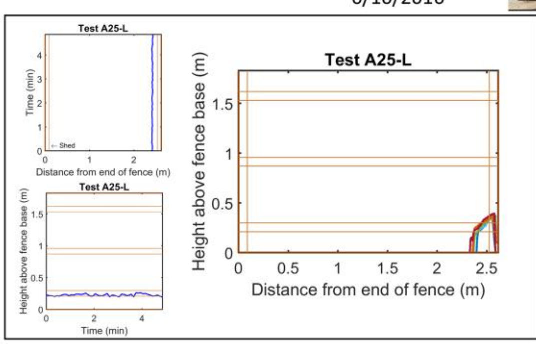


Test # A-25

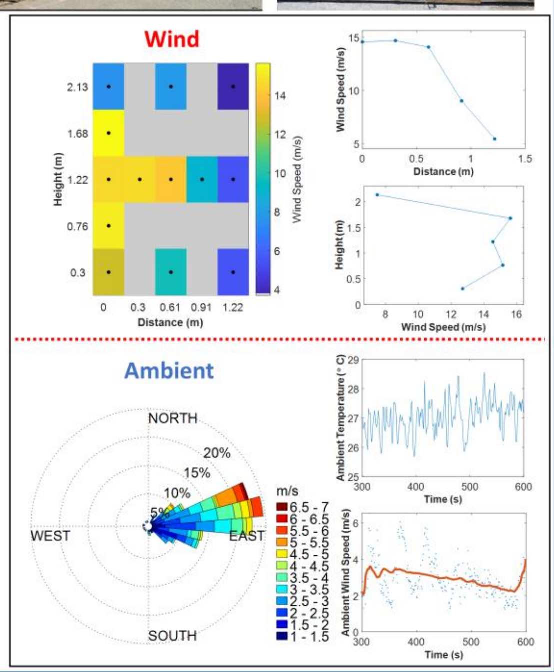
Fence only

Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 0.9 m (3 ft)

6/10/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:05	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:11	0:20
Time to spot reaching wall (min:s)	3:11	0:20
Time to flames on wall (min:s)	3:50	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.5	1.0
Ambient wind speed (m/s)	2.97	0.24
Ambient wind direction (°)	87	10
Ambient temperature (°C)	27.0	4.5

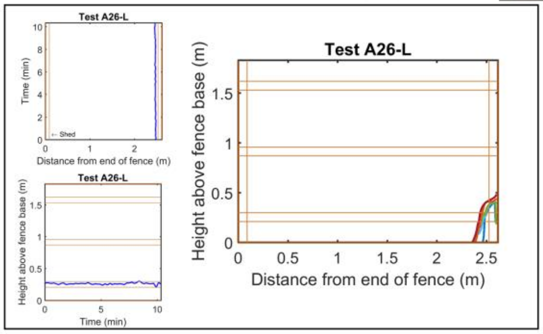


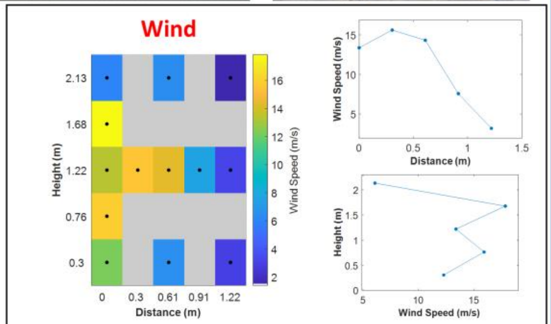
Test # A-26

Fence only

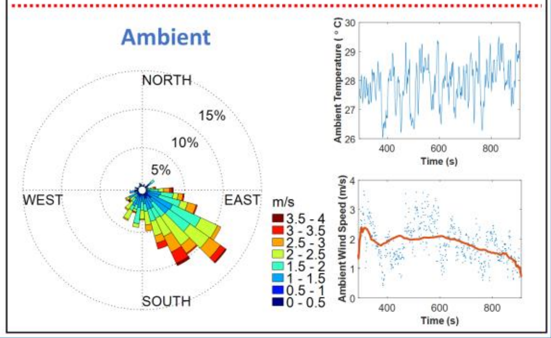
Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 1.8 m (6 ft)

6/10/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:22	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	7:53	0:20
Time to spot reaching wall (min:s)	7:53	0:20
Time to flames on wall (min:s)	8:22	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.8	1.1
Ambient wind speed (m/s)	1.86	0.21
Ambient wind direction (°)	146	10
Ambient temperature (°C)	27.9	4.5

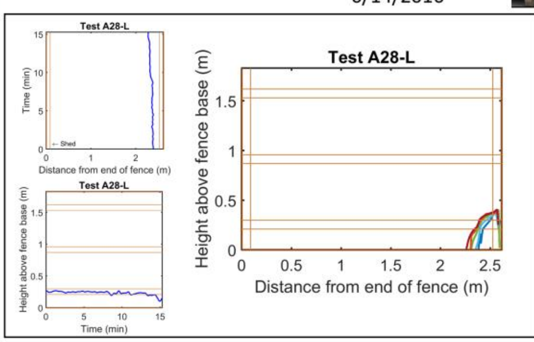


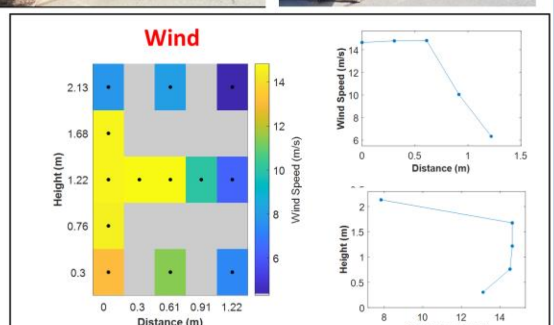
Test # A-28

Fence only

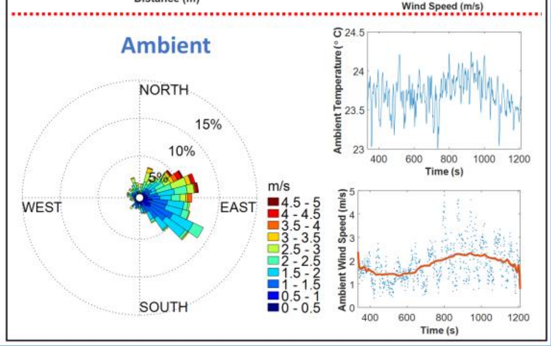
Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 0 m (0 ft)

6/14/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:52	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	12:07	0:20
Time to spot reaching wall (min:s)	12:07	0:20
Time to flames on wall (min:s)	13:23	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	1.84	0.21
Ambient wind direction (°)	91	10
Ambient temperature (°C)	23.7	4.5

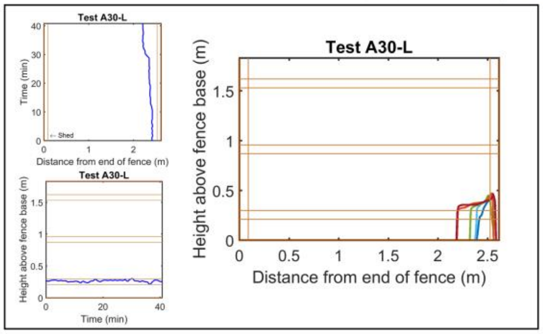


Test # A-30

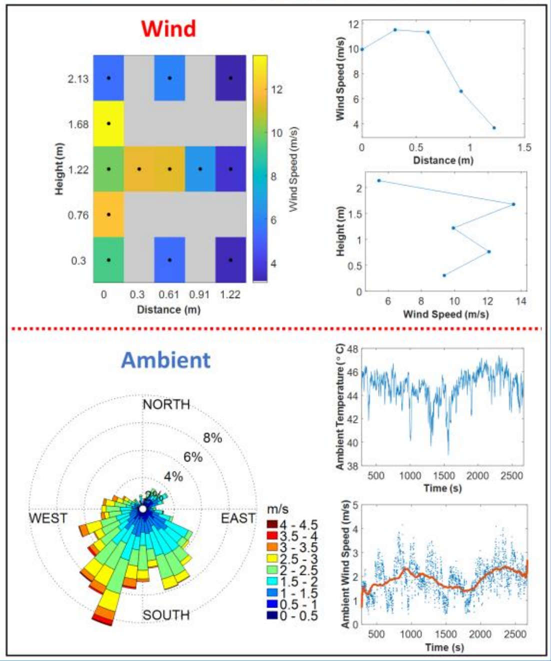
Fence only

Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

6/14/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	40:00	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	11.2	0.8
Ambient wind speed (m/s)	1.88	0.20
Ambient wind direction (°)	191	10
Ambient temperature (°C)	44.7 (error)	4.8

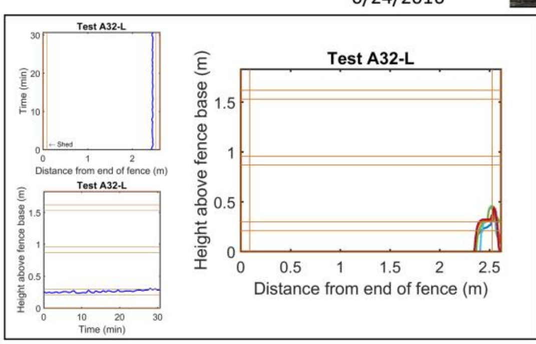


Test # A-32

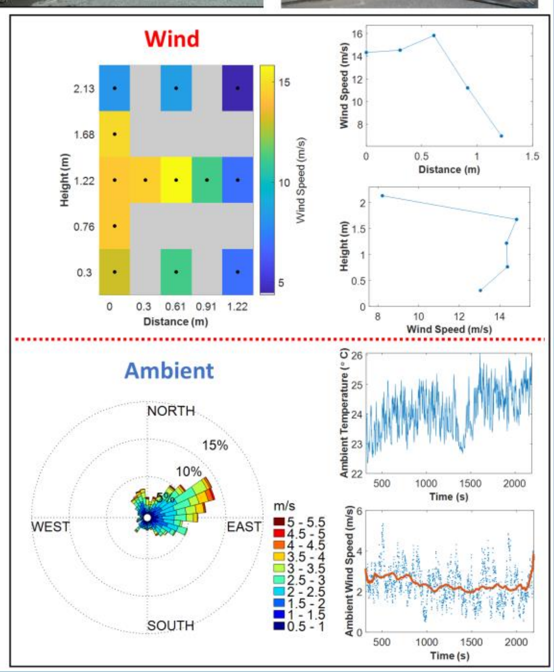
Fence only

Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 0.3 m (1 ft)

6/24/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	31:17	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	2.35	0.20
Ambient wind direction (°)	67	10
Ambient temperature (°C)	24.1	4.5

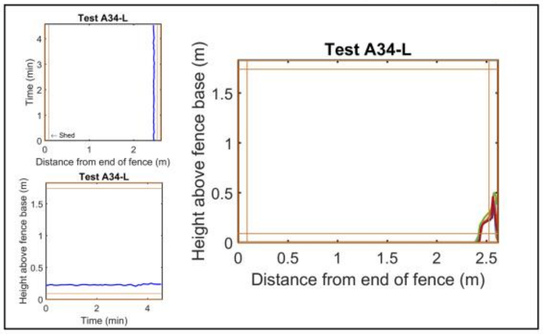


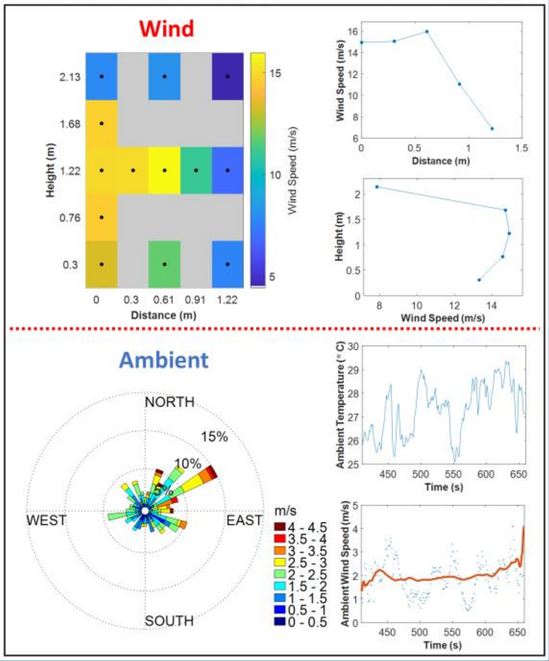
Test # A-34

Fence only

Vinyl Privacy Fence
Wind speed: High
Sep. distance: 0 m (0 ft)

6/24/2016





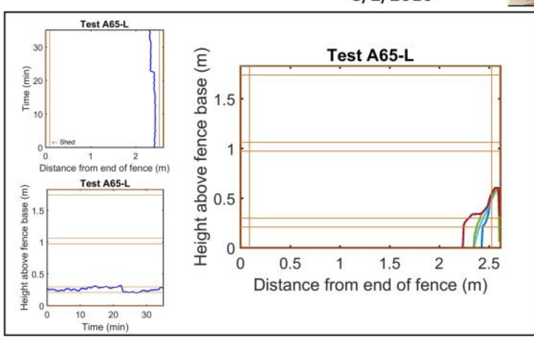
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:16	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.4	1.0
Ambient wind speed (m/s)	1.93	0.22
Ambient wind direction (°)	61	10
Ambient temperature (°C)	27.3	4.5

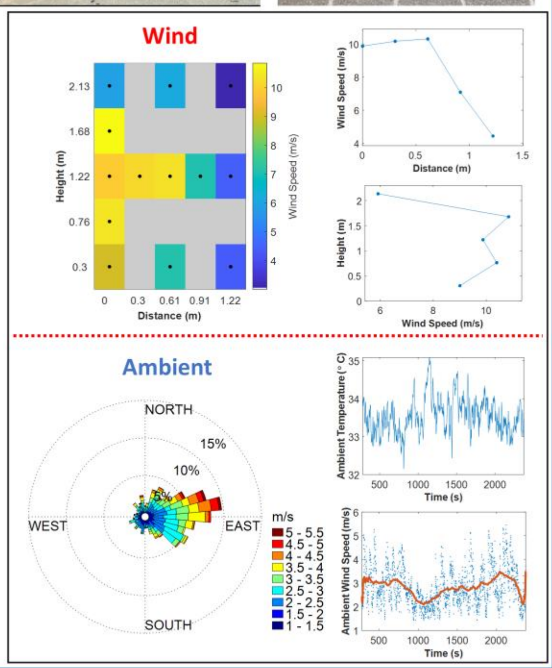
Test # A-65

Fence only

Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

8/2/2016





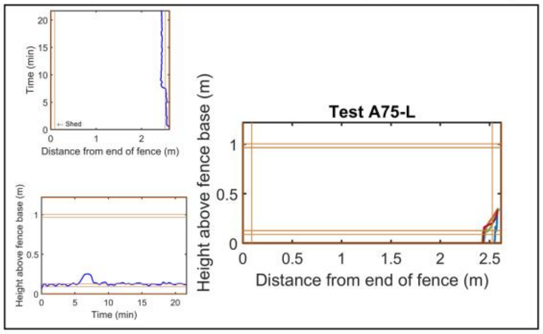
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	35:01	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	2.84	0.20
Ambient wind direction (°)	87	10
Ambient temperature (°C)	33.5	4.6

Test # A-75

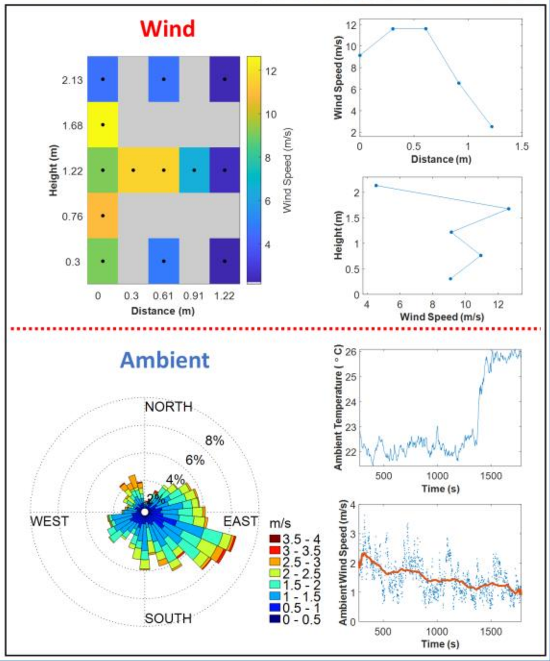
Fence only

Redwood Lattice Fence
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

9/12/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	25:09	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	20:13	0:20
Time to spot reaching wall (min:s)	20:13	0:20
Time to flames on wall (min:s)	23:49	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.4	0.7
Ambient wind speed (m/s)	1.50	0.20
Ambient wind direction (°)	131	10
Ambient temperature (°C)	23.1	4.4

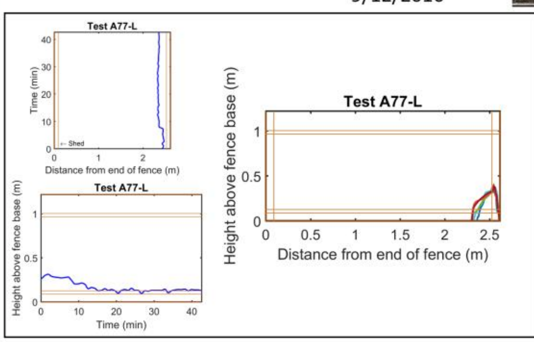


Test # A-77

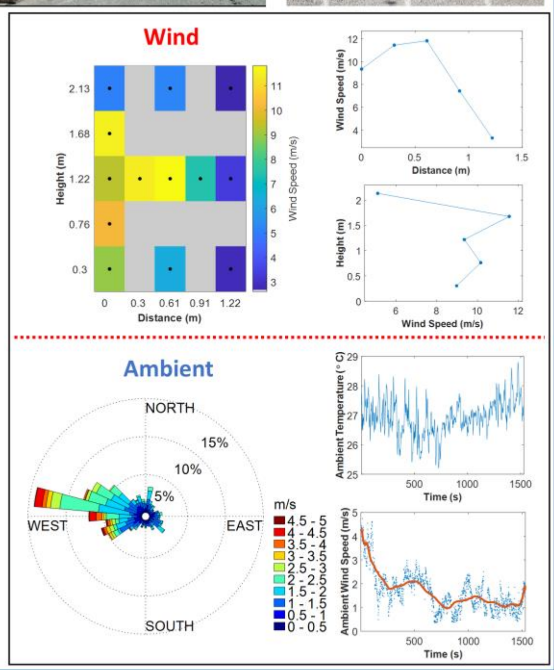
Fence only

Redwood Lattice Fence
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

9/12/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	42:50	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.64	0.20
Ambient wind direction (°)	285	10
Ambient temperature (°C)	26.9	4.5

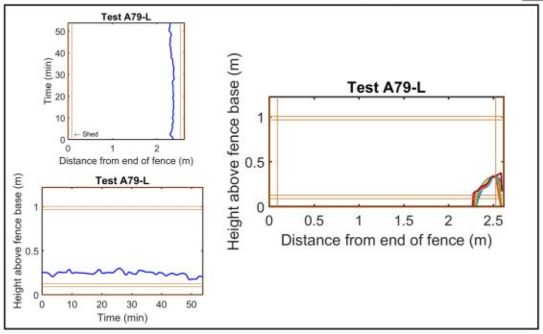


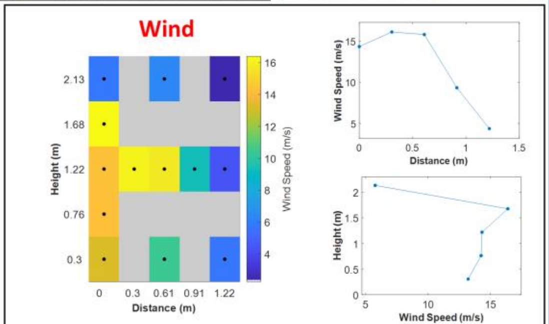
Test # A-79

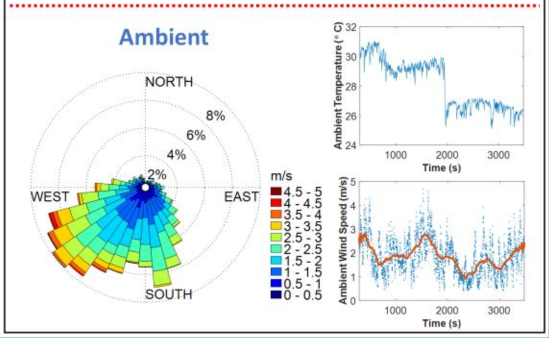
Fence only

Redwood Lattice Fence
Wind speed: High
Sep. distance: 0.3 m (1 ft)

9/15/2016







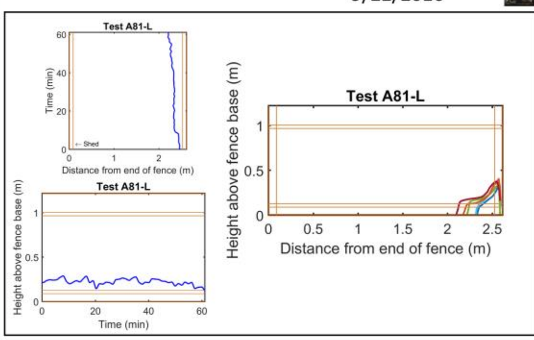
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	53:44	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.5	1.0
Ambient wind speed (m/s)	1.84	0.20
Ambient wind direction (°)	205	10
Ambient temperature (°C)	28.1	4.5

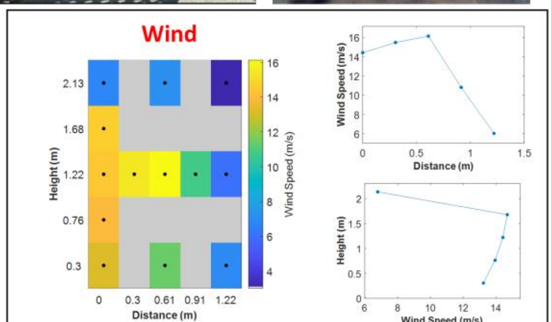
Test # A-81

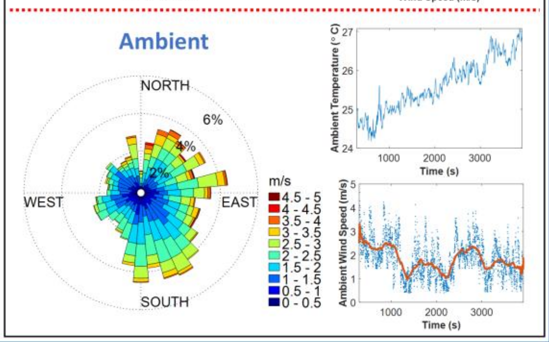
Fence only

Redwood Lattice Fence
Wind speed: High
Sep. distance: 0 m (0 ft)

9/22/2016







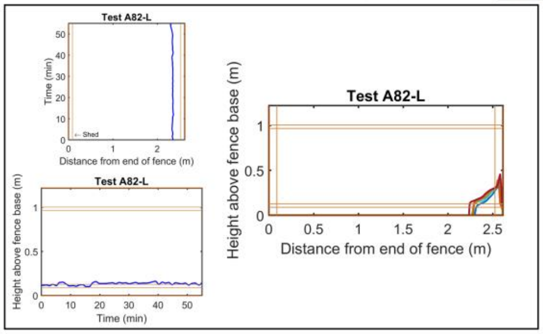
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	60:34	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	1.82	0.20
Ambient wind direction (°)	122	10
Ambient temperature (°C)	25.6	4.5

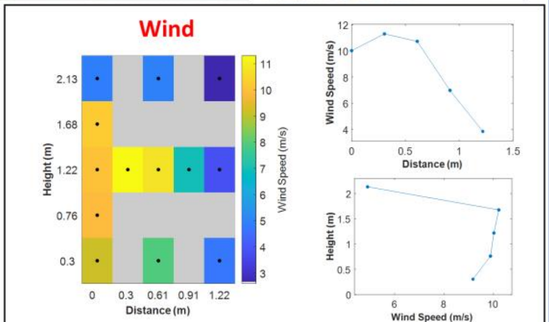
Test # A-82

Fence only

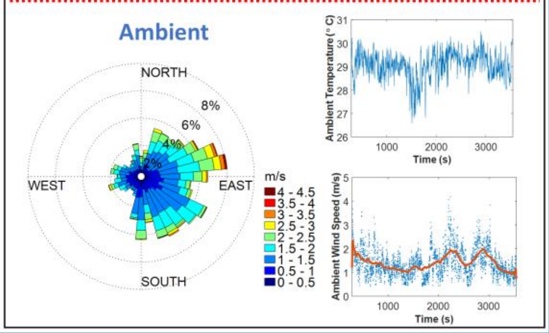
Redwood Lattice Fence
Wind speed: Medium
Sep. distance: 0 m (0 ft)

9/22/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	54:30	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	9.8	0.7
Ambient wind speed (m/s)	1.39	0.20
Ambient wind direction (°)	105	10
Ambient temperature (°C)	29.1	4.5

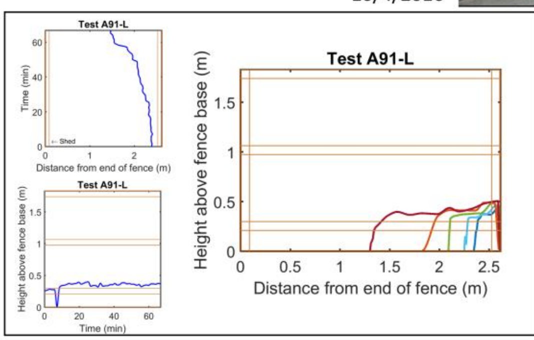


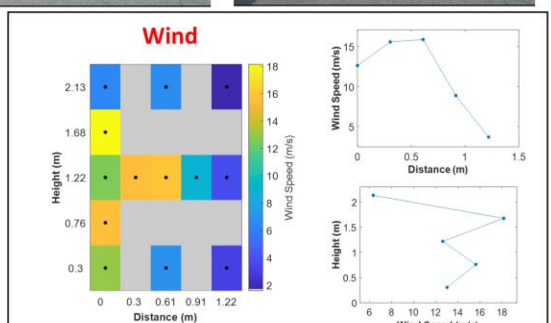
Test # A-91

Fence only

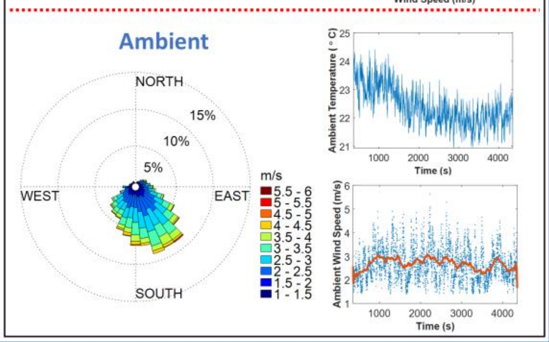
Western Red Cedar Privacy Fence
Wind speed: High
Sep. distance: 1.8 m (6 ft)

10/4/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	66:42	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	35:42	0:20
Time to spot reaching wall (min:s)	35:42	0:20
Time to flames on wall (min:s)	54:15	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.8	1.1
Ambient wind speed (m/s)	2.67	0.20
Ambient wind direction (°)	165	10
Ambient temperature (°C)	22.4	4.4

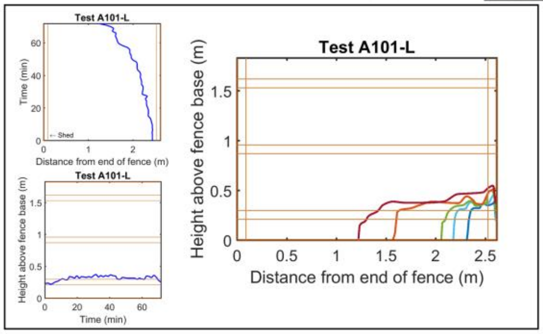


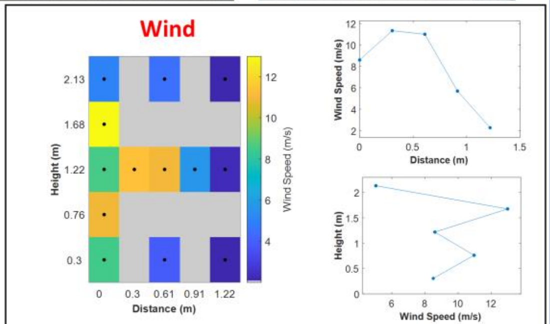
Test # A-101

Fence only

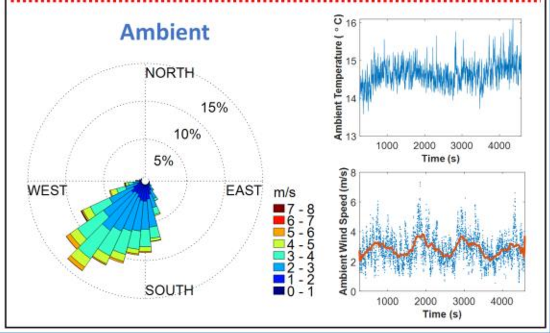
Western Red Cedar Privacy Fence
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

11/1/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	72:06	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.3	0.7
Ambient wind speed (m/s)	2.86	0.20
Ambient wind direction (°)	207	10
Ambient temperature (°C)	14.6	4.4

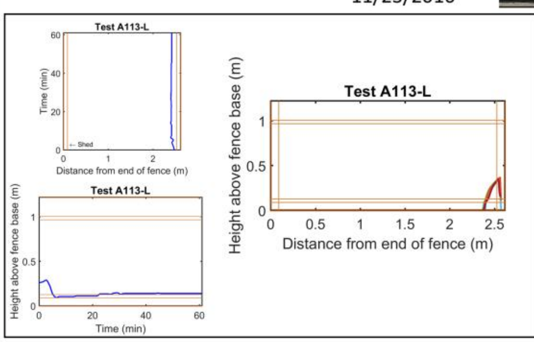


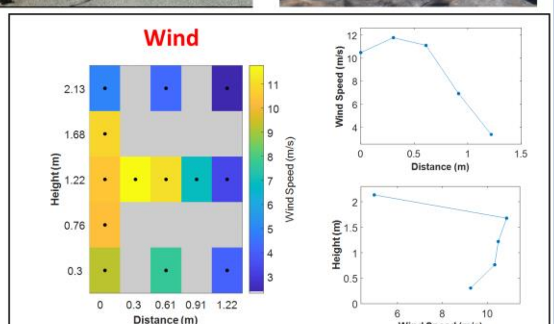
Test # A-113

Fence only

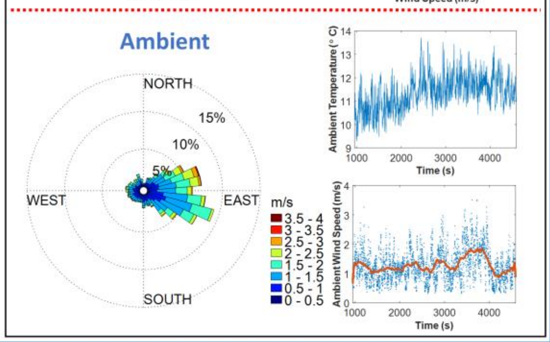
Redwood Lattice Fence
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

11/23/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	60:48	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.2	0.7
Ambient wind speed (m/s)	1.28	0.20
Ambient wind direction (°)	98	10
Ambient temperature (°C)	11.3	4.4

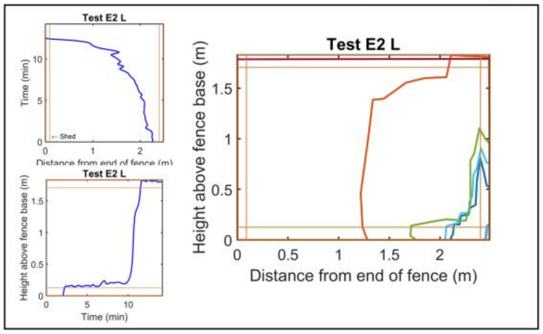


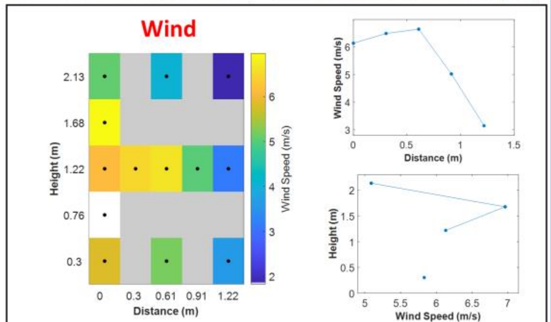
Test # E-2

Fence only

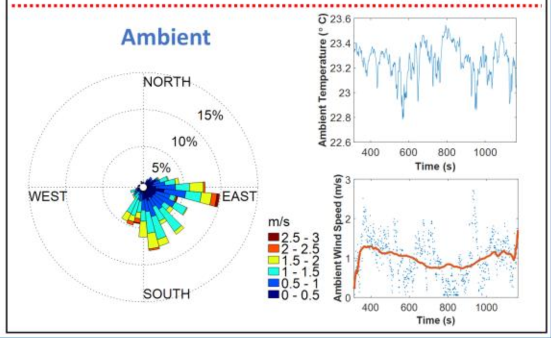
Wood-Plastic Composite (WPC #1) Fence
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

9/25/2020



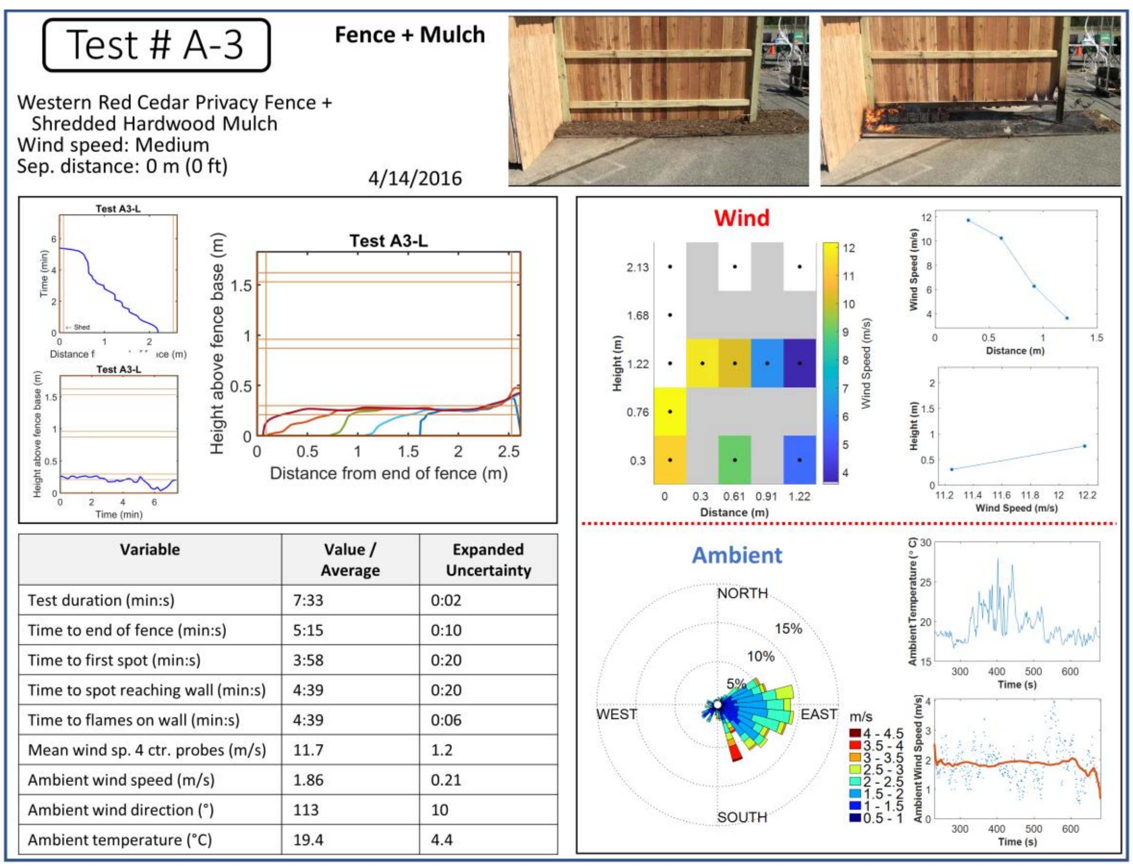


Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:16	0:02
Time to end of fence (min:s)	12:21	0:10
Time to first spot (min:s)	11:50	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.5
Ambient wind speed (m/s)	1.00	0.20
Ambient wind direction (°)	140	10
Ambient temperature (°C)	23.3	4.4



Appendix H. Case Details: Fence and Mulch

This appendix provides the data from all experimental cases in which the fence was mounted in a mulch pan containing mulch. The data includes a description of the experiment, photographs from before and during, flame spread plots, critical times, and ambient and applied winds. The data for each experiment can be read as described in Appendix E.



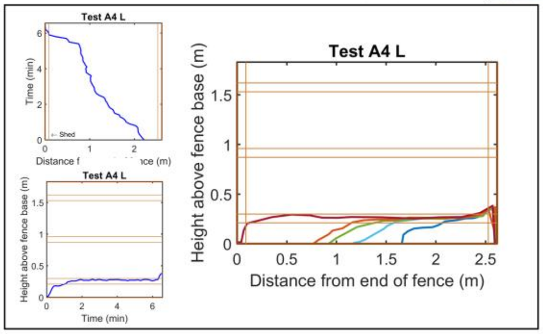
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:33	0:02
Time to end of fence (min:s)	5:15	0:10
Time to first spot (min:s)	3:58	0:20
Time to spot reaching wall (min:s)	4:39	0:20
Time to flames on wall (min:s)	4:39	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.7	1.2
Ambient wind speed (m/s)	1.86	0.21
Ambient wind direction (°)	113	10
Ambient temperature (°C)	19.4	4.4

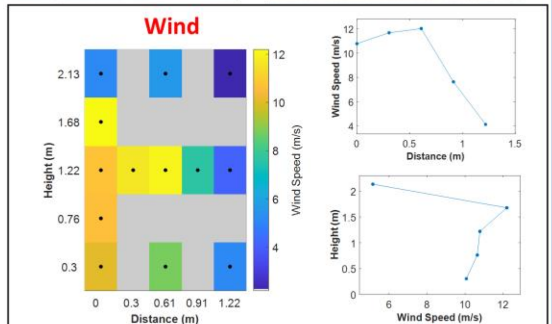
Test # A-4

Fence + Mulch

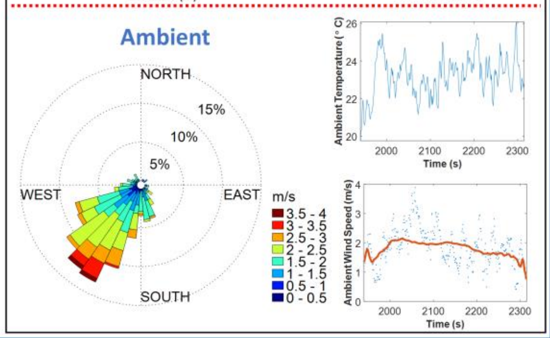
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

4/20/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:25	0:02
Time to end of fence (min:s)	6:10	0:10
Time to first spot (min:s)	2:32	0:20
Time to spot reaching wall (min:s)	3:40	0:20
Time to flames on wall (min:s)	3:40	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	1.87	0.21
Ambient wind direction (°)	215	10
Ambient temperature (°C)	23.2	4.4

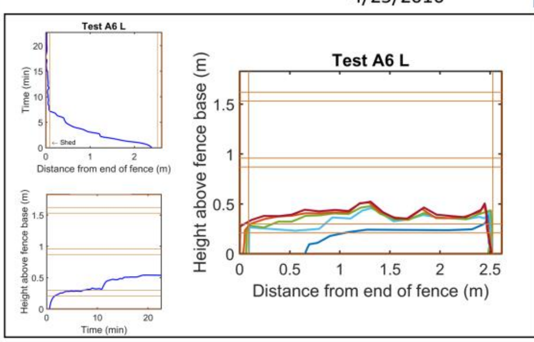


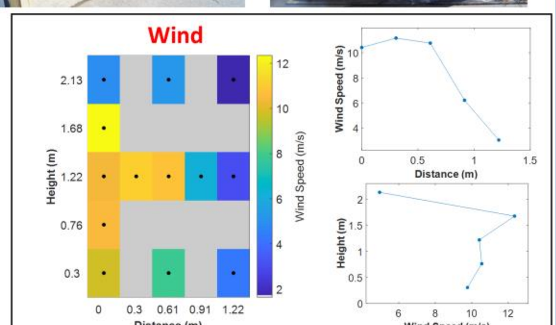
Test # A-6

Fence + Mulch

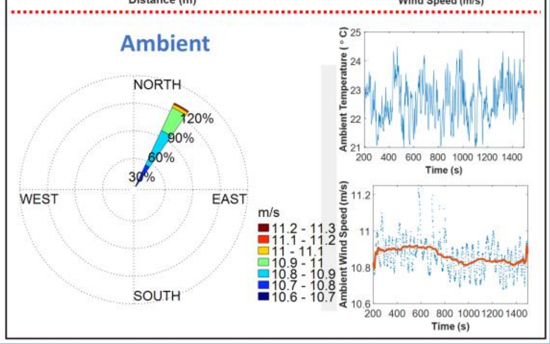
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

4/25/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	21:39	0:02
Time to end of fence (min:s)	8:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	10.8	0.8
Ambient wind speed (m/s)	10.86 (error)	0.43
Ambient wind direction (°)	31	10
Ambient temperature (°C)	22.6	4.4

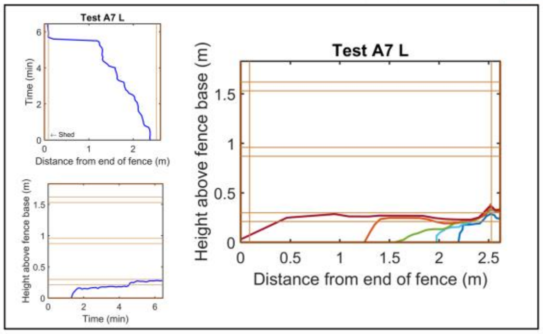


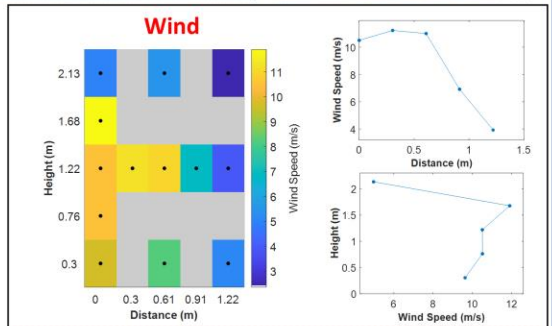
Test # A-7

Fence + Mulch

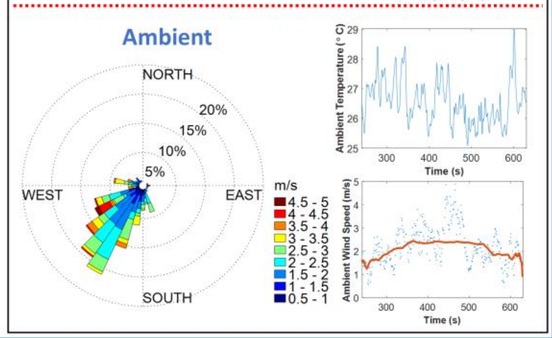
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

4/25/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:34	0:02
Time to end of fence (min:s)	5:35	0:10
Time to first spot (min:s)	3:22	0:20
Time to spot reaching wall (min:s)	3:38	0:20
Time to flames on wall (min:s)	5:38	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.6	0.8
Ambient wind speed (m/s)	2.22	0.22
Ambient wind direction (°)	220	10
Ambient temperature (°C)	26.6	4.5

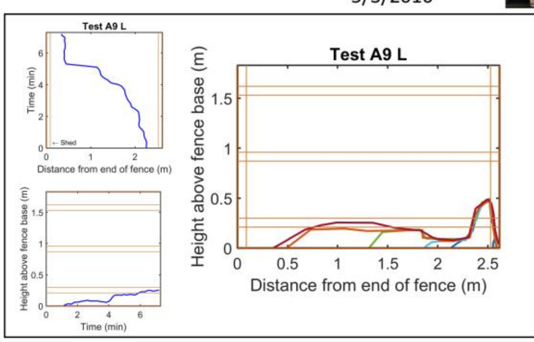


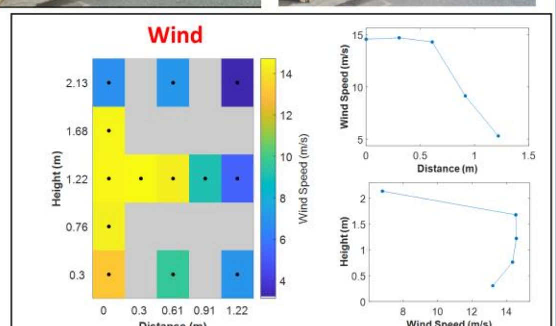
Test # A-9

Fence + Mulch

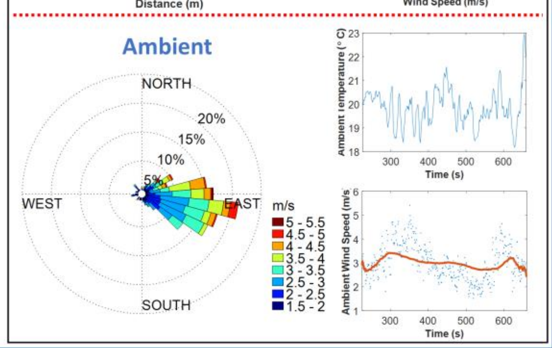
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

5/3/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:24	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	5:15	0:20
Time to spot reaching wall (min:s)	5:15	0:20
Time to flames on wall (min:s)	5:15	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	3.00	0.21
Ambient wind direction (°)	99	10
Ambient temperature (°C)	19.8	4.4

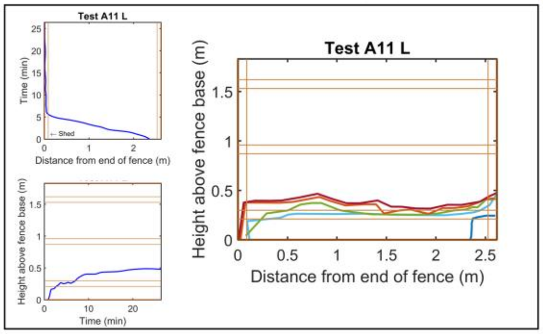


Test # A-11

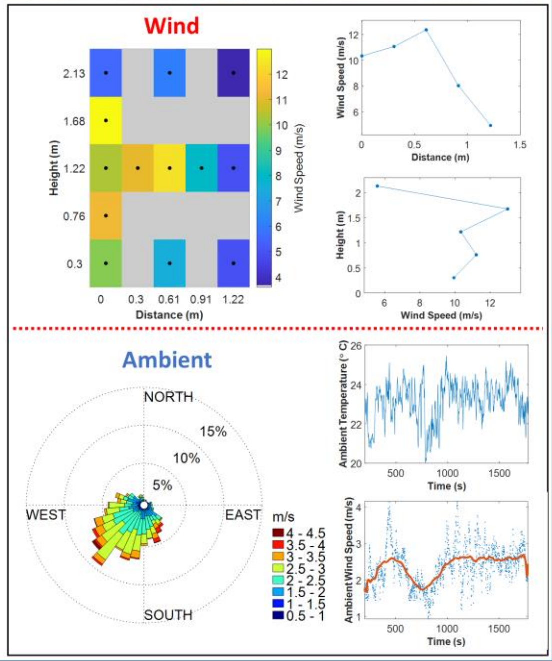
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

5/12/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	26:26	0:02
Time to end of fence (min:s)	5:55	0:30
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	11.1	0.8
Ambient wind speed (m/s)	2.38	0.20
Ambient wind direction (°)	217	10
Ambient temperature (°C)	23.1	4.4

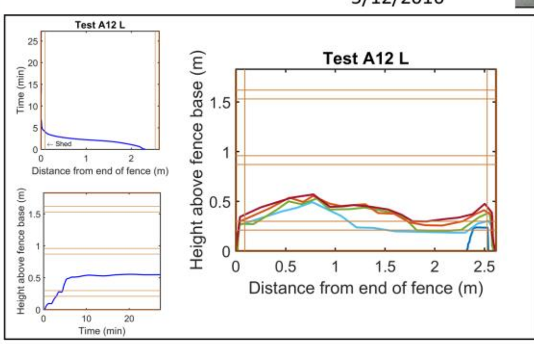


Test # A-12

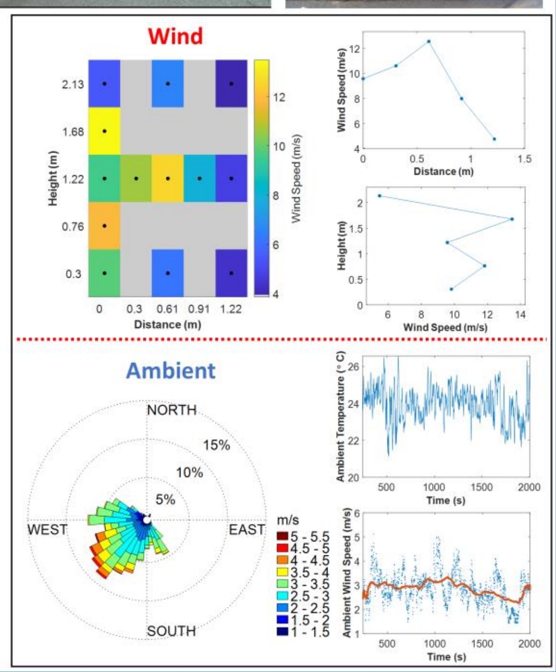
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

5/12/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	29:21	0:02
Time to end of fence (min:s)	4:50	0:30
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	11.2	0.8
Ambient wind speed (m/s)	2.86	0.20
Ambient wind direction (°)	231	10
Ambient temperature (°C)	23.9	4.5

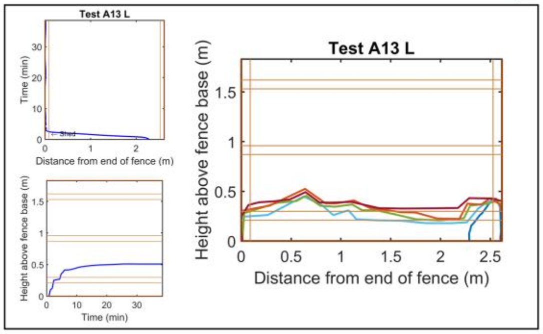


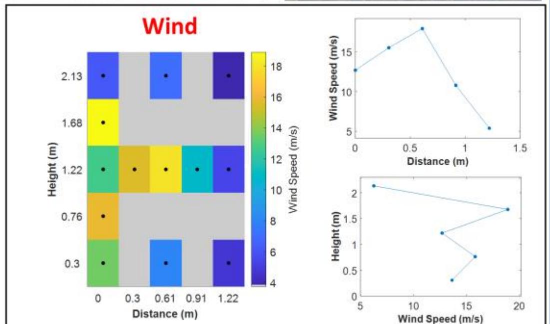
Test # A-13

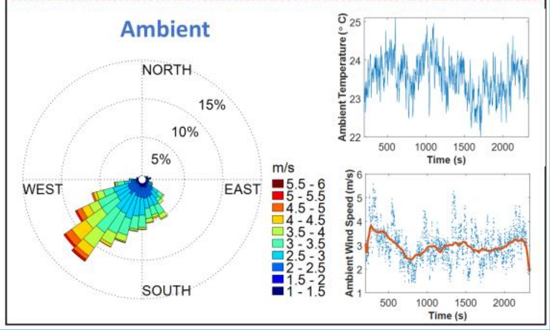
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

5/12/2016







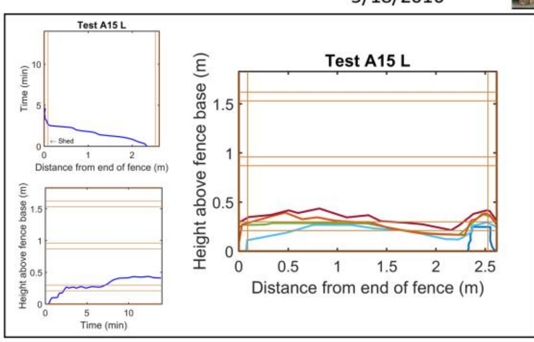
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	35:51	0:02
Time to end of fence (min:s)	3:00	0:30
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	15.3	1.1
Ambient wind speed (m/s)	2.99	0.20
Ambient wind direction (°)	203	10
Ambient temperature (°C)	23.6	4.5

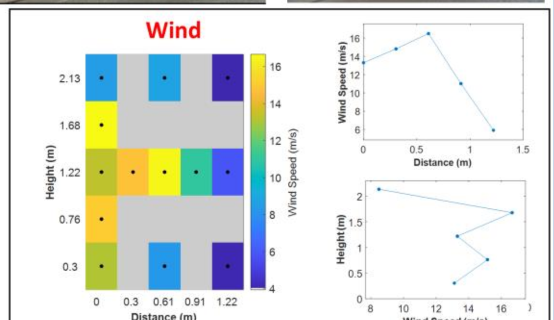
Test # A-15

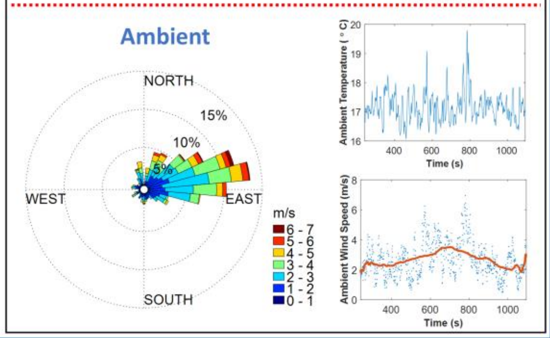
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

5/18/2016







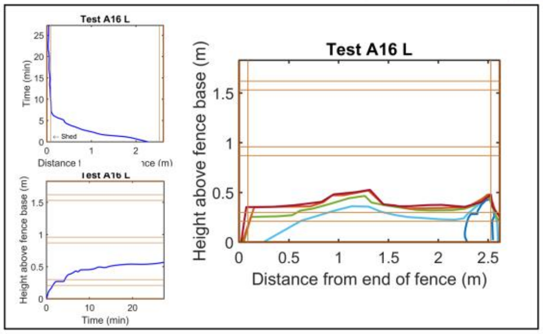
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:27	0:02
Time to end of fence (min:s)	3:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.6	1.0
Ambient wind speed (m/s)	2.66	0.21
Ambient wind direction (°)	69	10
Ambient temperature (°C)	17.2	4.4

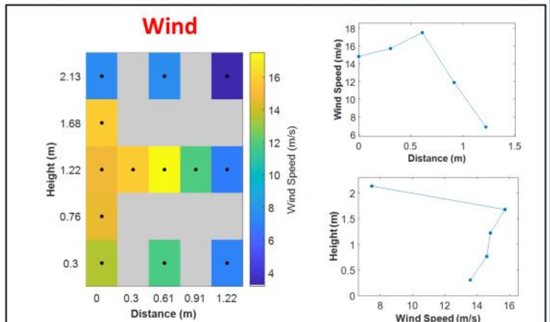
Test # A-16

Fence + Mulch

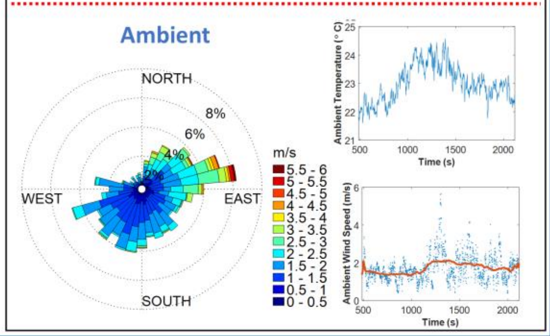
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

5/19/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	27:15	0:02
Time to end of fence (min:s)	7:00	0:30
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.7	1.0
Ambient wind speed (m/s)	1.69	0.20
Ambient wind direction (°)	143	10
Ambient temperature (°C)	23.0	4.4

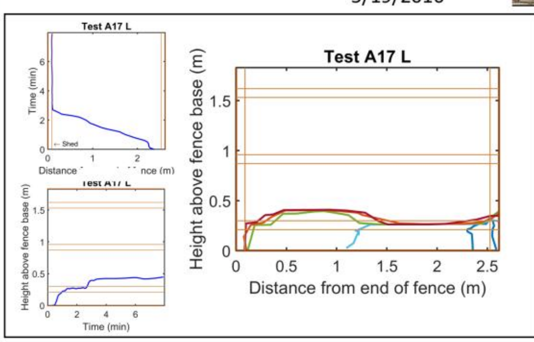


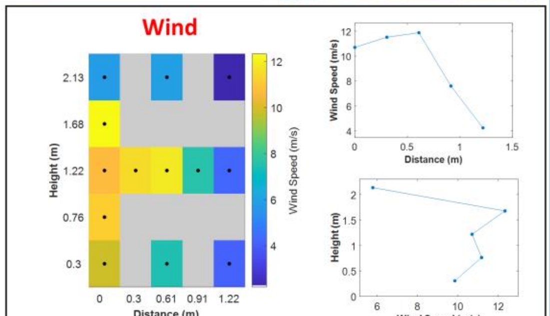
Test # A-17

Fence + Mulch

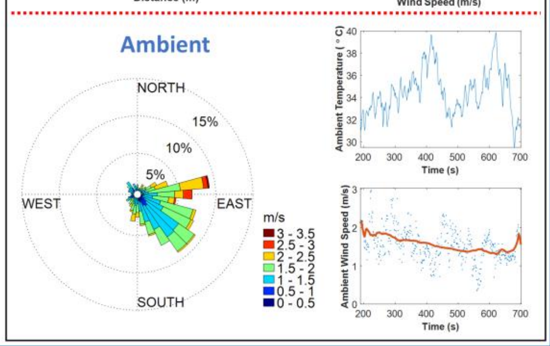
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

5/19/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:36	0:02
Time to end of fence (min:s)	2:40	0:20
Time to first spot (min:s)	2:07	0:20
Time to spot reaching wall (min:s)	2:07	0:20
Time to flames on wall (min:s)	3:31	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.0	0.8
Ambient wind speed (m/s)	1.54	0.20
Ambient wind direction (°)	124	10
Ambient temperature (°C)	34.5	4.6

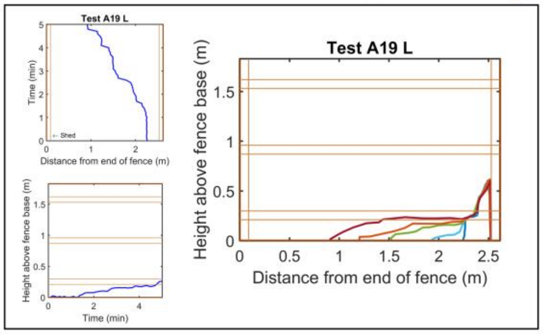


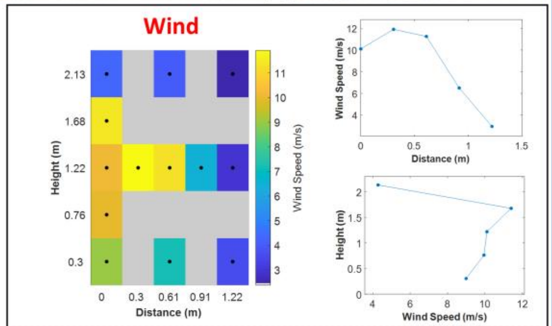
Test # A-19

Fence + Mulch

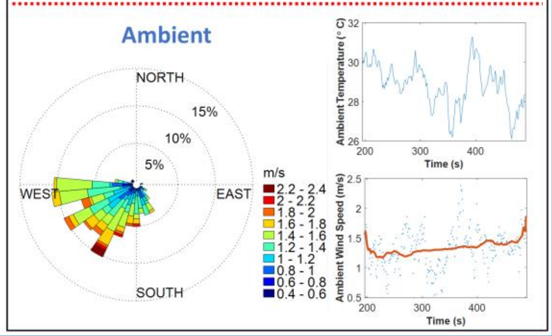
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

6/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:03	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:51	0:20
Time to spot reaching wall (min:s)	2:17	0:20
Time to flames on wall (min:s)	2:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.31	0.20
Ambient wind direction (°)	222	10
Ambient temperature (°C)	28.8	4.5

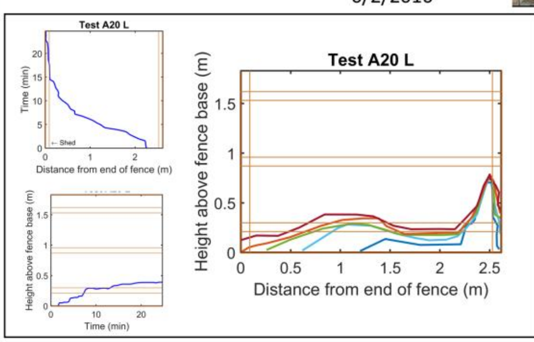


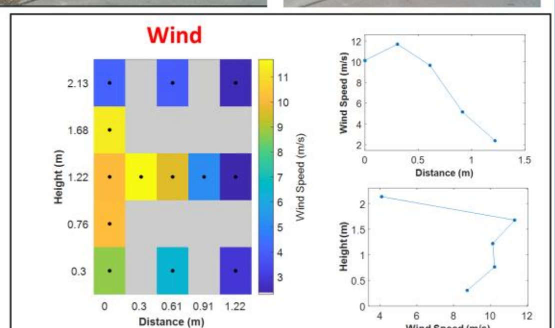
Test # A-20

Fence + Mulch

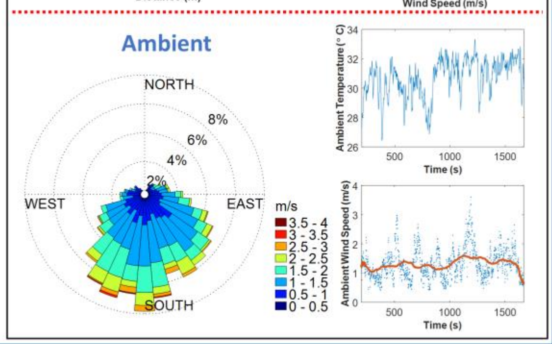
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

6/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	24:54	0:02
Time to end of fence (min:s)	14:30	0:30
Time to first spot (min:s)	13:54	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	23:55	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.31	0.20
Ambient wind direction (°)	173	10
Ambient temperature (°C)	30.7	4.6

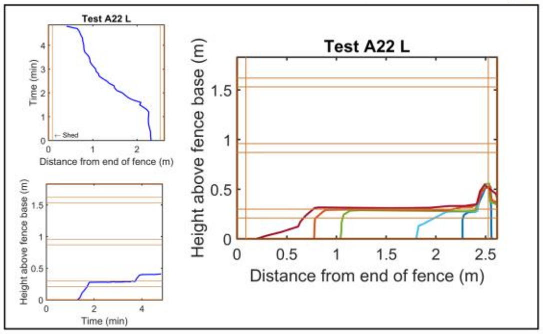


Test # A-22

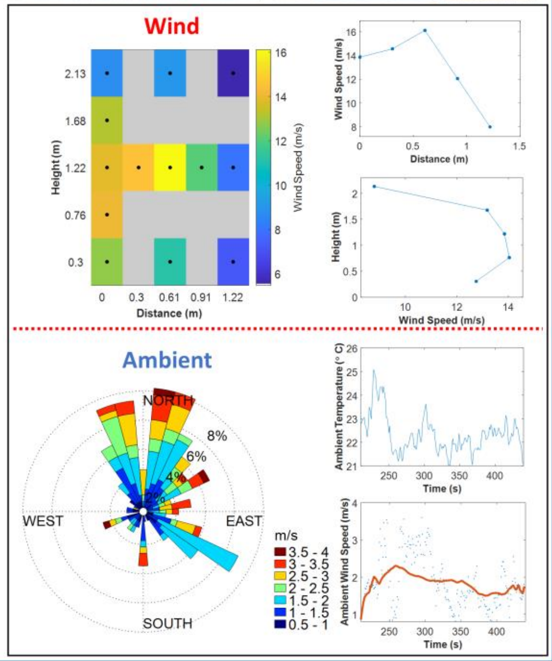
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

6/10/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:04	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:59	0:20
Time to spot reaching wall (min:s)	2:23	0:20
Time to flames on wall (min:s)	2:41	0:06
Mean wind sp. 4 ctr. probes (m/s)	13.5	1.0
Ambient wind speed (m/s)	1.88	0.22
Ambient wind direction (°)	33	10
Ambient temperature (°C)	22.3	4.4

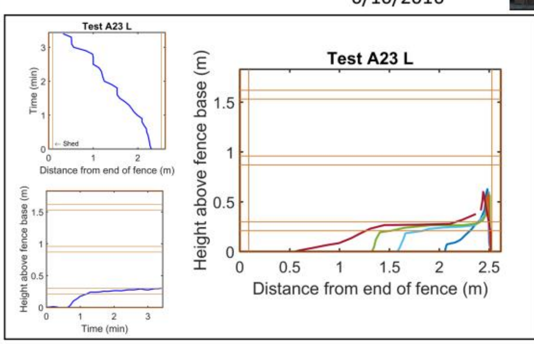


Test # A-23

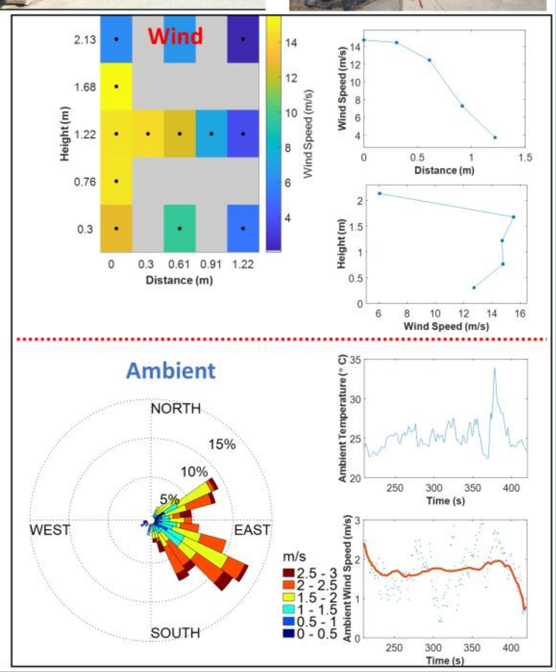
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

6/10/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:40	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:20	0:20
Time to spot reaching wall (min:s)	1:20	0:20
Time to flames on wall (min:s)	1:46	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.4	1.0
Ambient wind speed (m/s)	1.72	0.21
Ambient wind direction (°)	110	10
Ambient temperature (°C)	25.3	4.5



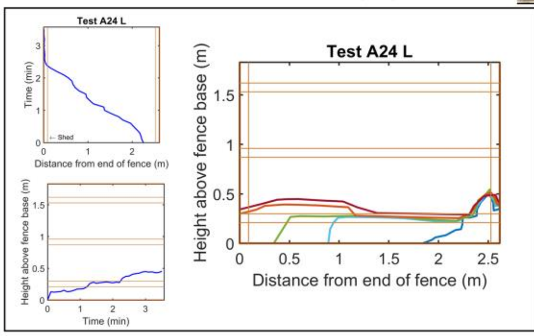
Test # A-24

Fence + Mulch

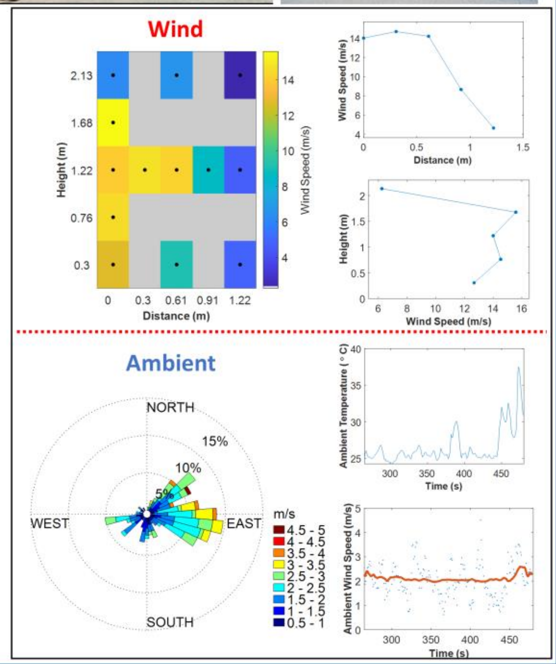
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

6/10/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:38	0:02
Time to end of fence (min:s)	2:30	0:10
Time to first spot (min:s)	1:48	0:20
Time to spot reaching wall (min:s)	2:38	0:20
Time to flames on wall (min:s)	2:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	2.06	0.22
Ambient wind direction (°)	103	10
Ambient temperature (°C)	26.5	4.5



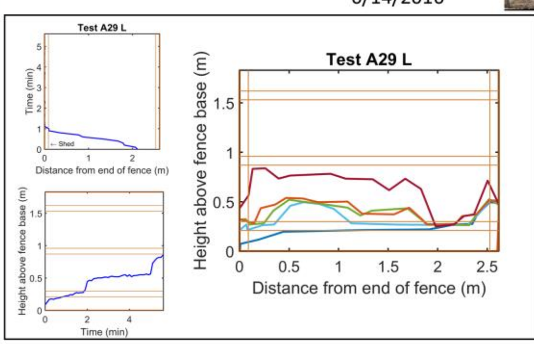
Test # A-29

Fence + Mulch

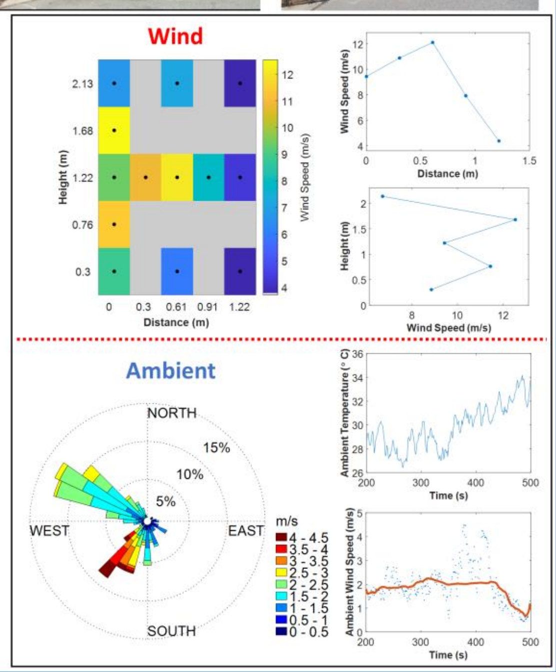
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

6/14/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:03	0:02
Time to end of fence (min:s)	1:15	0:10
Time to first spot (min:s)	2:11	0:20
Time to spot reaching wall (min:s)	3:14	0:20
Time to flames on wall (min:s)	4:06	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.6	0.8
Ambient wind speed (m/s)	1.98	0.22
Ambient wind direction (°)	256	10
Ambient temperature (°C)	29.8	4.5

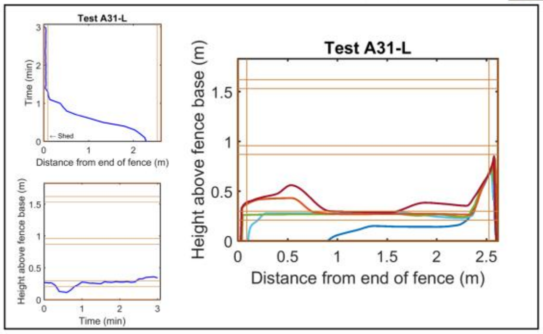


Test # A-31

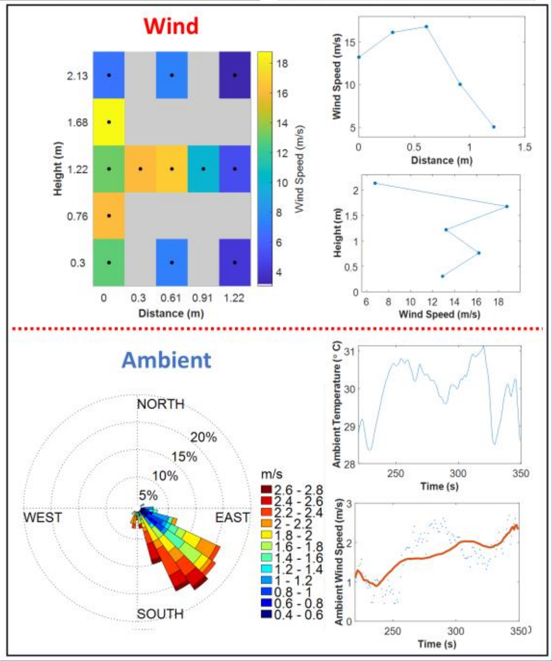
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

6/14/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	2:20	0:02
Time to end of fence (min:s)	1:25	0:10
Time to first spot (min:s)	0:54	0:20
Time to spot reaching wall (min:s)	1:24	0:20
Time to flames on wall (min:s)	1:55	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.3	1.1
Ambient wind speed (m/s)	1.68	0.23
Ambient wind direction (°)	138	10
Ambient temperature (°C)	30.0	4.5

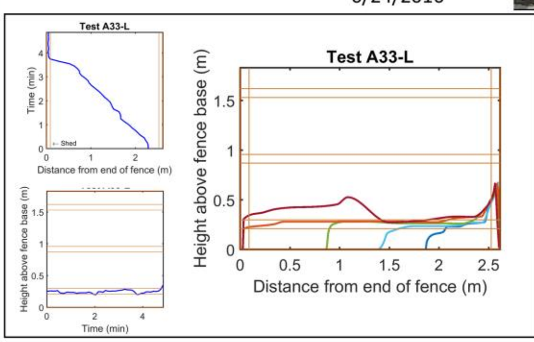


Test # A-33

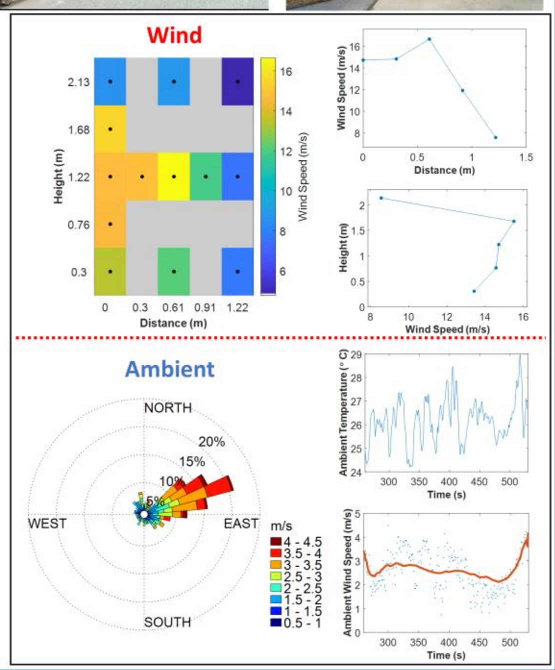
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

6/24/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:38	0:02
Time to end of fence (min:s)	3:45	0:10
Time to first spot (min:s)	1:08	0:20
Time to spot reaching wall (min:s)	2:21	0:20
Time to flames on wall (min:s)	3:25	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.6	1.0
Ambient wind speed (m/s)	2.56	0.22
Ambient wind direction (°)	70	10
Ambient temperature (°C)	26.2	4.5

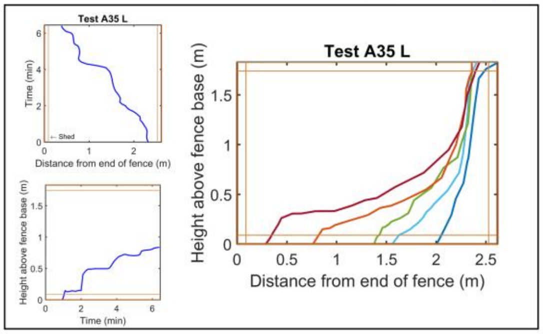


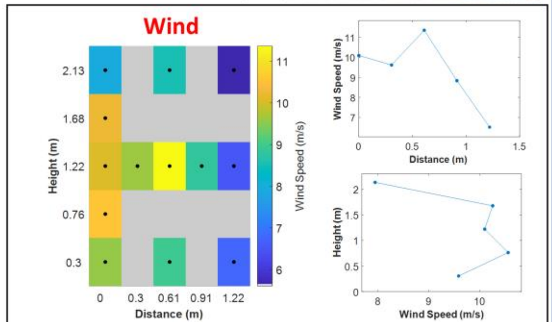
Test # A-35

Fence + Mulch

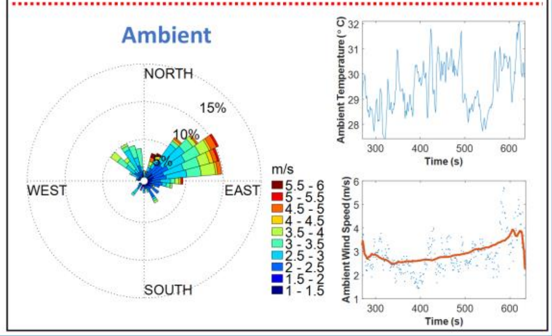

Vinyl Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

6/24/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:17	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	2:20	0:20
Time to spot reaching wall (min:s)	3:06	0:20
Time to flames on wall (min:s)	3:59	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	2.85	0.21
Ambient wind direction (°)	49	10
Ambient temperature (°C)	29.5	4.5

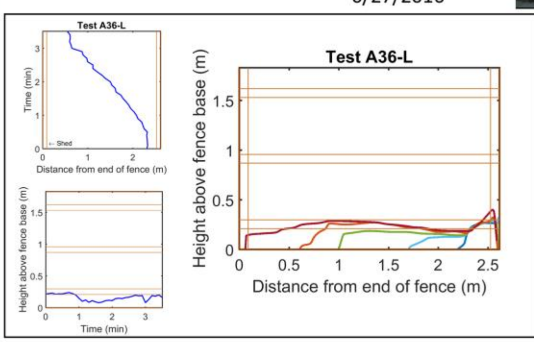


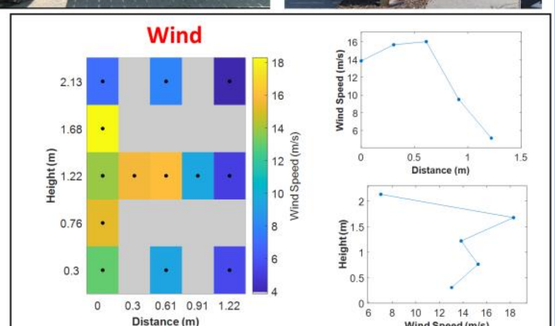
Test # A-36

Fence + Mulch

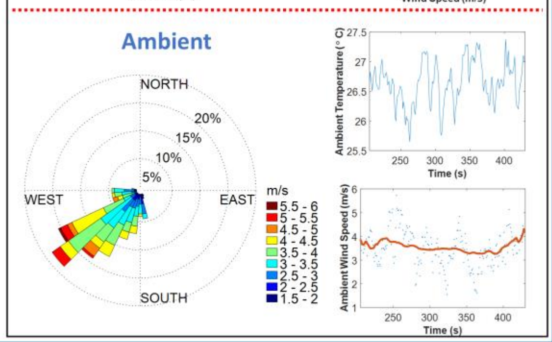

Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

6/27/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:52	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	0:28	0:20
Time to spot reaching wall (min:s)	1:31	0:20
Time to flames on wall (min:s)	2:51	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.1	1.1
Ambient wind speed (m/s)	3.49	0.22
Ambient wind direction (°)	222	10
Ambient temperature (°C)	26.6	4.5

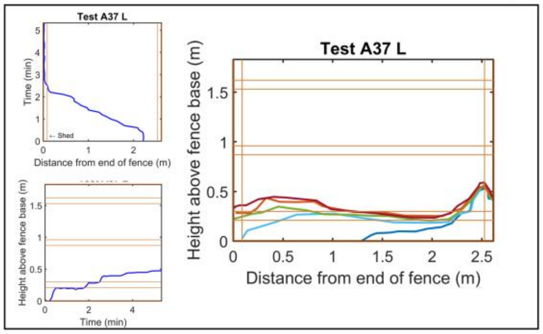


Test # A-37

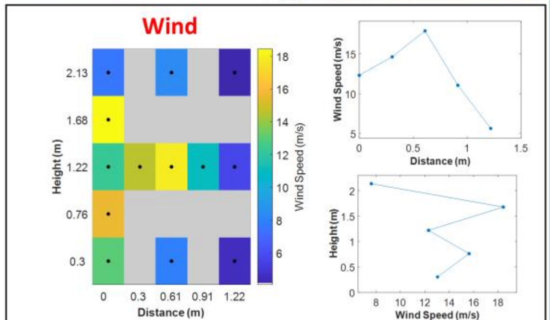
Fence + Mulch

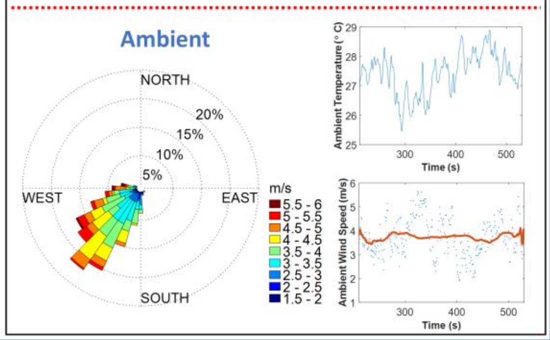
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

6/27/2016

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:22	0:02
Time to end of fence (min:s)	2:45	0:10
Time to first spot (min:s)	1:25	0:20
Time to spot reaching wall (min:s)	2:12	0:20
Time to flames on wall (min:s)	4:11	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.8	1.1
Ambient wind speed (m/s)	3.73	0.22
Ambient wind direction (°)	225	10
Ambient temperature (°C)	27.4	4.5



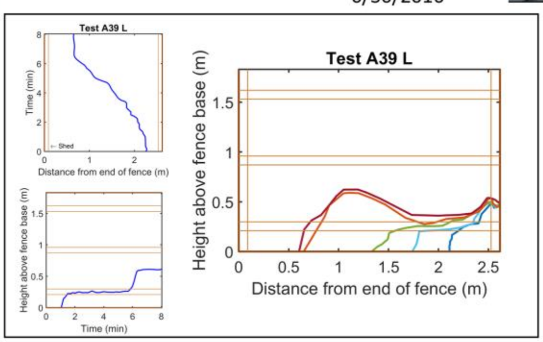


Test # A-39

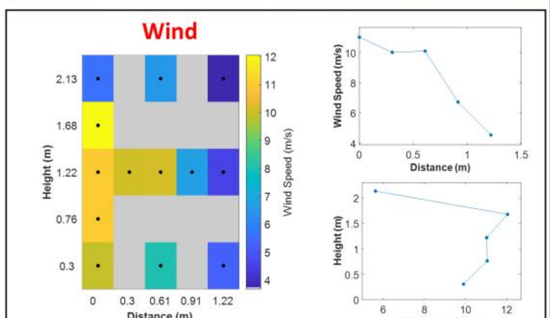
Fence + Mulch

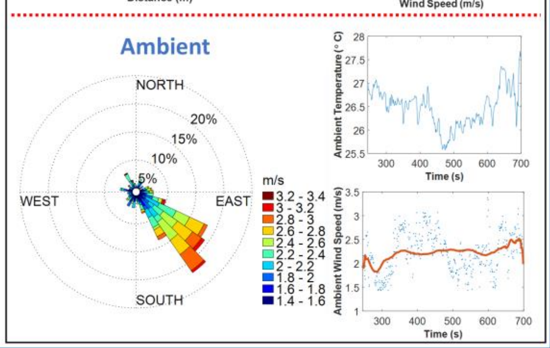
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

6/30/2016

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:08	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:40	0:20
Time to spot reaching wall (min:s)	4:59	0:20
Time to flames on wall (min:s)	6:02	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.0	0.8
Ambient wind speed (m/s)	2.22	0.20
Ambient wind direction (°)	134	10
Ambient temperature (°C)	26.5	4.5



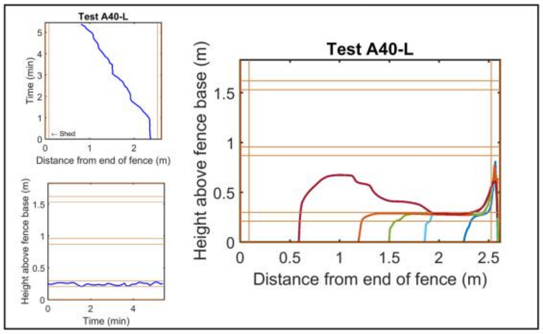


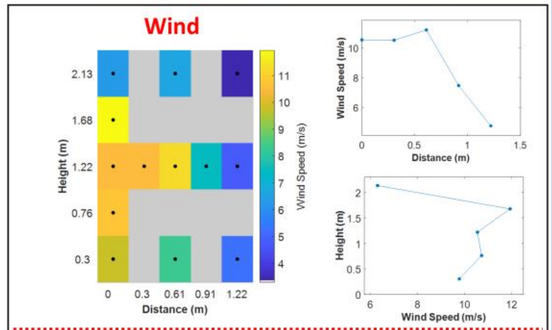
Test # A-40

Fence + Mulch

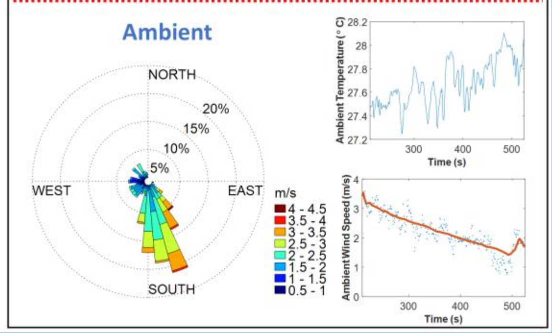
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

6/30/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:32	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:10	0:20
Time to spot reaching wall (min:s)	3:10	0:20
Time to flames on wall (min:s)	4:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.7	0.8
Ambient wind speed (m/s)	2.19	0.21
Ambient wind direction (°)	186	10
Ambient temperature (°C)	27.7	4.5

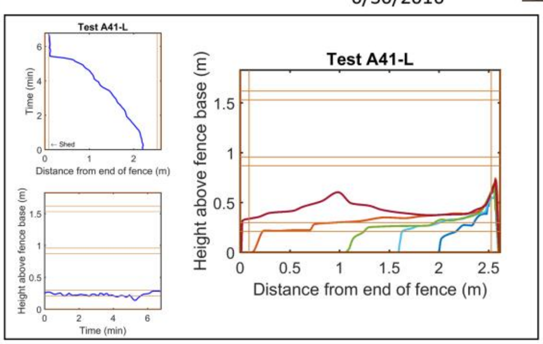


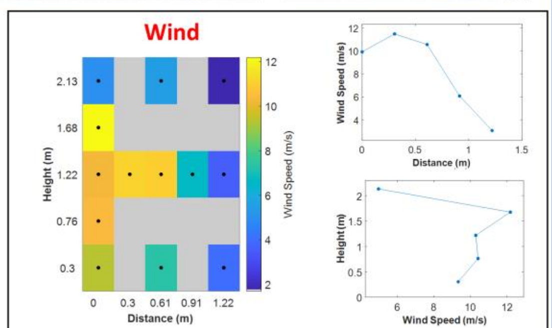
Test # A-41

Fence + Mulch

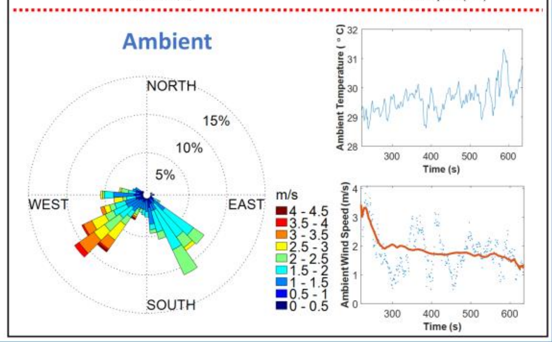
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

6/30/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:03	0:02
Time to end of fence (min:s)	5:20	0:10
Time to first spot (min:s)	2:56	0:20
Time to spot reaching wall (min:s)	2:56	0:20
Time to flames on wall (min:s)	6:05	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.6	0.7
Ambient wind speed (m/s)	1.81	0.21
Ambient wind direction (°)	200	10
Ambient temperature (°C)	29.6	4.5

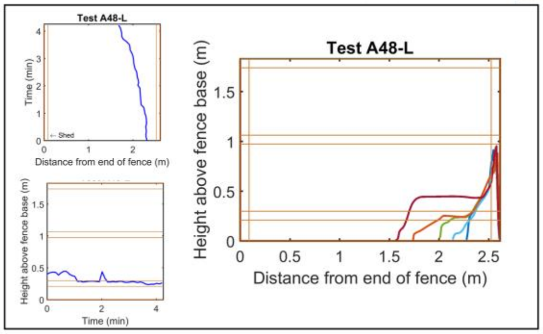


Test # A-48

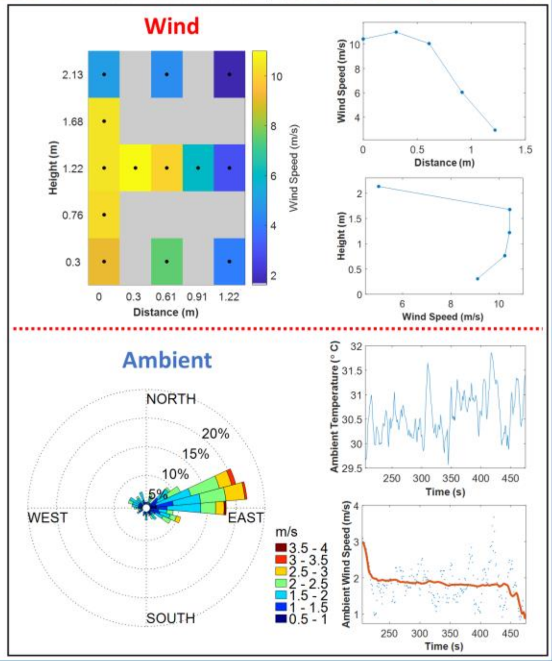
Fence + Mulch

Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

7/19/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:40	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	2:10	0:20
Time to spot reaching wall (min:s)	2:10	0:20
Time to flames on wall (min:s)	3:36	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.1	0.7
Ambient wind speed (m/s)	1.84	0.21
Ambient wind direction (°)	77	10
Ambient temperature (°C)	30.6	4.6

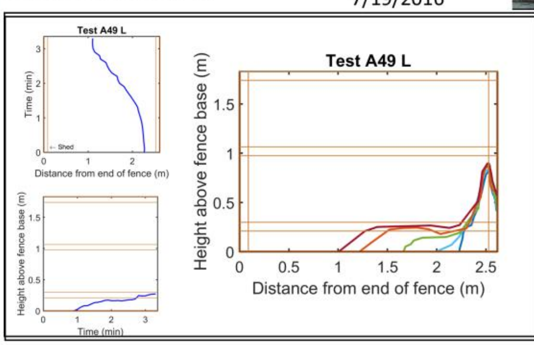


Test # A-49

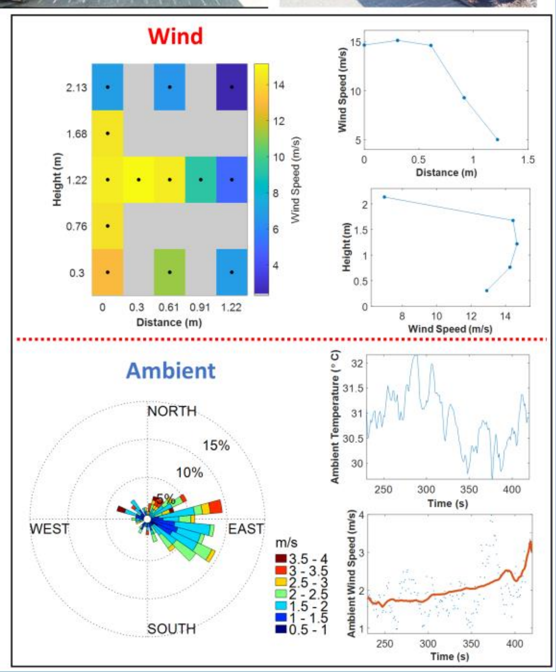
Fence + Mulch

Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

7/19/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:25	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:59	0:20
Time to spot reaching wall (min:s)	1:59	0:20
Time to flames on wall (min:s)	2:39	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	1.96	0.22
Ambient wind direction (°)	94	10
Ambient temperature (°C)	30.9	4.6

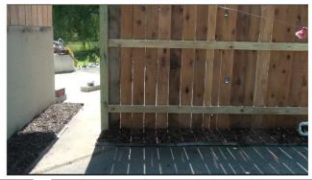


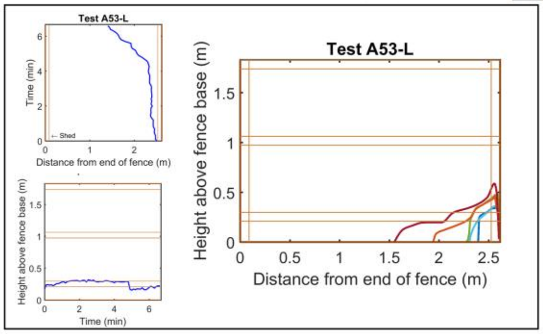
Test # A-53

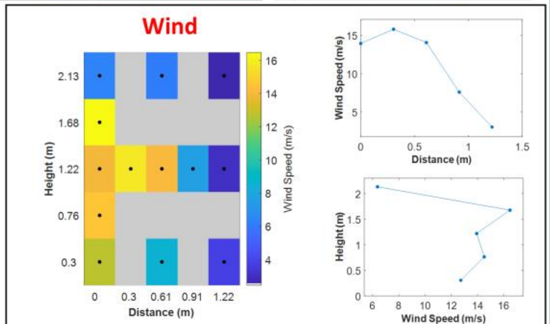
Fence + Mulch

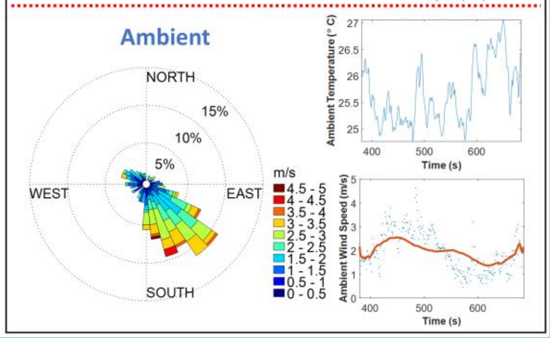
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

7/20/2016







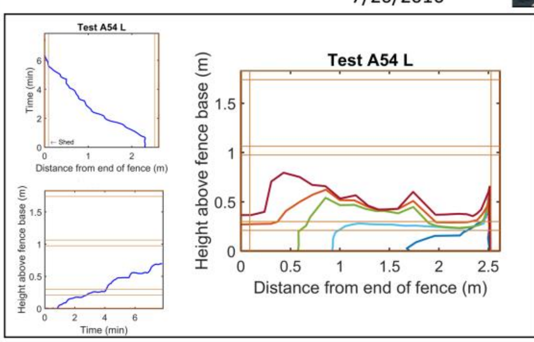
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:15	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	2:15	0:20
Time to spot reaching wall (min:s)	2:29	0:20
Time to flames on wall (min:s)	3:44	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.4	1.0
Ambient wind speed (m/s)	1.97	0.22
Ambient wind direction (°)	154	10
Ambient temperature (°C)	25.7	4.5

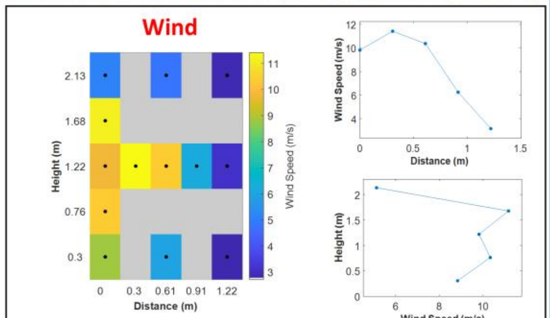
Test # A-54

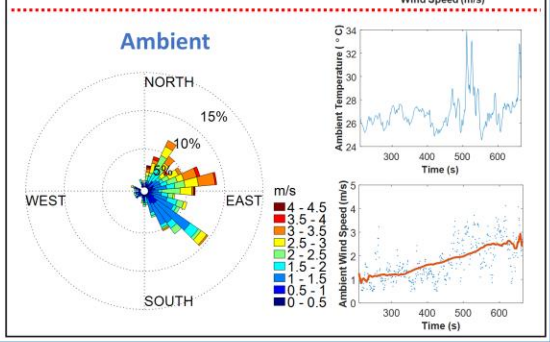
Fence + Mulch

Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

7/20/2016





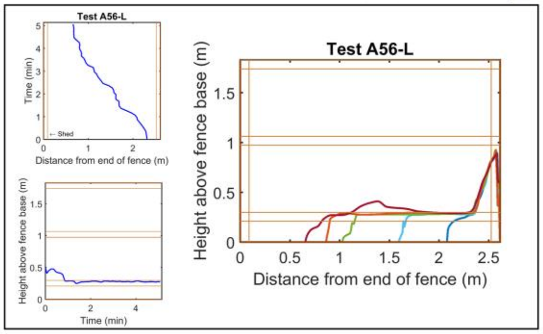
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:53	0:02
Time to end of fence (min:s)	6:20	0:20
Time to first spot (min:s)	5:00	0:20
Time to spot reaching wall (min:s)	6:34	0:20
Time to flames on wall (min:s)	7:03	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	1.77	0.21
Ambient wind direction (°)	92	10
Ambient temperature (°C)	26.9	4.5

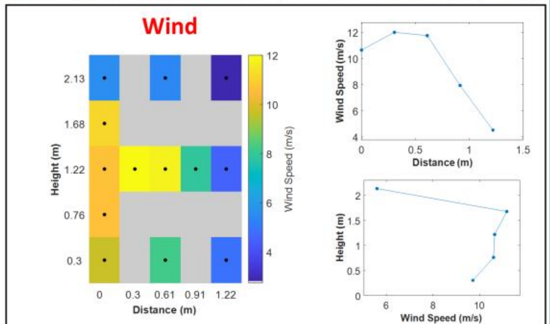
Test # A-56

Fence + Mulch

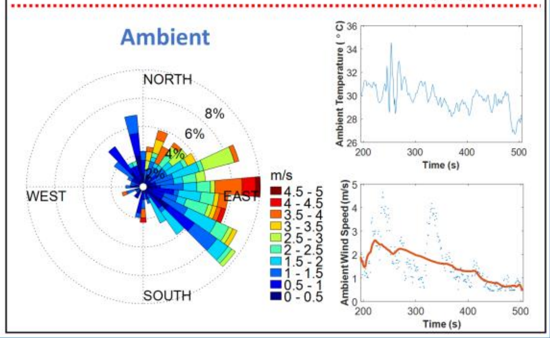
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

7/20/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:18	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	2:47	0:20
Time to spot reaching wall (min:s)	3:32	0:20
Time to flames on wall (min:s)	4:08	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.5	0.7
Ambient wind speed (m/s)	1.60	0.23
Ambient wind direction (°)	79	10
Ambient temperature (°C)	29.8	4.5

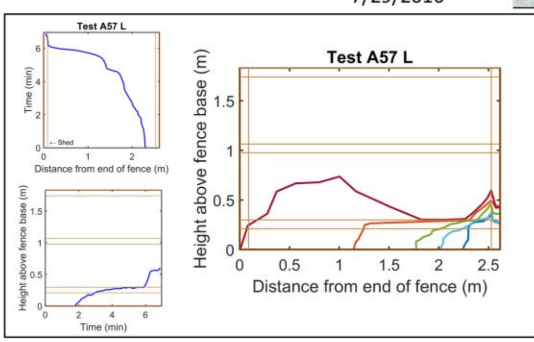


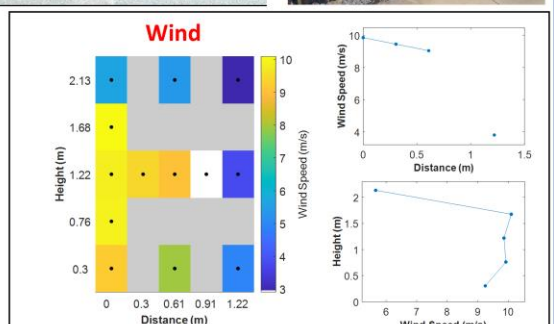
Test # A-57

Fence + Mulch

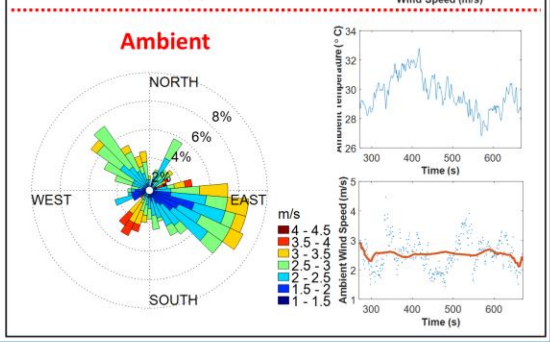
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

7/29/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:53	0:02
Time to end of fence (min:s)	6:15	0:10
Time to first spot (min:s)	2:21	0:20
Time to spot reaching wall (min:s)	3:27	0:20
Time to flames on wall (min:s)	4:14	0:06
Mean wind sp. 4 ctr. probes (m/s)	9.8	0.7
Ambient wind speed (m/s)	2.53	0.21
Ambient wind direction (°)	115	10
Ambient temperature (°C)	29.7	4.5

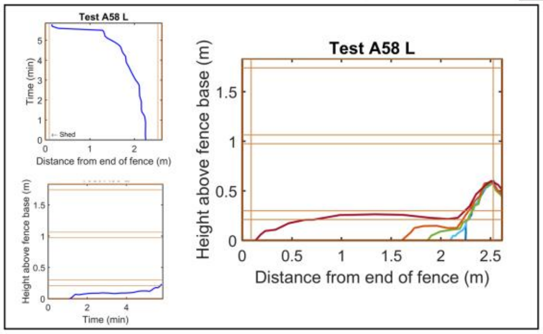


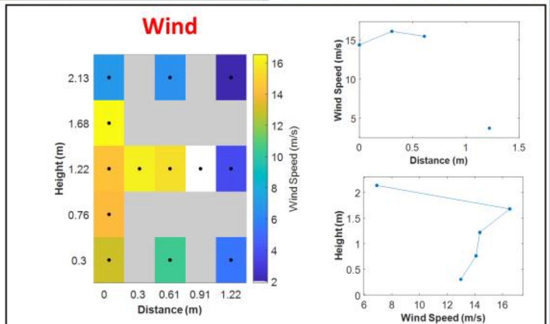
Test # A-58

Fence + Mulch

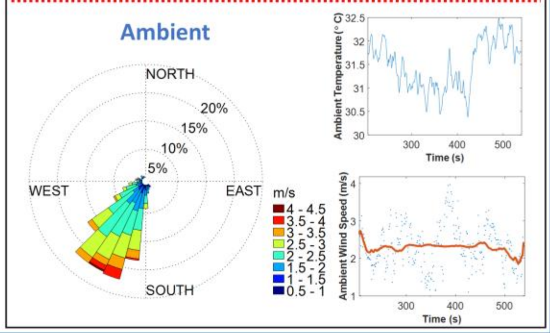
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

7/29/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:47	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:29	0:20
Time to spot reaching wall (min:s)	1:29	0:20
Time to flames on wall (min:s)	1:51	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.5	1.0
Ambient wind speed (m/s)	2.31	0.21
Ambient wind direction (°)	214	10
Ambient temperature (°C)	31.5	4.6

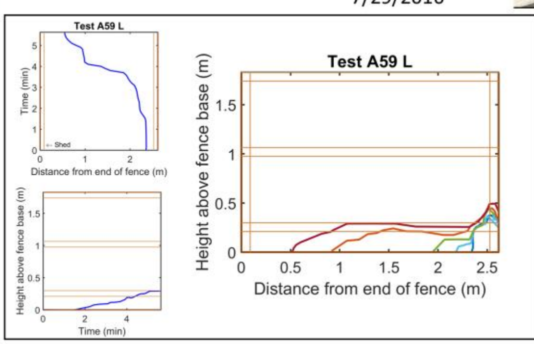


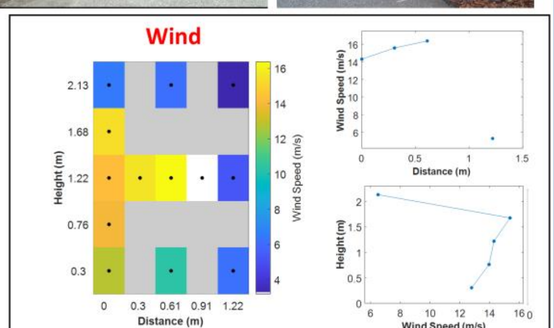
Test # A-59

Fence + Mulch

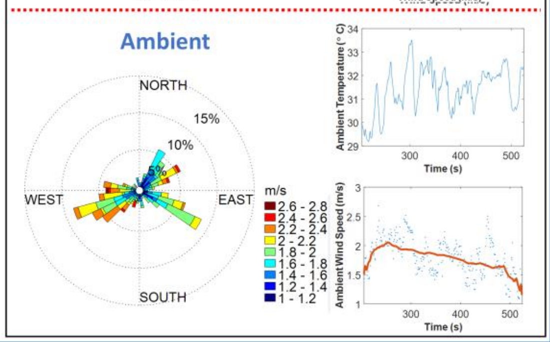
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

7/29/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:32	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:59	0:20
Time to spot reaching wall (min:s)	1:59	0:20
Time to flames on wall (min:s)	3:56	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.1	1.0
Ambient wind speed (m/s)	1.81	0.20
Ambient wind direction (°)	169	10
Ambient temperature (°C)	31.4	4.6

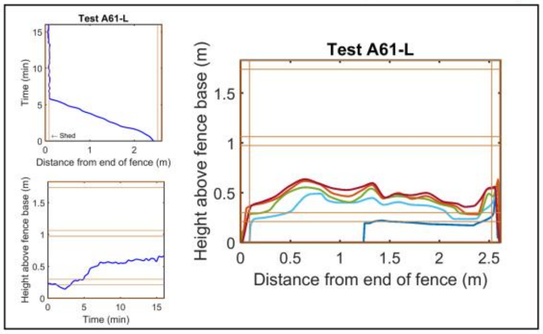


Test # A-61

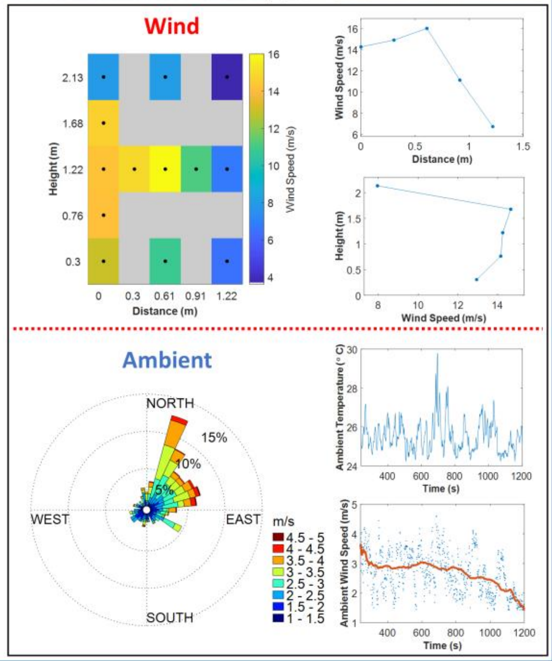
Fence + Mulch

Western Red Cedar Privacy Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

8/2/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	16:09	0:02
Time to end of fence (min:s)	5:45	0:02
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	14.0	1.0
Ambient wind speed (m/s)	2.68	0.21
Ambient wind direction (°)	52	10
Ambient temperature (°C)	25.5	4.5

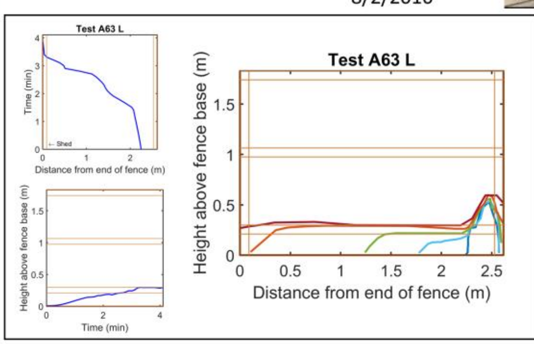


Test # A-63

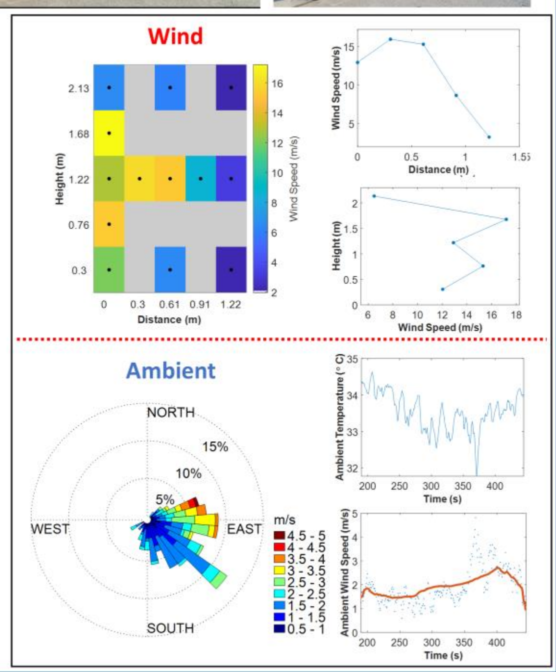
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

8/2/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:17	0:02
Time to end of fence (min:s)	3:20	0:10
Time to first spot (min:s)	1:11	0:20
Time to spot reaching wall (min:s)	1:44	0:20
Time to flames on wall (min:s)	2:31	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.4	1.0
Ambient wind speed (m/s)	1.93	0.22
Ambient wind direction (°)	123	10
Ambient temperature (°C)	33.5	4.6

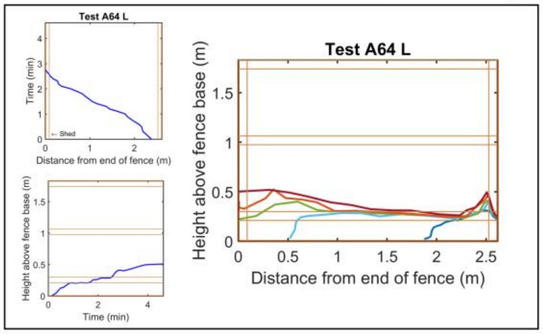


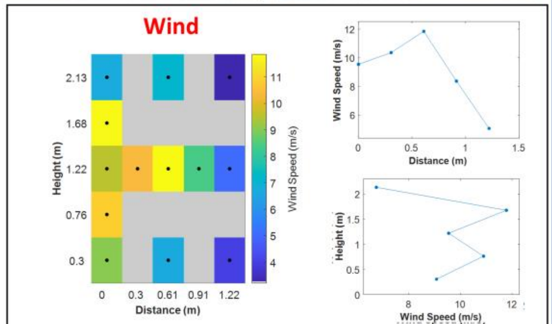
Test # A-64

Fence + Mulch

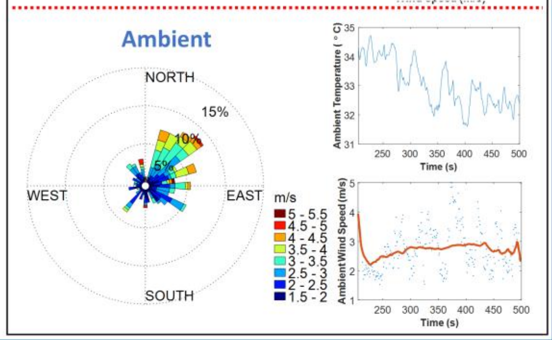
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

8/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:58	0:02
Time to end of fence (min:s)	2:40	0:10
Time to first spot (min:s)	2:44	0:20
Time to spot reaching wall (min:s)	3:50	0:20
Time to flames on wall (min:s)	4:17	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.3	0.7
Ambient wind speed (m/s)	2.75	0.22
Ambient wind direction (°)	60	10
Ambient temperature (°C)	33.1	4.6

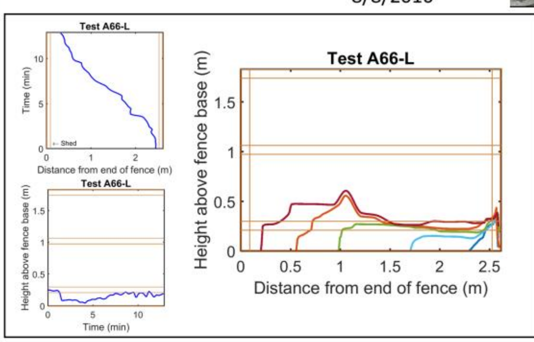


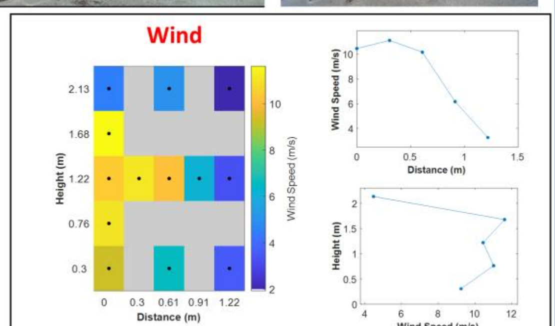
Test # A-66

Fence + Mulch

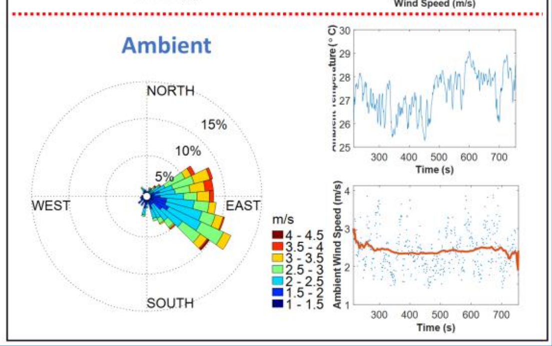
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

8/8/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	13:17	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	8:02	0:20
Time to spot reaching wall (min:s)	9:20	0:20
Time to flames on wall (min:s)	10:13	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.6	0.7
Ambient wind speed (m/s)	2.42	0.21
Ambient wind direction (°)	105	10
Ambient temperature (°C)	27.3	4.5

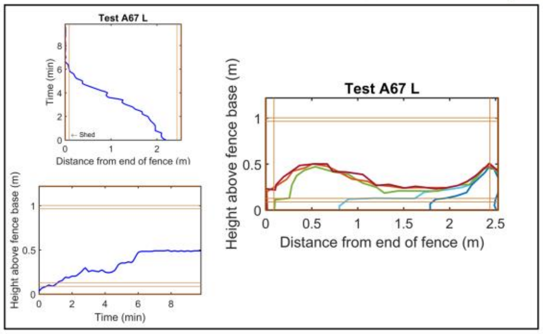


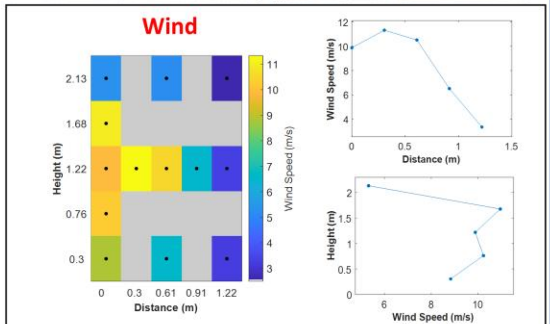
Test # A-67

Fence + Mulch

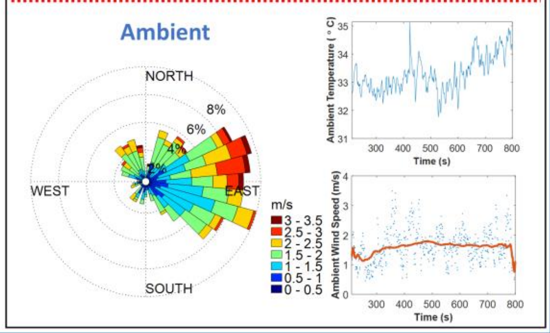
Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

8/8/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	9:53	0:02
Time to end of fence (min:s)	6:30	0:10
Time to first spot (min:s)	7:38	0:20
Time to spot reaching wall (min:s)	8:04	0:20
Time to flames on wall (min:s)	8:55	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.0	0.7
Ambient wind speed (m/s)	1.61	0.21
Ambient wind direction (°)	79	10
Ambient temperature (°C)	33.3	4.6

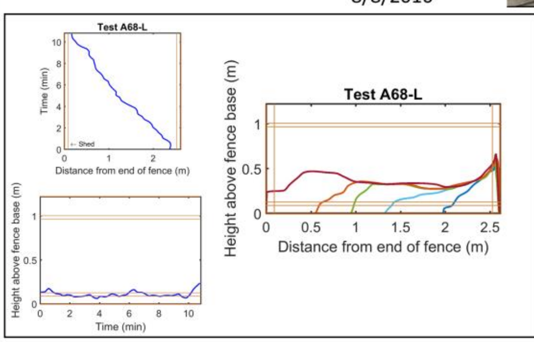


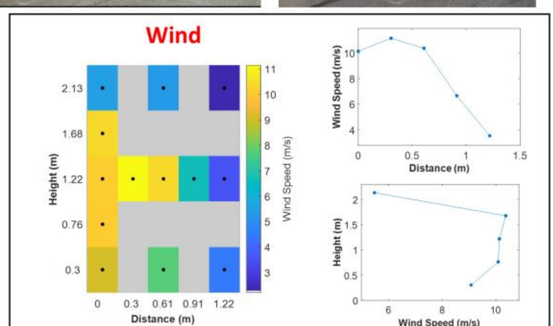
Test # A-68

Fence + Mulch

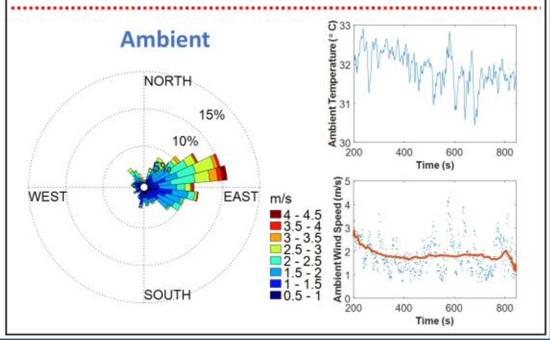
Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)

8/8/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:52	0:02
Time to end of fence (min:s)	10:00	0:30
Time to first spot (min:s)	3:11	0:20
Time to spot reaching wall (min:s)	3:11	0:20
Time to flames on wall (min:s)	4:23	0:06
Mean wind sp. 4 ctr. probes (m/s)	9.9	0.7
Ambient wind speed (m/s)	1.82	0.21
Ambient wind direction (°)	83	10
Ambient temperature (°C)	31.9	4.6

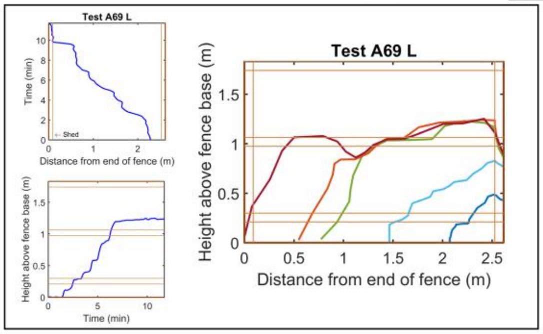


Test # A-69

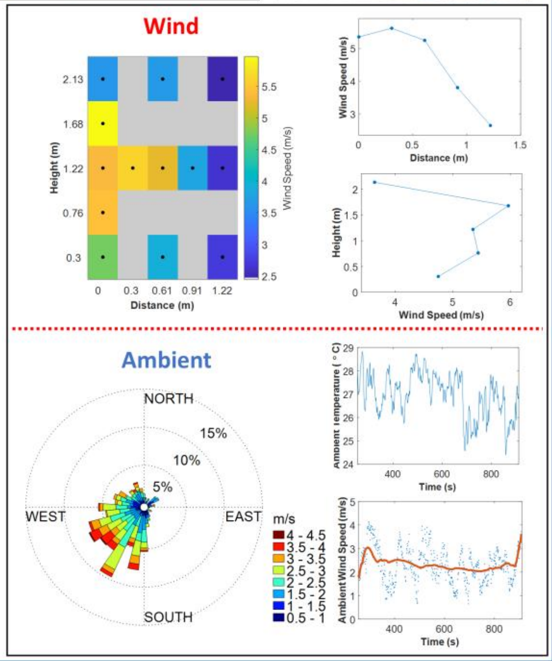
Fence + Mulch

Western Red Cedar Privacy Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

8/23/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:41	0:02
Time to end of fence (min:s)	9:50	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	11:17	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.4	0.4
Ambient wind speed (m/s)	2.29	0.21
Ambient wind direction (°)	239	10
Ambient temperature (°C)	27.0	4.5

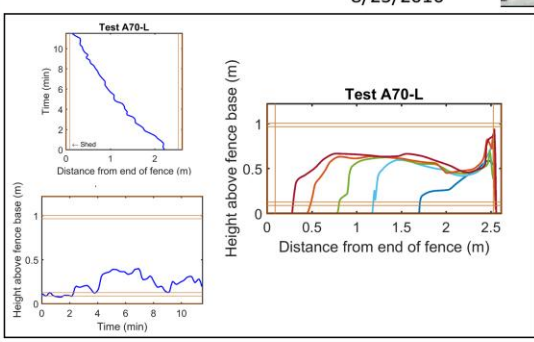


Test # A-70

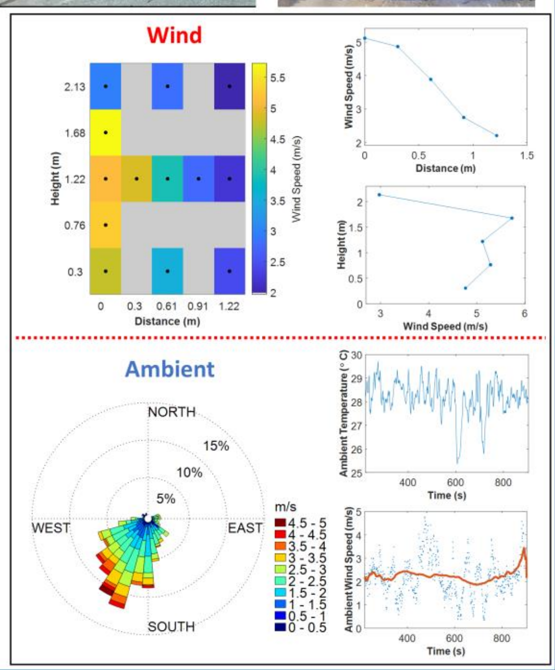
Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

8/23/2016



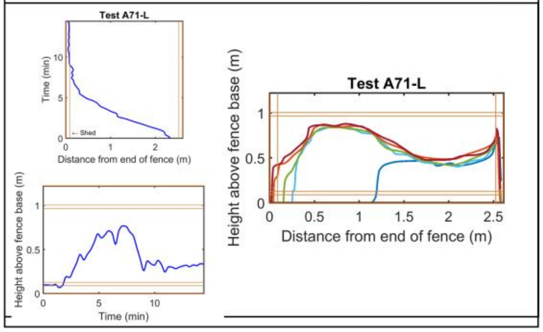
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:31	0:02
Time to end of fence (min:s)	11:20	0:20
Time to first spot (min:s)	5:32	0:20
Time to spot reaching wall (min:s)	5:32	0:20
Time to flames on wall (min:s)	8:12	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.2	0.4
Ambient wind speed (m/s)	2.21	0.21
Ambient wind direction (°)	201	10
Ambient temperature (°C)	28.2	4.5

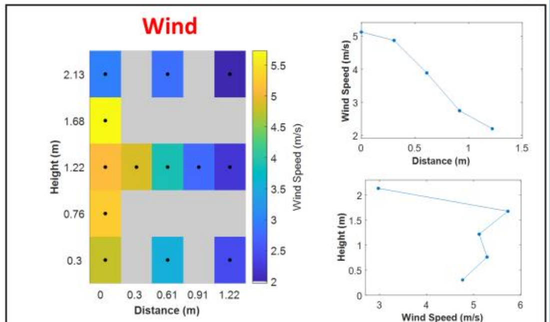


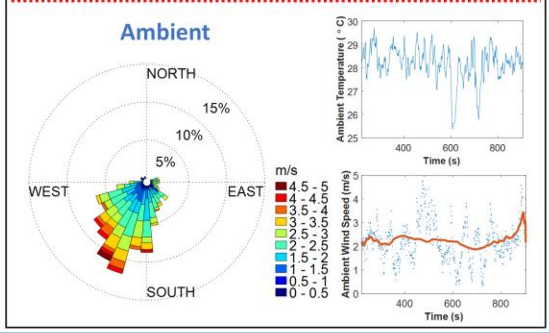
Test # A-71

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.3 m (1 ft)
8/23/2016





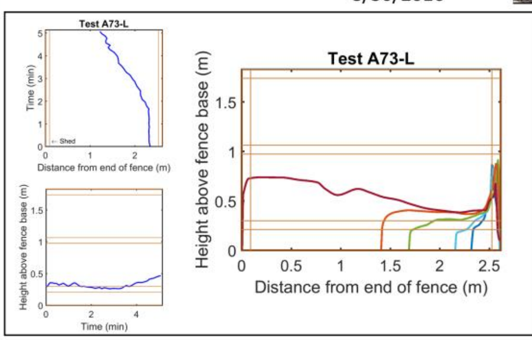


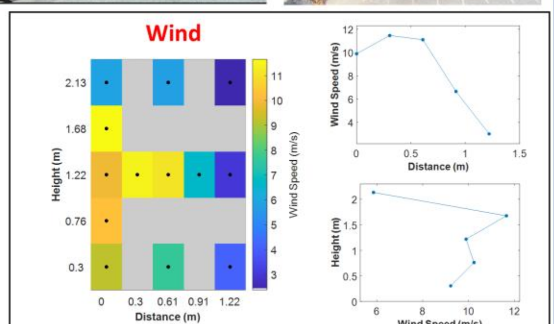
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:28	0:02
Time to end of fence (min:s)	8:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.1	0.4
Ambient wind speed (m/s)	2.11	0.21
Ambient wind direction (°)	220	10
Ambient temperature (°C)	28.8	4.5

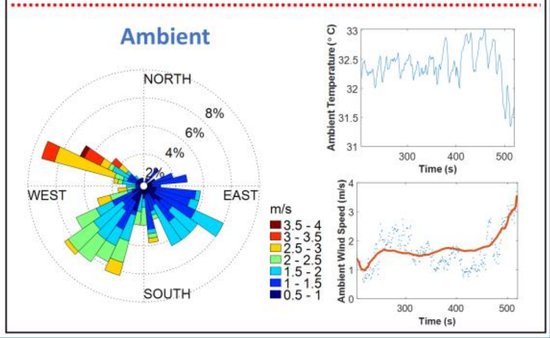
Test # A-73

Fence + Mulch

Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 0.3 m (1 ft)
8/30/2016







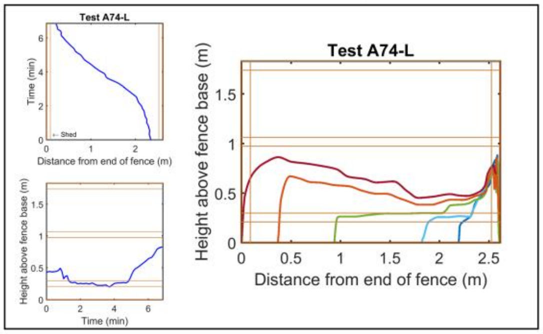
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:54	0:02
Time to end of fence (min:s)	5:50	0:10
Time to first spot (min:s)	1:49	0:20
Time to spot reaching wall (min:s)	3:04	0:20
Time to flames on wall (min:s)	3:52	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.3	0.7
Ambient wind speed (m/s)	1.66	0.21
Ambient wind direction (°)	195	10
Ambient temperature (°C)	32.4	4.6

Test # A-74

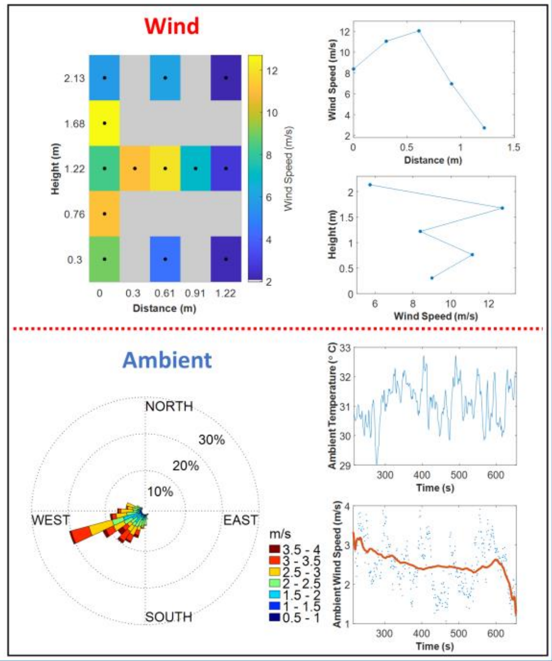
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

8/30/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:31	0:02
Time to end of fence (min:s)	6:50	0:20
Time to first spot (min:s)	2:04	0:20
Time to spot reaching wall (min:s)	2:04	0:20
Time to flames on wall (min:s)	4:55	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.3	0.7
Ambient wind speed (m/s)	2.51	0.21
Ambient wind direction (°)	238	10
Ambient temperature (°C)	31.1	4.6

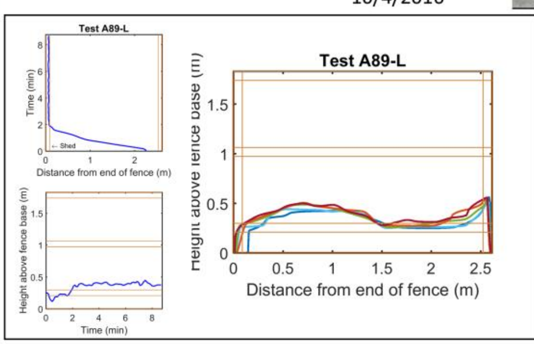


Test # A-89

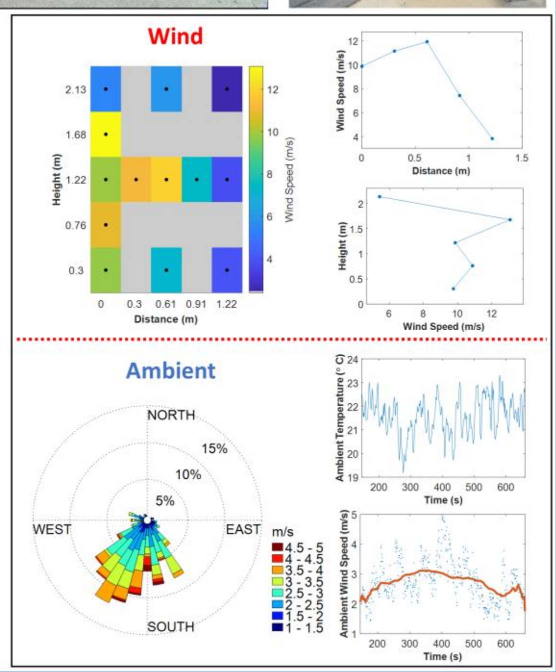
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

10/4/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:47	0:02
Time to end of fence (min:s)	2:00	0:10
Time to first spot (min:s)	6:22	0:20
Time to spot reaching wall (min:s)	6:22	0:20
Time to flames on wall (min:s)	7:33	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	2.77	0.21
Ambient wind direction (°)	196	10
Ambient temperature (°C)	21.6	4.4

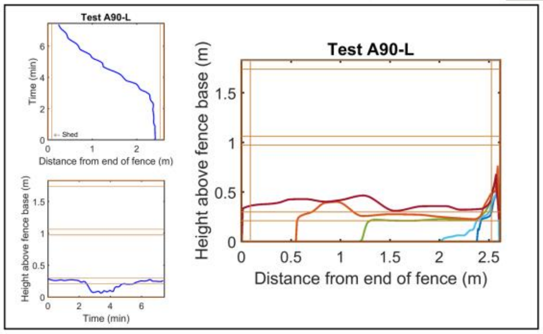


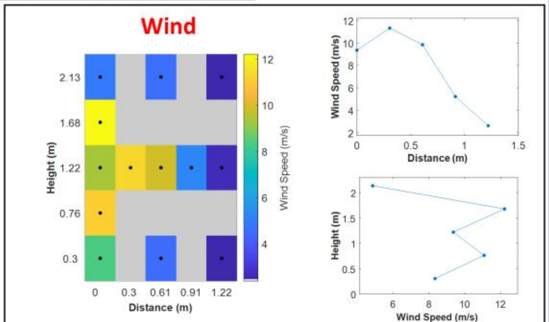
Test # A-90

Fence + Mulch

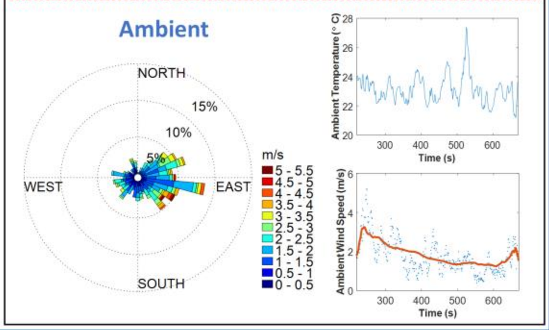
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

10/4/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:45	0:02
Time to end of fence (min:s)	7:00	0:20
Time to first spot (min:s)	1:50	0:20
Time to spot reaching wall (min:s)	3:10	0:20
Time to flames on wall (min:s)	4:09	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.2	0.7
Ambient wind speed (m/s)	1.77	0.22
Ambient wind direction (°)	113	10
Ambient temperature (°C)	23.1	4.4

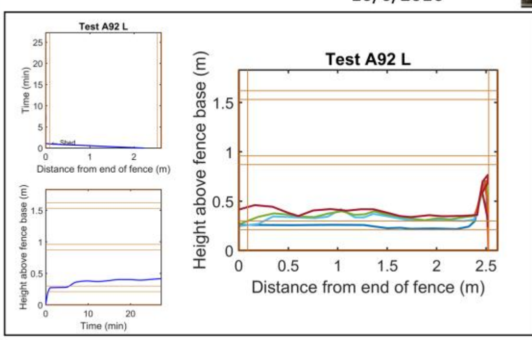


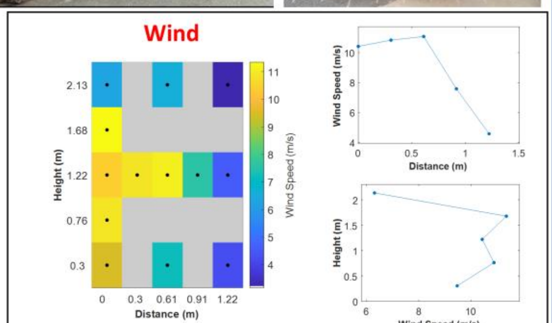
Test # A-92

Fence + Mulch

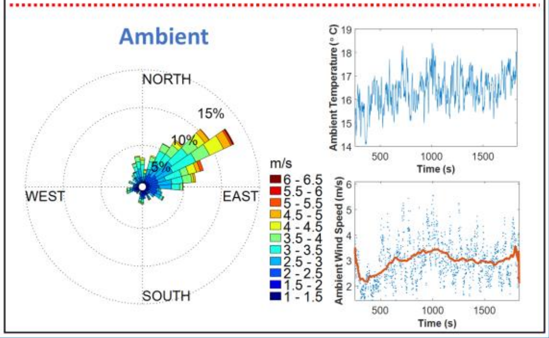
Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Medium
Sep. distance: 0.9 m (3 ft)

10/6/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	27:39	0:02
Time to end of fence (min:s)	1:00	0:10
Time to first spot (min:s)	13:42	0:20
Time to spot reaching wall (min:s)	16:53	0:20
Time to flames on wall (min:s)	26:21	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.5	0.7
Ambient wind speed (m/s)	2.96	0.20
Ambient wind direction (°)	52	10
Ambient temperature (°C)	16.4	4.4

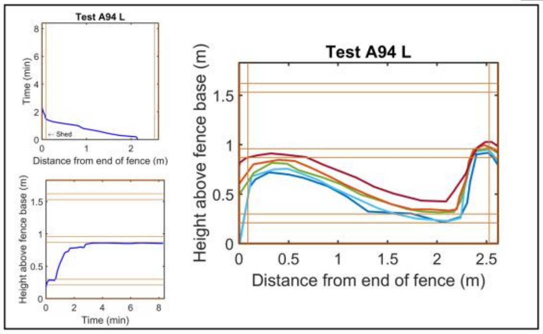


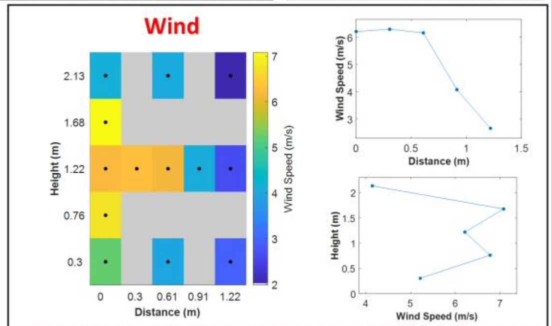
Test # A-94

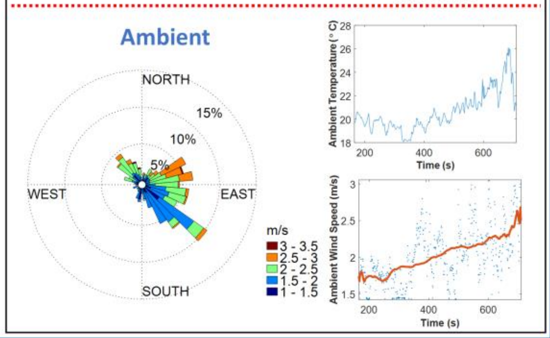
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

10/6/2016





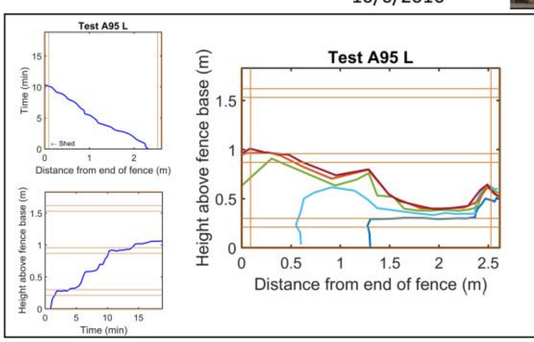
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	9:09	0:02
Time to end of fence (min:s)	2:10	0:10
Time to first spot (min:s)	3:51	0:20
Time to spot reaching wall (min:s)	5:03	0:20
Time to flames on wall (min:s)	5:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.4
Ambient wind speed (m/s)	2.02	0.20
Ambient wind direction (°)	95	10
Ambient temperature (°C)	20.6	4.4

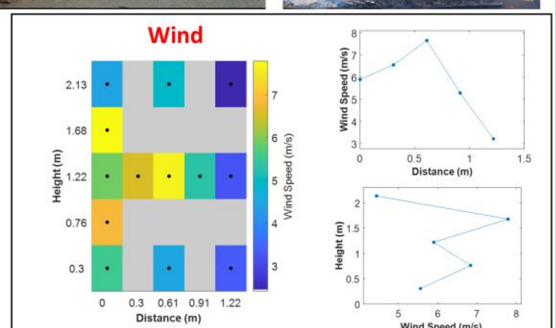
Test # A-95

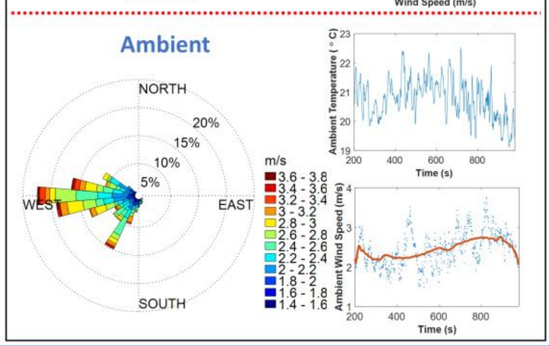
Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

10/6/2016





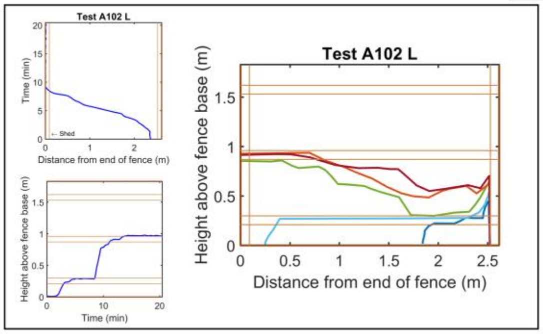
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	19:38	0:02
Time to end of fence (min:s)	10:40	0:20
Time to first spot (min:s)	14:18	0:20
Time to spot reaching wall (min:s)	14:18	0:20
Time to flames on wall (min:s)	18:44	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.5	0.5
Ambient wind speed (m/s)	2.45	0.20
Ambient wind direction (°)	252	10
Ambient temperature (°C)	20.8	4.4

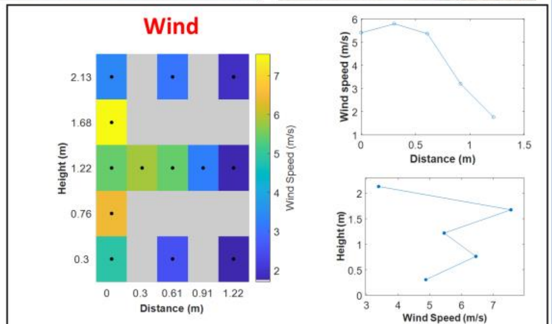
Test # A-102

Fence + Mulch

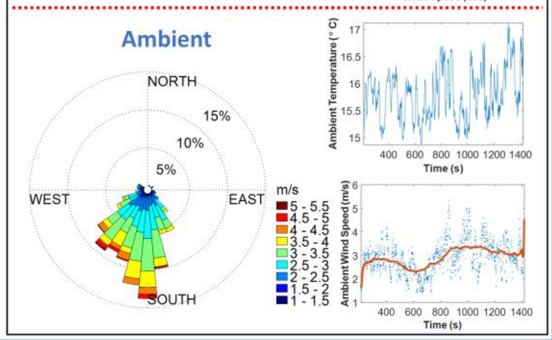
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

11/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	20:15	0:01
Time to end of fence (min:s)	9:05	0:20
Time to first spot (min:s)	12:33	0:20
Time to spot reaching wall (min:s)	12:33	0:20
Time to flames on wall (min:s)	17:19	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.1	0.4
Ambient wind speed (m/s)	2.91	0.20
Ambient wind direction (°)	194	10
Ambient temperature (°C)	15.8	4.4

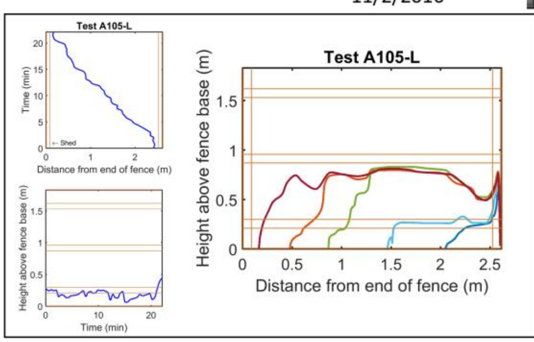


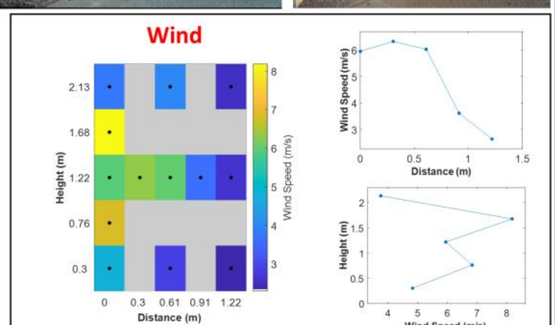
Test # A-105

Fence + Mulch

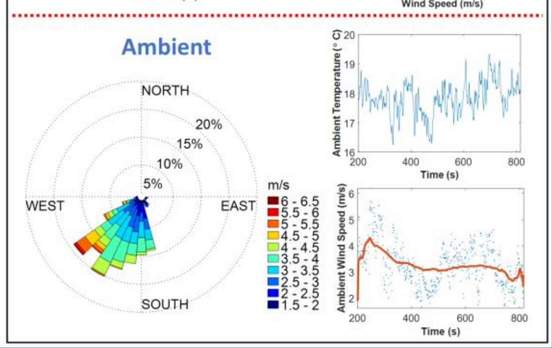
Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.3 m (1 ft)

11/2/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	22:07	0:02
Time to end of fence (min:s)	21:00	0:30
Time to first spot (min:s)	21:07	0:20
Time to spot reaching wall (min:s)	21:07	0:20
Time to flames on wall (min:s)	21:36	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	2.71	0.20
Ambient wind direction (°)	200	10
Ambient temperature (°C)	24.1	4.5

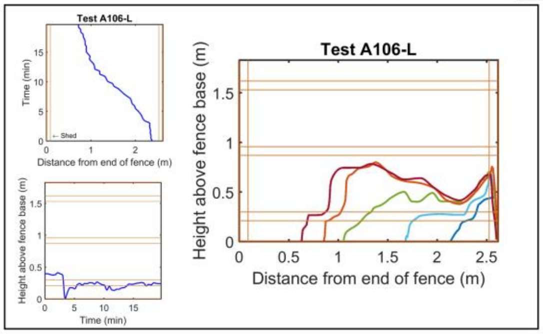


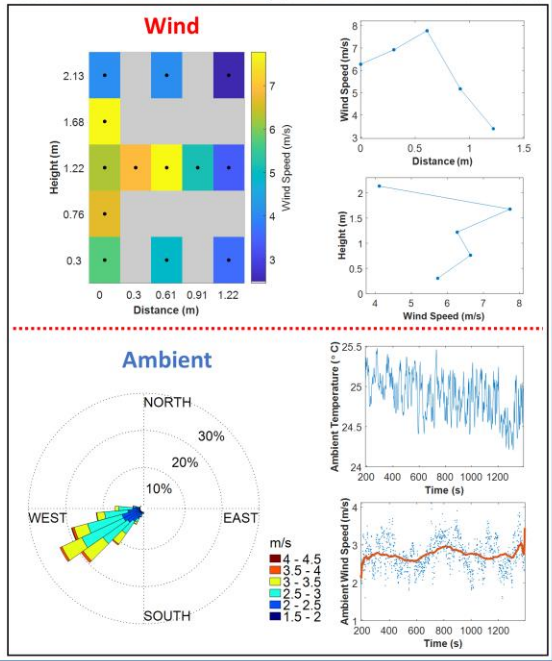
Test # A-106

Fence + Mulch

Western Red Cedar Privacy Fence +
Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

11/2/2016



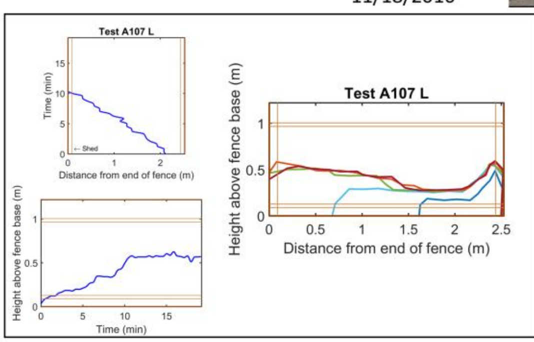
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	20:12	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	16:48	0:20
Time to spot reaching wall (min:s)	16:48	0:20
Time to flames on wall (min:s)	17:44	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.6	0.5
Ambient wind speed (m/s)	2.74	0.20
Ambient wind direction (°)	241	10
Ambient temperature (°C)	24.9	4.5

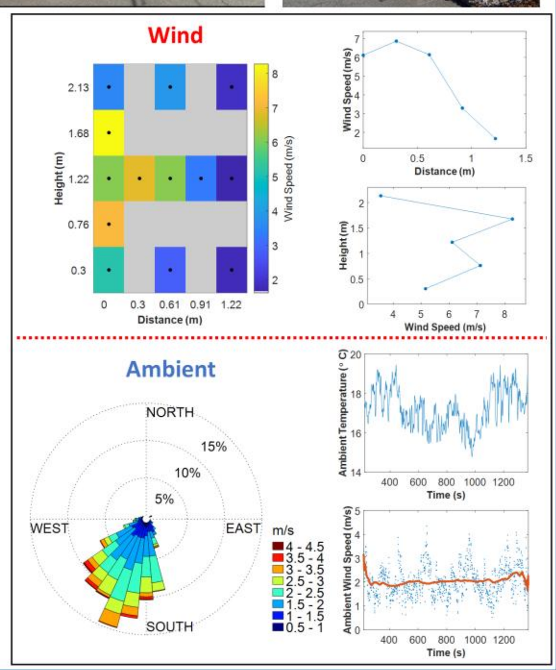
Test # A-107

Fence + Mulch

Redwood Lattice Fence + Pine Bark Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

11/18/2016



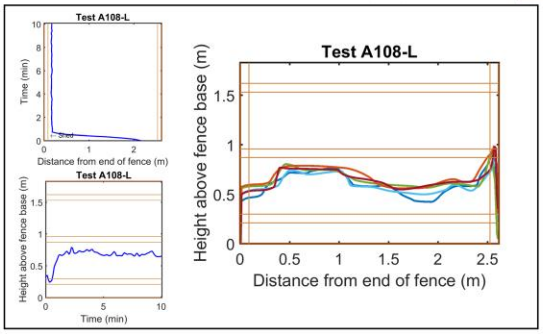
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	19:14	0:02
Time to end of fence (min:s)	10:40	0:20
Time to first spot (min:s)	2:38	0:20
Time to spot reaching wall (min:s)	14:33	0:20
Time to flames on wall (min:s)	17:33	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.7	0.5
Ambient wind speed (m/s)	2.03	0.20
Ambient wind direction (°)	202	10
Ambient temperature (°C)	17.2	4.4

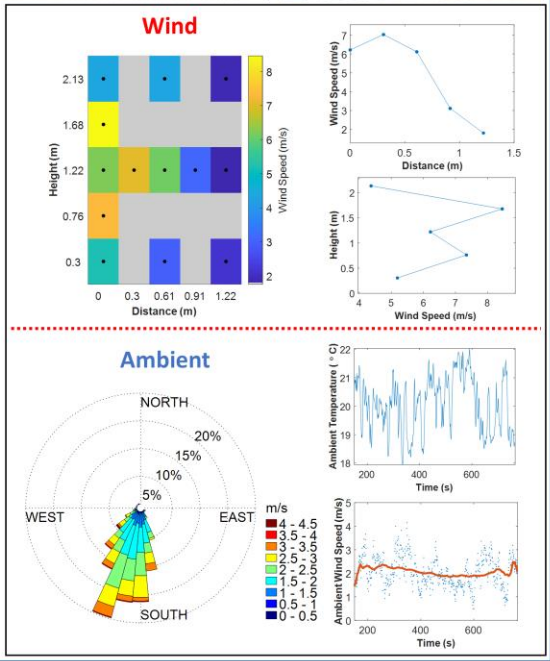
Test # A-108

Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

11/18/2016





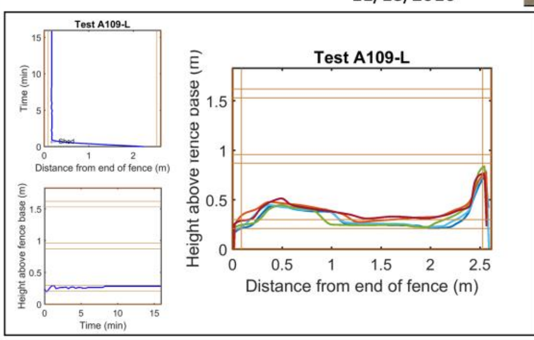
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:21	0:02
Time to end of fence (min:s)	1:00	0:20
Time to first spot (min:s)	4:29	0:20
Time to spot reaching wall (min:s)	4:29	0:20
Time to flames on wall (min:s)	10:03	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.8	0.5
Ambient wind speed (m/s)	2.06	0.21
Ambient wind direction (°)	195	10
Ambient temperature (°C)	20.1	4.4

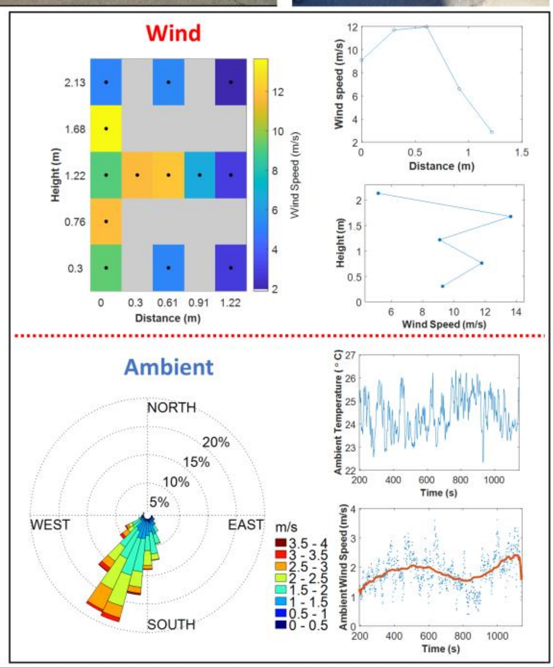
Test # A-109

Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

11/18/2016





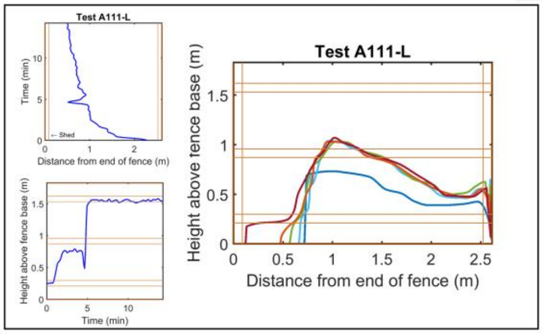
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	15:59	0:02
Time to end of fence (min:s)	1:30	0:30
Time to first spot (min:s)	3:03	0:20
Time to spot reaching wall (min:s)	4:03	0:20
Time to flames on wall (min:s)	15:52	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	1.85	0.20
Ambient wind direction (°)	198	10
Ambient temperature (°C)	24.4	4.5

Test # A-111

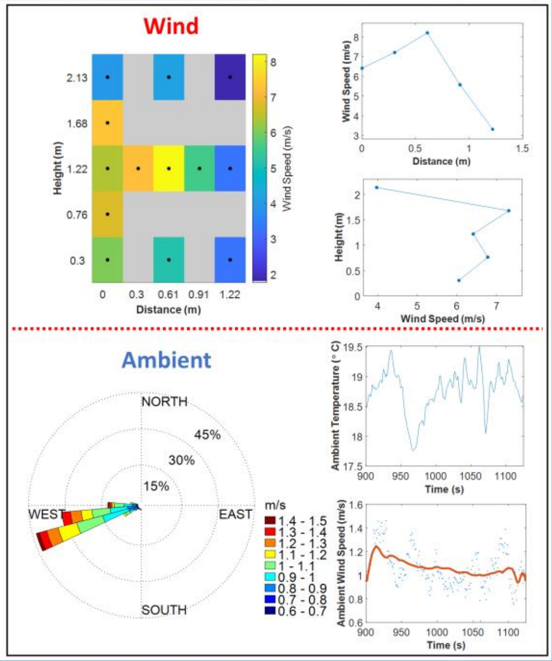
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

11/18/2016

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:50	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	6:31	0:20
Time to spot reaching wall (min:s)	13:35	0:20
Time to flames on wall (min:s)	13:59	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.6	0.5
Ambient wind speed (m/s)	1.06	0.20
Ambient wind direction (°)	255	10
Ambient temperature (°C)	18.8	4.4

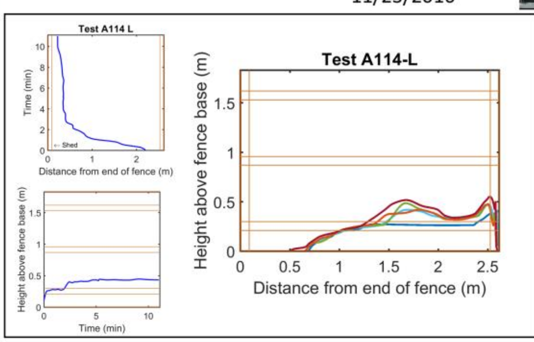


Test # A-114

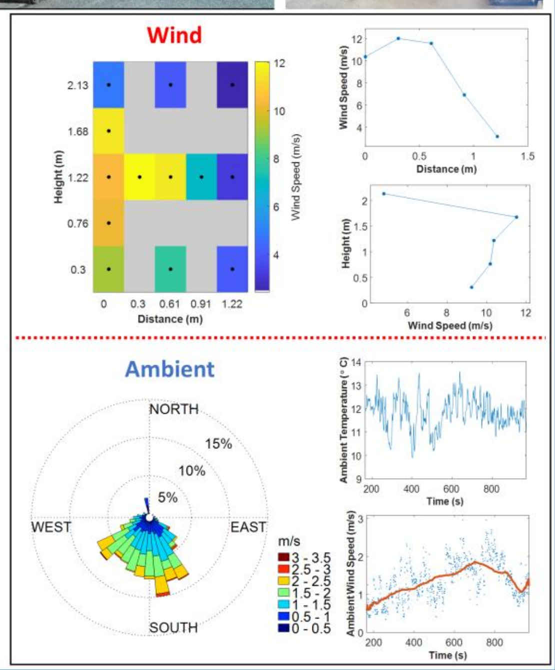
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Straw Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

11/23/2016

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	13:33	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:27	0:20
Time to spot reaching wall (min:s)	3:27	0:20
Time to flames on wall (min:s)	12:49	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.3	0.7
Ambient wind speed (m/s)	1.37	0.20
Ambient wind direction (°)	191	10
Ambient temperature (°C)	11.8	4.4

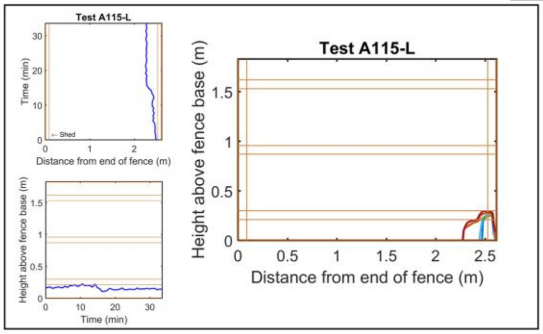


Test # A-115

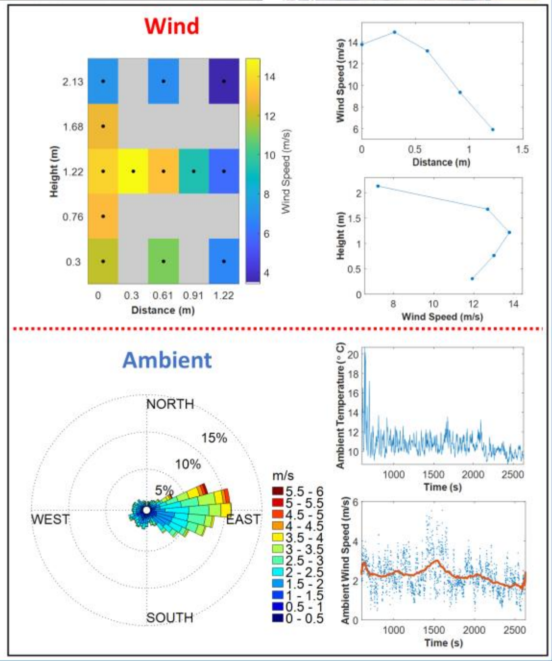
Fence + Mulch

Western Red Cedar Privacy Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)
Winds applied at 45 degree angle

12/7/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	34:06	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	12.8	0.9
Ambient wind speed (m/s)	2.25	0.20
Ambient wind direction (°)	105	10
Ambient temperature (°C)	10.7	4.4

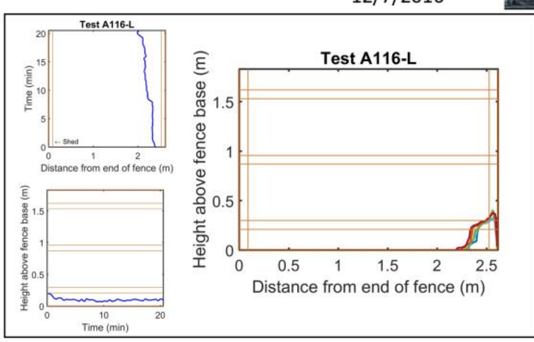


Test # A-116

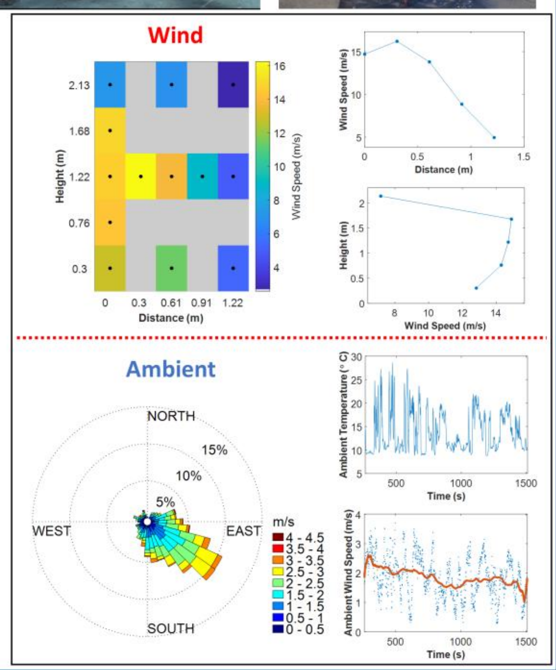
Fence + Mulch

Western Red Cedar Privacy Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)
Winds applied at 45 degree angle

12/7/2016



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	21:01	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	12:01	0:20
Time to spot reaching wall (min:s)	15:14	0:20
Time to flames on wall (min:s)	20:09	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.2	1.0
Ambient wind speed (m/s)	1.85	0.20
Ambient wind direction (°)	134	10
Ambient temperature (°C)	13.7	4.4

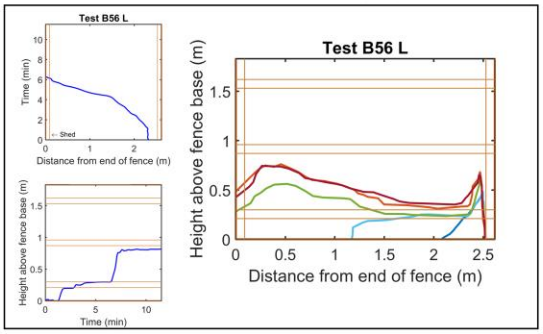


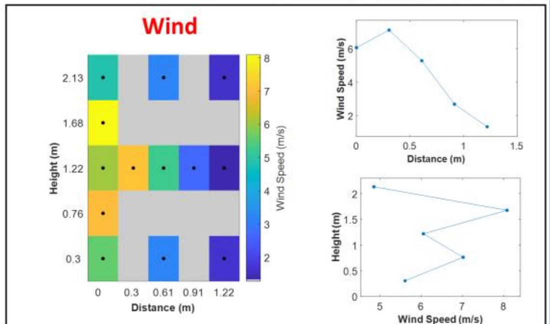
Test # B-56

Fence + Mulch

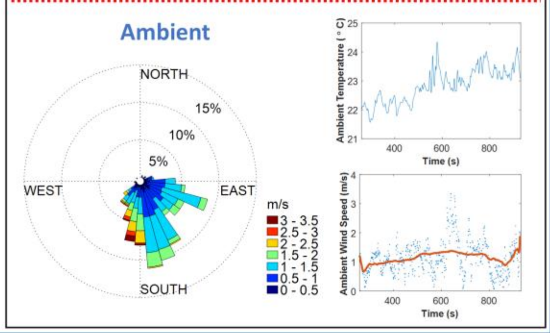
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

8/30/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:34	0:02
Time to end of fence (min:s)	6:10	0:20
Time to first spot (min:s)	4:56	0:20
Time to spot reaching wall (min:s)	9:05	0:20
Time to flames on wall (min:s)	10:23	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.7	0.5
Ambient wind speed (m/s)	1.14	0.20
Ambient wind direction (°)	153	10
Ambient temperature (°C)	22.8	4.4

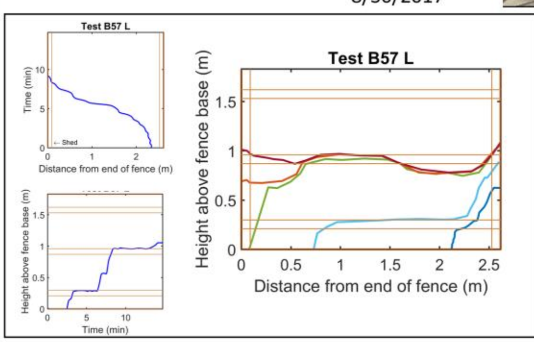


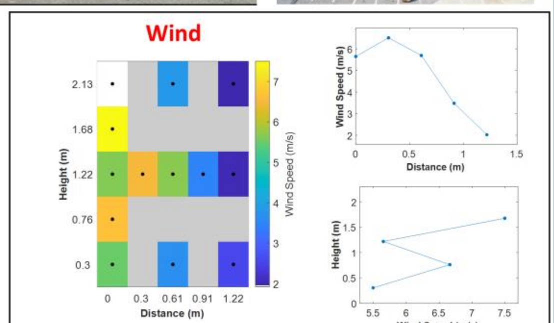
Test # B-57

Fence + Mulch

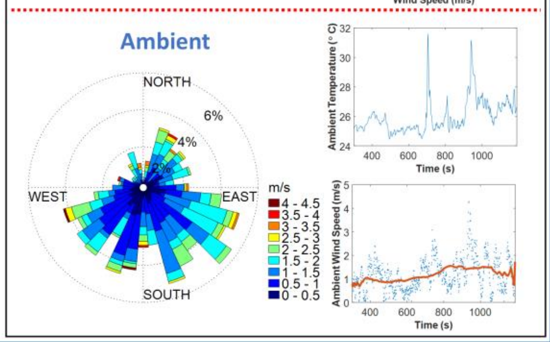
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

8/30/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	15:01	0:02
Time to end of fence (min:s)	9:10	0:20
Time to first spot (min:s)	8:33	0:20
Time to spot reaching wall (min:s)	11:50	0:20
Time to flames on wall (min:s)	13:14	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.5
Ambient wind speed (m/s)	1.18	0.21
Ambient wind direction (°)	156	10
Ambient temperature (°C)	26.0	4.5

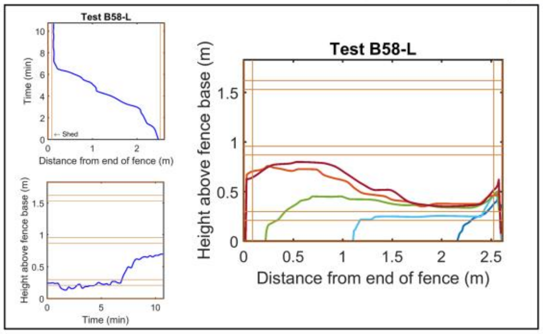


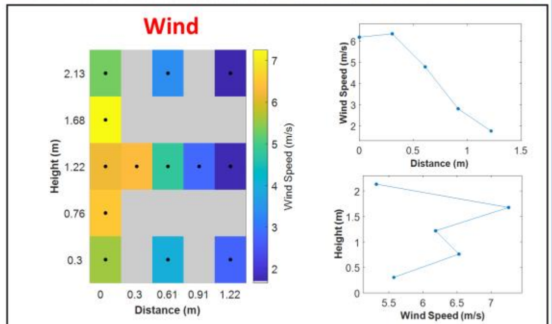
Test # B-58

Fence + Mulch

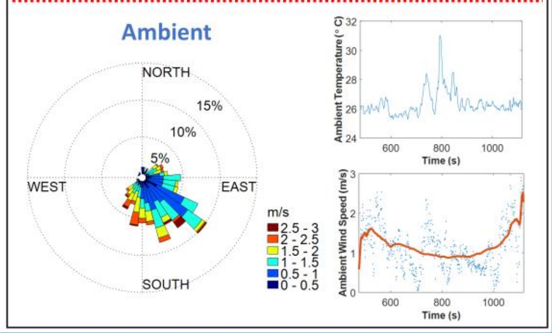
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

8/30/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:49	0:02
Time to end of fence (min:s)	7:10	0:20
Time to first spot (min:s)	7:59	0:20
Time to spot reaching wall (min:s)	8:25	0:20
Time to flames on wall (min:s)	9:35	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.5
Ambient wind speed (m/s)	1.13	0.20
Ambient wind direction (°)	142	10
Ambient temperature (°C)	26.4	4.5

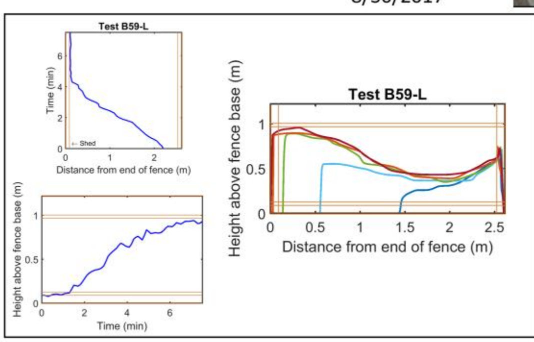


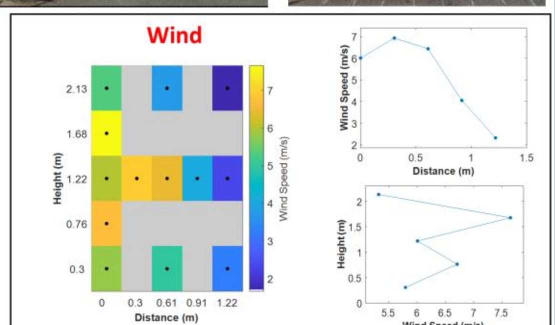
Test # B-59

Fence + Mulch

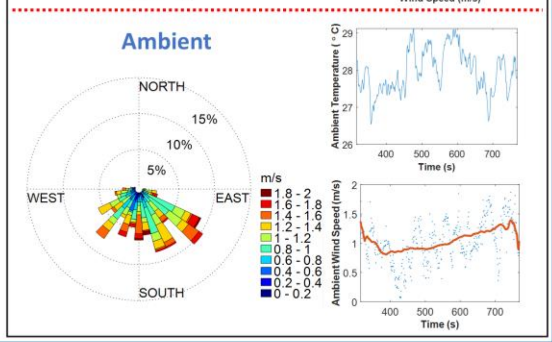
Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

8/30/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:42	0:02
Time to end of fence (min:s)	4:15	0:20
Time to first spot (min:s)	4:26	0:20
Time to spot reaching wall (min:s)	5:17	0:20
Time to flames on wall (min:s)	6:36	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.5	0.5
Ambient wind speed (m/s)	1.02	0.20
Ambient wind direction (°)	175	10
Ambient temperature (°C)	28.0	4.5

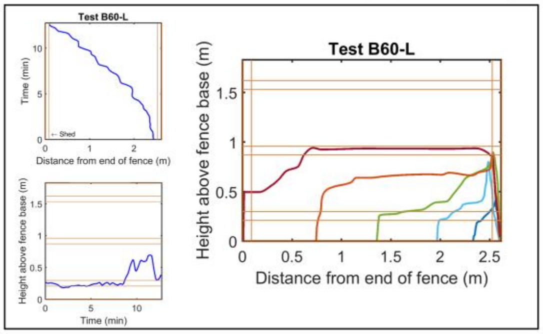


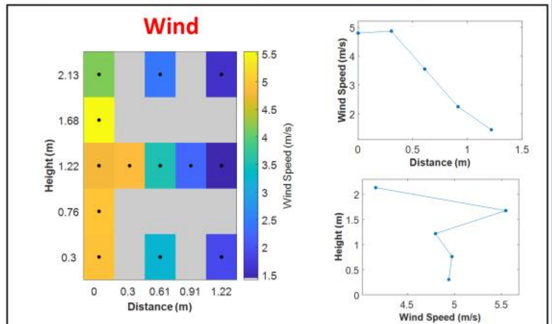
Test # B-60

Fence + Mulch

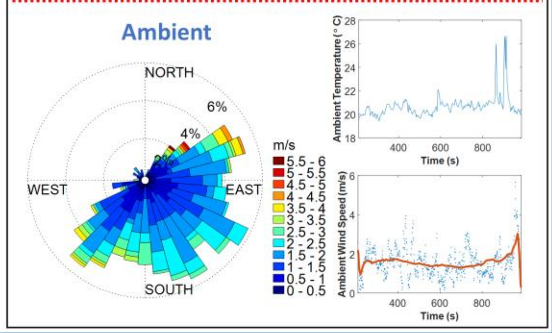
Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Low
Sep. distance: 0.9 m (3 ft)

9/29/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	12:56	0:02
Time to end of fence (min:s)	12:20	0:20
Time to first spot (min:s)	1:25	0:20
Time to spot reaching wall (min:s)	2:13	0:20
Time to flames on wall (min:s)	4:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.1	0.4
Ambient wind speed (m/s)	1.56	0.21
Ambient wind direction (°)	145	10
Ambient temperature (°C)	20.7	4.4

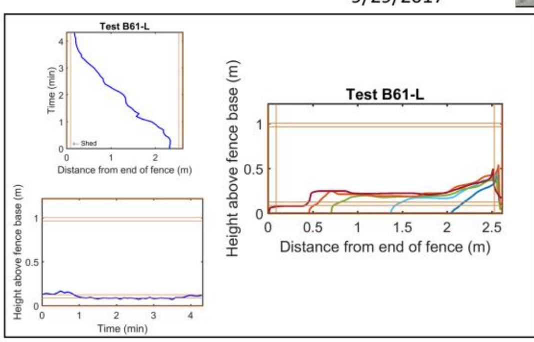


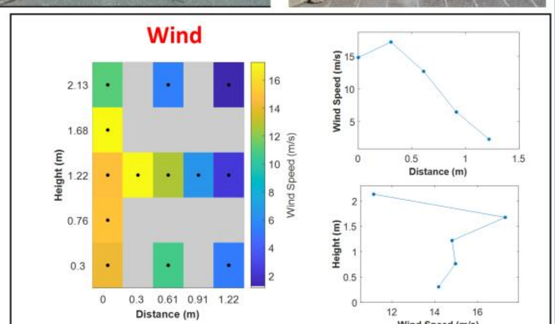
Test # B-61

Fence + Mulch

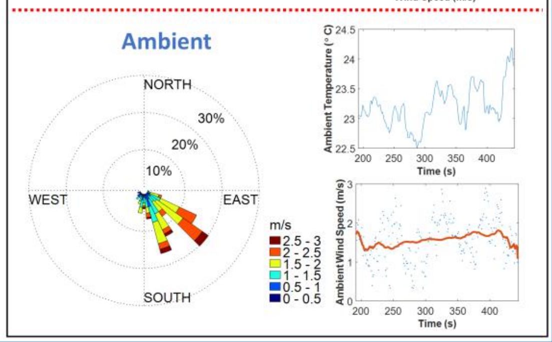
Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.9 m (3 ft)

9/29/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:21	0:02
Time to end of fence (min:s)	4:00	0:20
Time to first spot (min:s)	2:05	0:20
Time to spot reaching wall (min:s)	2:28	0:20
Time to flames on wall (min:s)	3:05	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.3	1.1
Ambient wind speed (m/s)	1.57	0.21
Ambient wind direction (°)	150	10
Ambient temperature (°C)	23.2	4.4

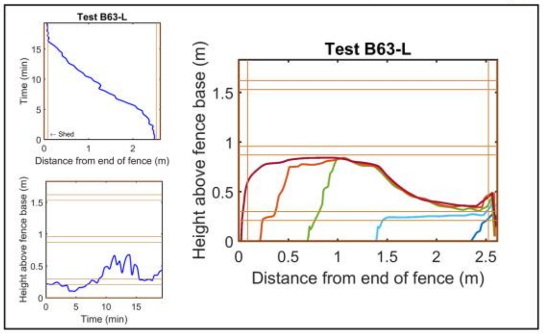


Test # B-63

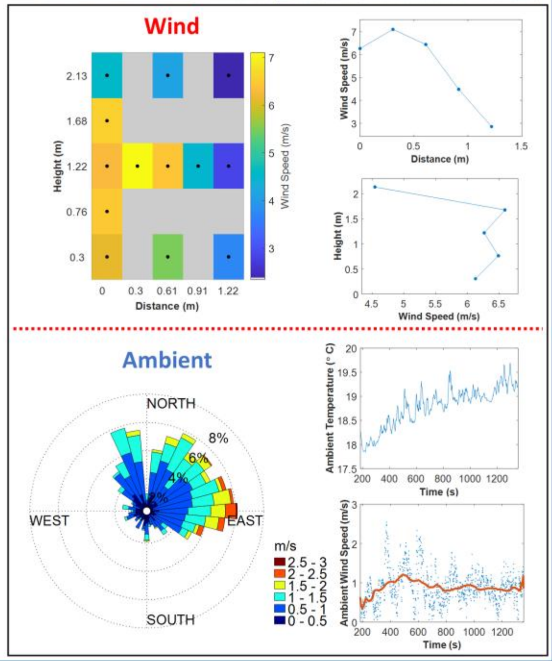
Fence + Mulch

Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.3 m (1 ft)

10/3/2017



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	19:34	0:02
Time to end of fence (min:s)	17:20	0:20
Time to first spot (min:s)	10:50	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.4
Ambient wind speed (m/s)	0.89	0.20
Ambient wind direction (°)	46	10
Ambient temperature (°C)	18.8	4.4

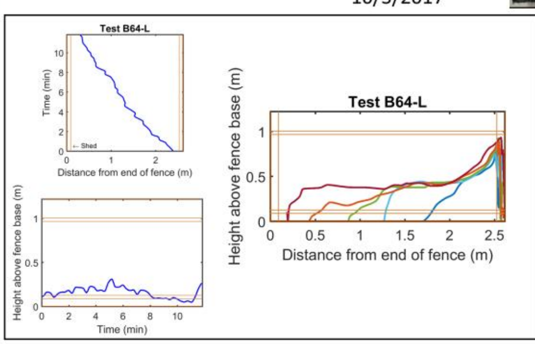


Test # B-64

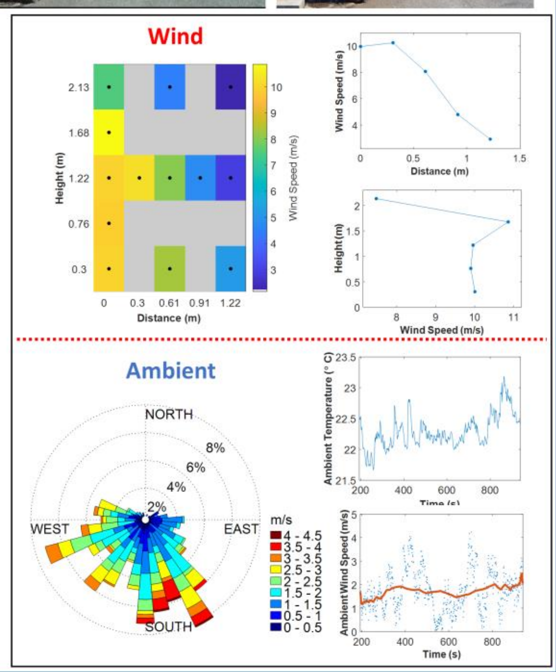
Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 0 m (0 ft)

10/3/2017



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	12:31	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:12	0:20
Time to spot reaching wall (min:s)	1:12	0:20
Time to flames on wall (min:s)	3:16	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.2	0.7
Ambient wind speed (m/s)	1.73	0.21
Ambient wind direction (°)	191	10
Ambient temperature (°C)	22.3	4.4

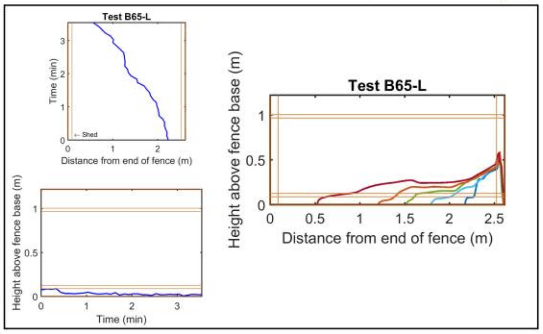


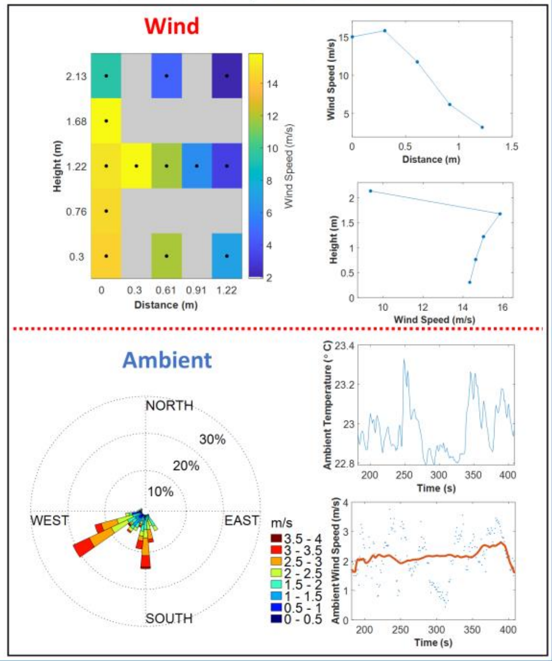
Test # B-65

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0 m (0 ft)

10/3/2017





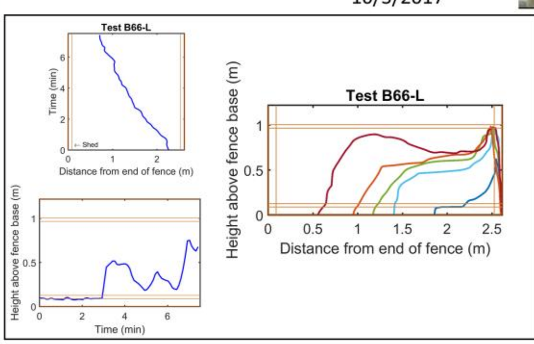
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:55	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	1:31	0:20
Time to spot reaching wall (min:s)	2:06	0:20
Time to flames on wall (min:s)	2:30	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.0	1.1
Ambient wind speed (m/s)	2.15	0.22
Ambient wind direction (°)	213	10
Ambient temperature (°C)	23.0	4.4

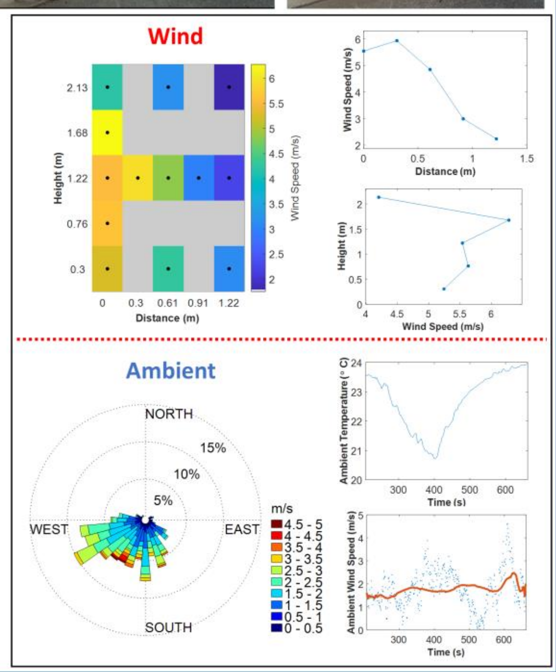
Test # B-66

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

10/3/2017





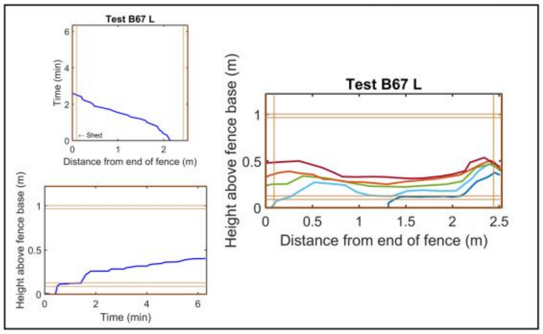
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:39	0:01
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:25	0:20
Time to spot reaching wall (min:s)	5:14	0:20
Time to flames on wall (min:s)	6:16	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.7	0.4
Ambient wind speed (m/s)	1.77	0.21
Ambient wind direction (°)	210	10
Ambient temperature (°C)	22.7	4.4

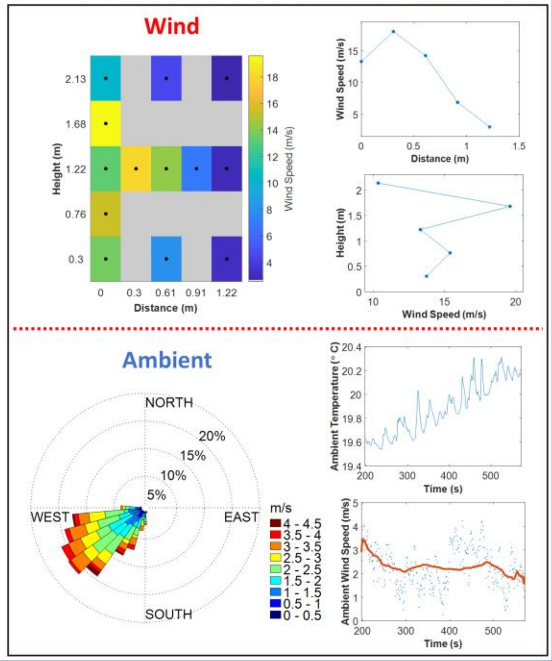
Test # B-67

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

10/4/2017





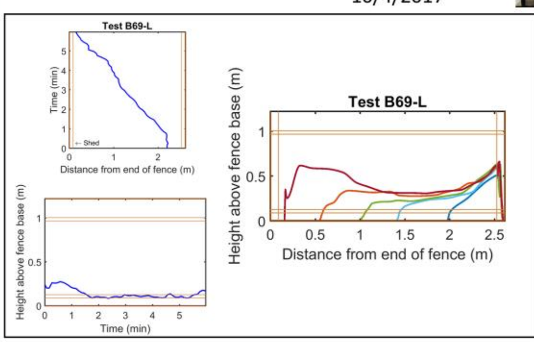
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:19	0:02
Time to end of fence (min:s)	2:40	0:10
Time to first spot (min:s)	4:28	0:20
Time to spot reaching wall (min:s)	4:28	0:20
Time to flames on wall (min:s)	5:16	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.5	1.1
Ambient wind speed (m/s)	2.27	0.22
Ambient wind direction (°)	232	10
Ambient temperature (°C)	19.9	4.4

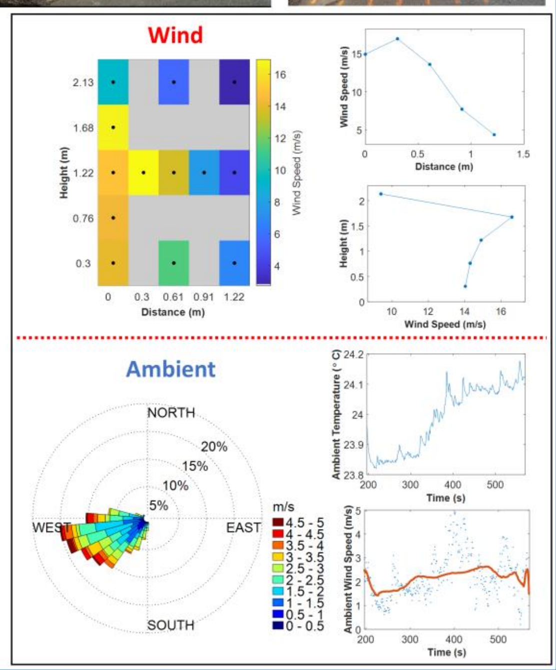
Test # B-69

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 0.3 m (1 ft)

10/4/2017





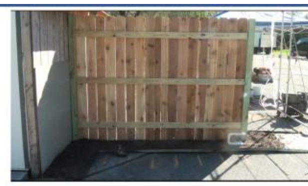
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:21	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	2:49	0:20
Time to spot reaching wall (min:s)	2:49	0:20
Time to flames on wall (min:s)	3:20	0:06
Mean wind sp. 4 ctr. probes (m/s)	14.9	1.1
Ambient wind speed (m/s)	2.21	0.22
Ambient wind direction (°)	242	10
Ambient temperature (°C)	24.0	4.5

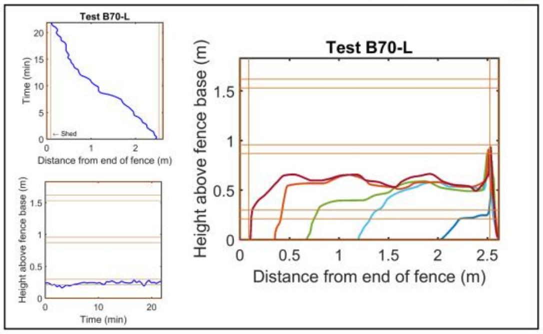
Test # B-70

Fence + Mulch

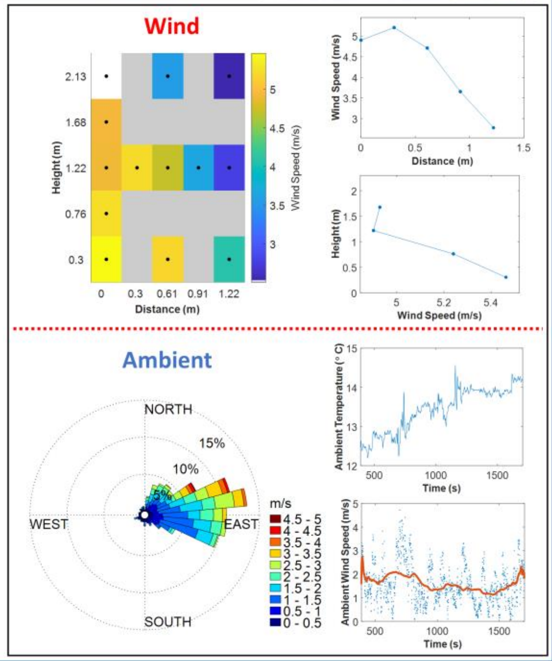
Western Red Cedar Privacy Fence +
½ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

10/17/2017



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	22:00	0:02
Time to end of fence (min:s)	21:10	0:20
Time to first spot (min:s)	11:13	0:20
Time to spot reaching wall (min:s)	12:14	0:20
Time to flames on wall (min:s)	12:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.1	0.4
Ambient wind speed (m/s)	1.58	0.21
Ambient wind direction (°)	80	10
Ambient temperature (°C)	13.4	4.4

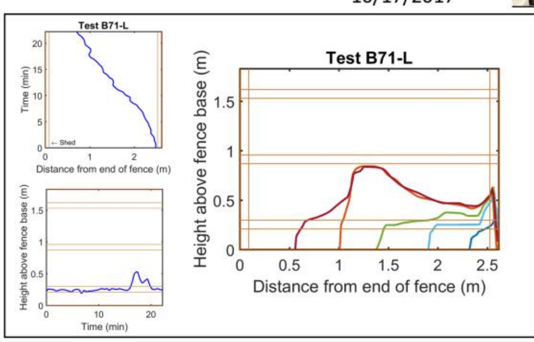


Test # B-71

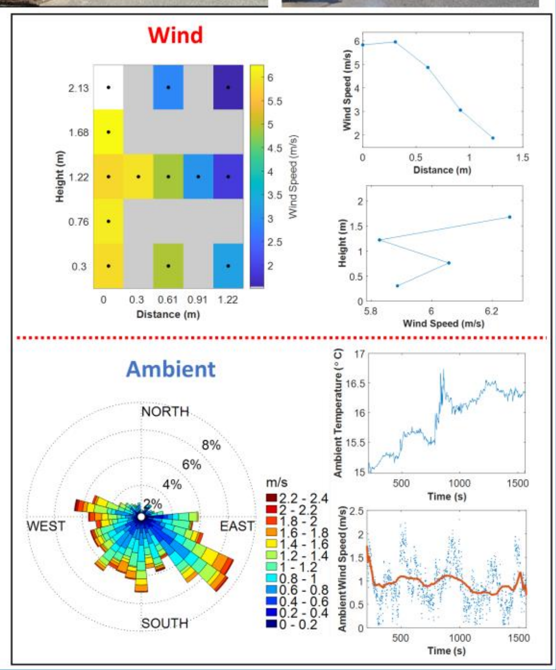
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Low
Sep. distance: 0 m (0 ft)

10/17/2017

Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	22:34	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	9:34	0:20
Time to spot reaching wall (min:s)	9:34	0:20
Time to flames on wall (min:s)	18:27	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	0.93	0.20
Ambient wind direction (°)	180	10
Ambient temperature (°C)	15.9	4.4

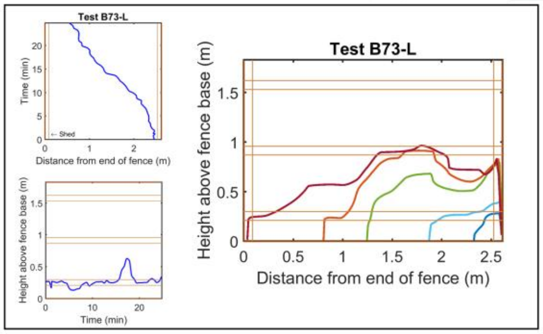


Test # B-73

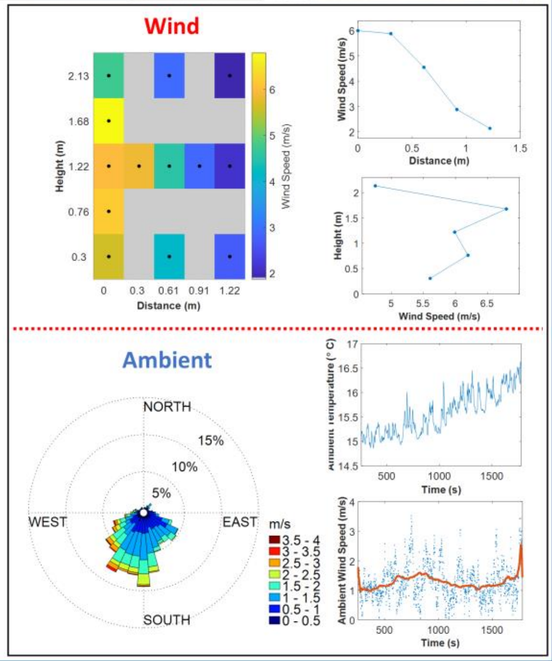
Fence + Mulch

Western Red Cedar Privacy Fence + Pine Bark Mulch
Wind speed: Low
Sep. distance: 0.3 m (1 ft)

10/18/2017



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	25:26	0:02
Time to end of fence (min:s)	23:45 (R side)	0:20
Time to first spot (min:s)	13:02	0:20
Time to spot reaching wall (min:s)	20:29	0:20
Time to flames on wall (min:s)	21:50	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.1	0.4
Ambient wind speed (m/s)	1.27	0.20
Ambient wind direction (°)	184	10
Ambient temperature (°C)	15.6	4.4

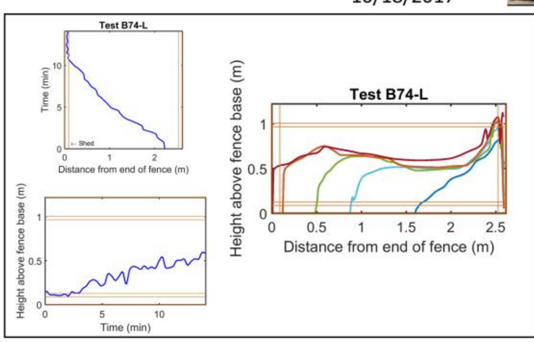


Test # B-74

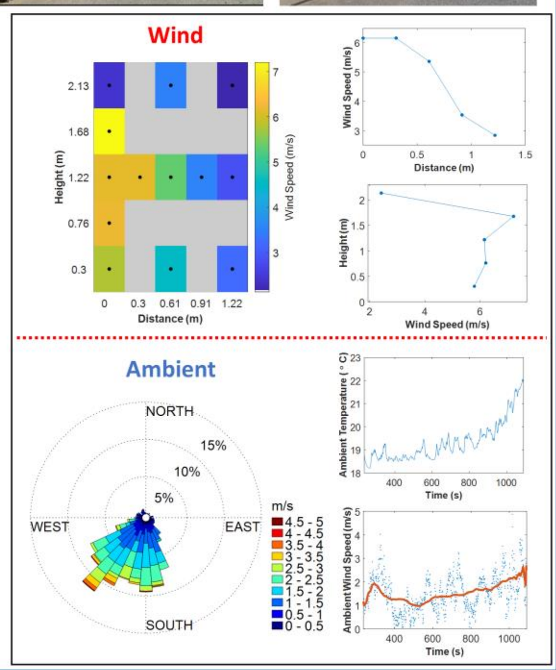
Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 0.3 m (1 ft)

10/18/2017



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:19	0:02
Time to end of fence (min:s)	12:20	0:20
Time to first spot (min:s)	9:02	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	13:34	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.4
Ambient wind speed (m/s)	1.52	0.21
Ambient wind direction (°)	202	10
Ambient temperature (°C)	19.3	4.4

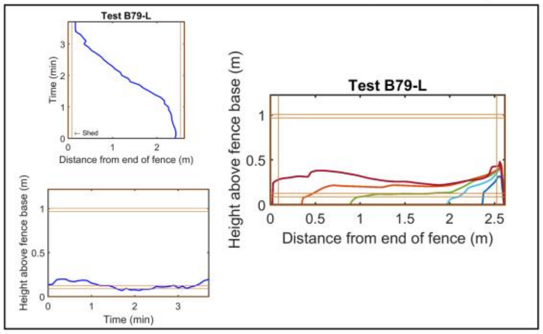


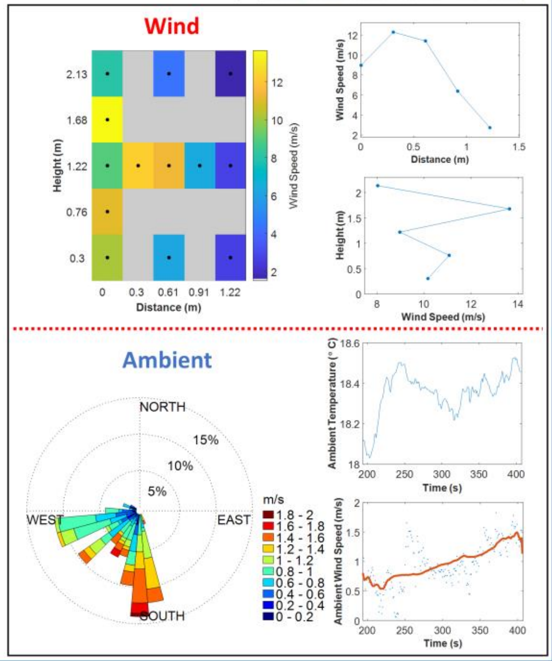
Test # B-79

Fence + Mulch

Redwood Lattice Fence + Shredded Hardwood Mul
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

11/3/2017





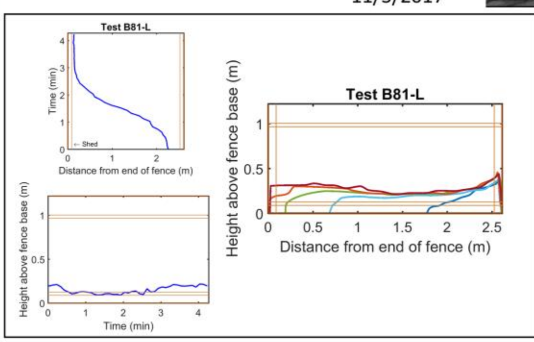
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:43	0:02
Time to end of fence (min:s)	3:20	0:10
Time to first spot (min:s)	1:58	0:20
Time to spot reaching wall (min:s)	1:58	0:20
Time to flames on wall (min:s)	2:34	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.0	0.8
Ambient wind speed (m/s)	0.95	0.21
Ambient wind direction (°)	217	10
Ambient temperature (°C)	18.4	4.4

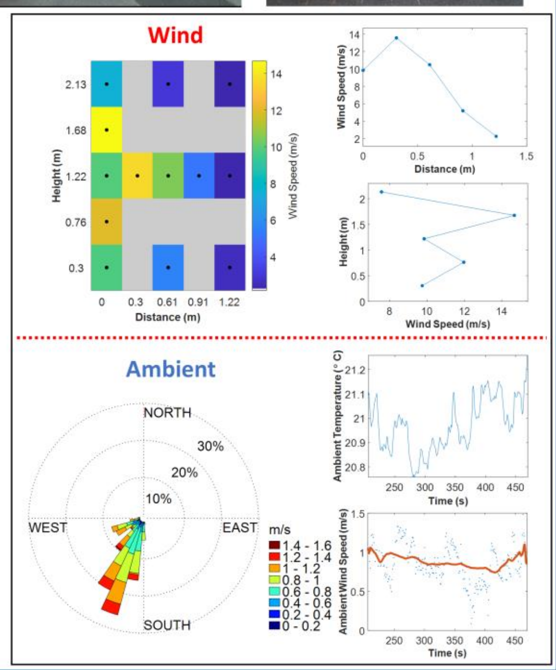
Test # B-81

Fence + Mulch

Pine Lattice Fence + Pine Bark Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

11/3/2017





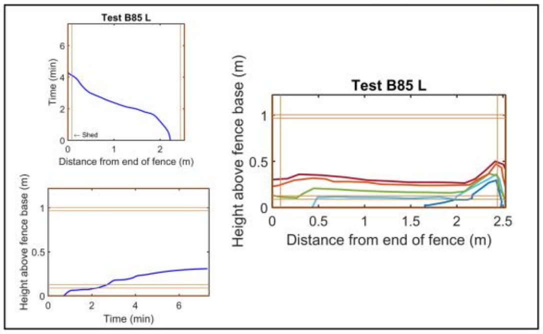
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:30	0:02
Time to end of fence (min:s)	3:00	0:20
Time to first spot (min:s)	1:28	0:20
Time to spot reaching wall (min:s)	2:47	0:20
Time to flames on wall (min:s)	3:00	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.6	0.8
Ambient wind speed (m/s)	0.86	0.20
Ambient wind direction (°)	211	10
Ambient temperature (°C)	21.0	4.4

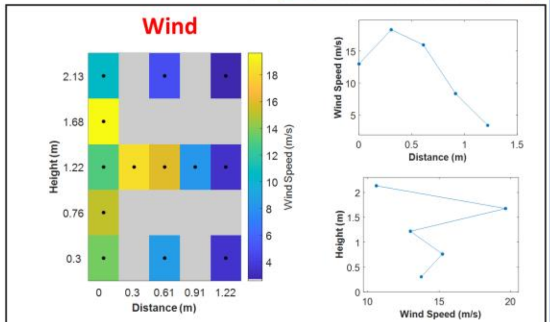
Test # B-85

Fence + Mulch

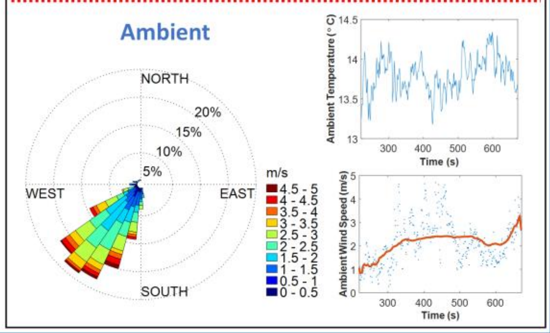
Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

11/15/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:42	0:02
Time to end of fence (min:s)	4:30	0:20
Time to first spot (min:s)	4:58	0:20
Time to spot reaching wall (min:s)	5:12	0:20
Time to flames on wall (min:s)	6:23	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.4	1.1
Ambient wind speed (m/s)	2.17	0.22
Ambient wind direction (°)	216	10
Ambient temperature (°C)	13.8	4.4

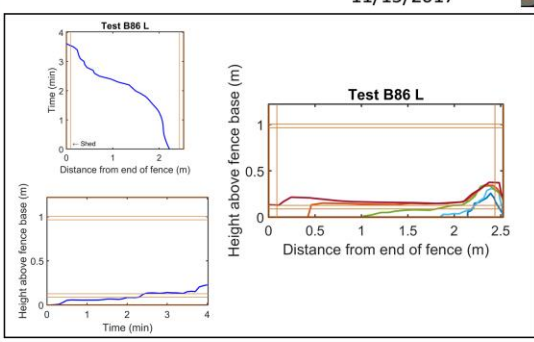


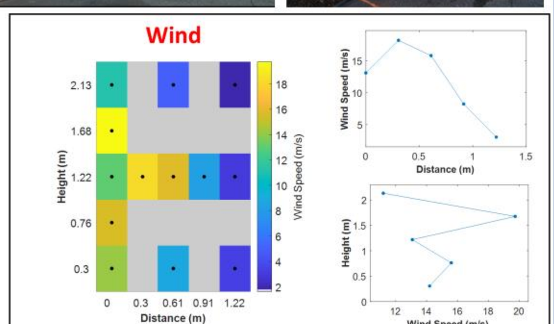
Test # B-86

Fence + Mulch

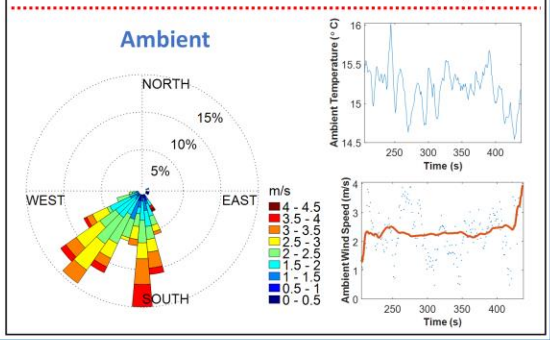
Pine Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

11/15/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:02	0:02
Time to end of fence (min:s)	3:45	0:10
Time to first spot (min:s)	0:58	0:20
Time to spot reaching wall (min:s)	0:58	0:20
Time to flames on wall (min:s)	1:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.6	1.1
Ambient wind speed (m/s)	2.28	0.22
Ambient wind direction (°)	202	10
Ambient temperature (°C)	15.2	4.4

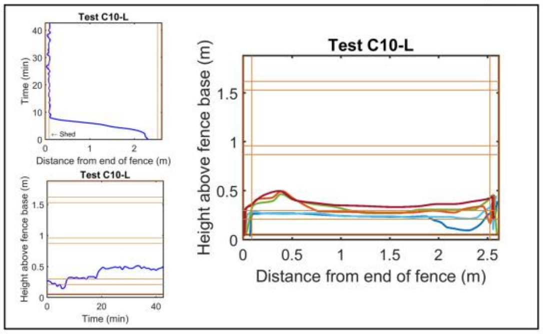


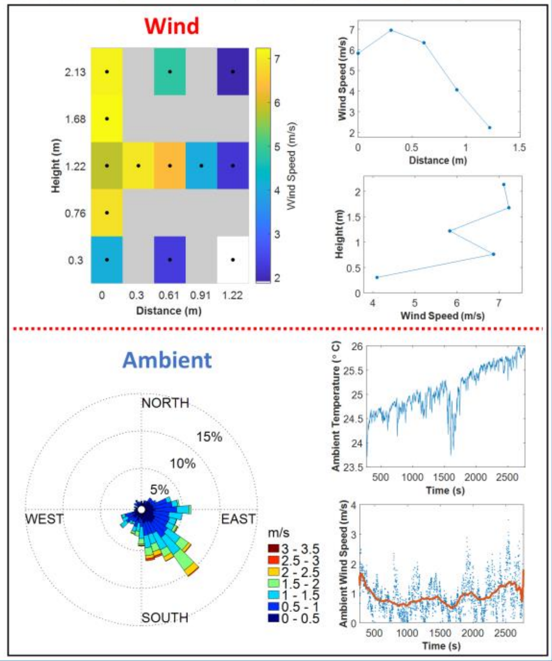
Test # C-10

Fence + Mulch

Western Red Cedar Privacy Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence elevation: 5.1 cm (2 in)

7/9/2018





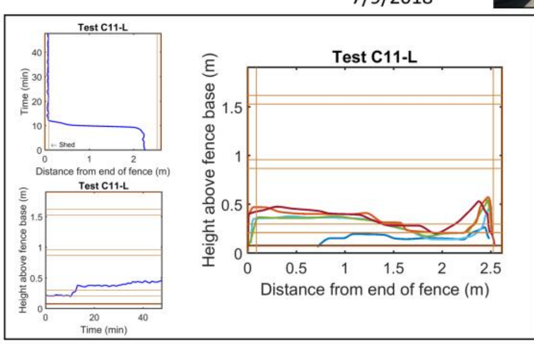
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	42:45	0:02
Time to end of fence (min:s)	8:00	0:30
Time to first spot (min:s)	16:44	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	0.90	0.20
Ambient wind direction (°)	139	10
Ambient temperature (°C)	25.1	4.5

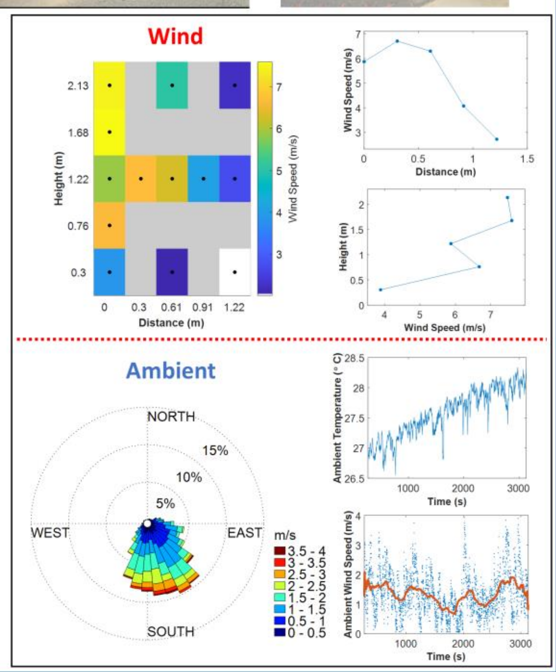
Test # C-11

Fence + Mulch

Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence elevation: 7.6 cm (3 in)

7/9/2018





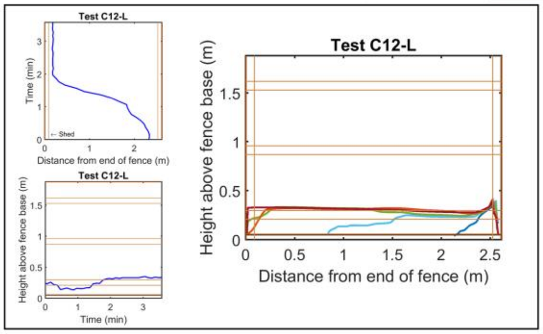
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	48:29	0:02
Time to end of fence (min:s)	13:00	0:30
Time to first spot (min:s)	23:25	0:20
Time to spot reaching wall (min:s)	30:35	0:20
Time to flames on wall (min:s)	48:07	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	1.34	0.20
Ambient wind direction (°)	157	10
Ambient temperature (°C)	27.6	4.5

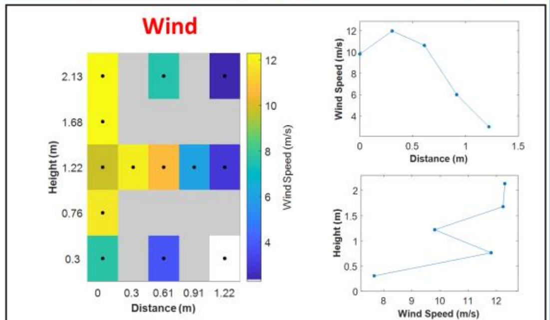
Test # C-12

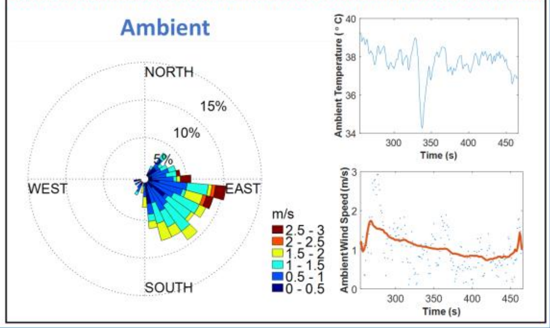
Fence + Mulch

Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)
Fence elevation: 5.1 cm (2 in)

7/9/2018







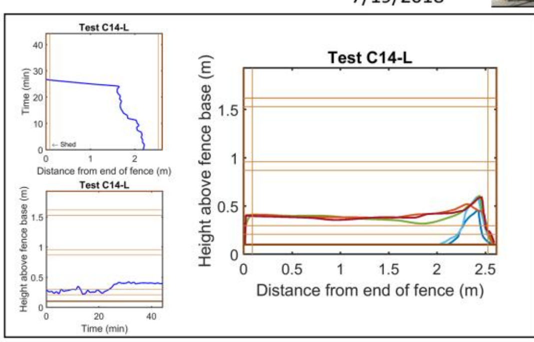
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:44	0:02
Time to end of fence (min:s)	1:55	0:10
Time to first spot (min:s)	0:52	0:20
Time to spot reaching wall (min:s)	1:13	0:20
Time to flames on wall (min:s)	2:07	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.4	0.7
Ambient wind speed (m/s)	1.02	0.22
Ambient wind direction (°)	123	10
Ambient temperature (°C)	37.8	4.7

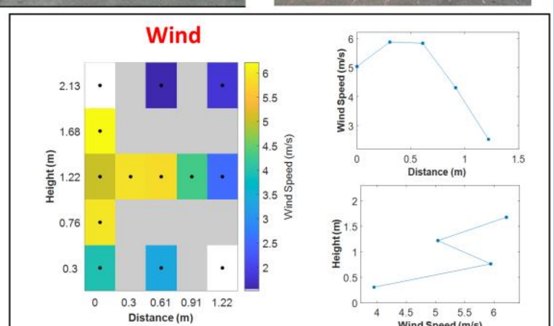
Test # C-14

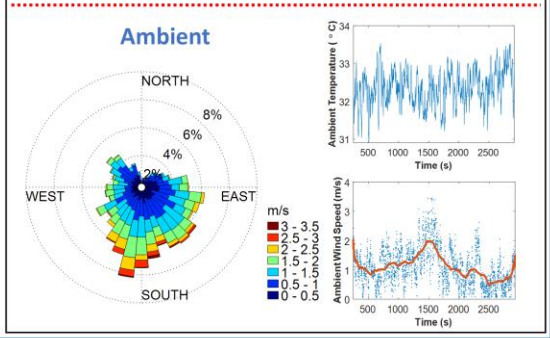
Fence + Mulch

Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence elevation: 10.2 cm (4 in)

7/19/2018







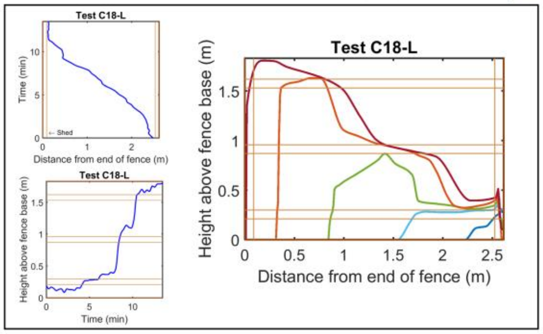
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	45:05	0:02
Time to end of fence (min:s)	27:30	0:30
Time to first spot (min:s)	33:26	0:20
Time to spot reaching wall (min:s)	42:40	0:20
Time to flames on wall (min:s)	43:48	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.3	0.4
Ambient wind speed (m/s)	1.09	0.20
Ambient wind direction (°)	173	10
Ambient temperature (°C)	32.4	4.6

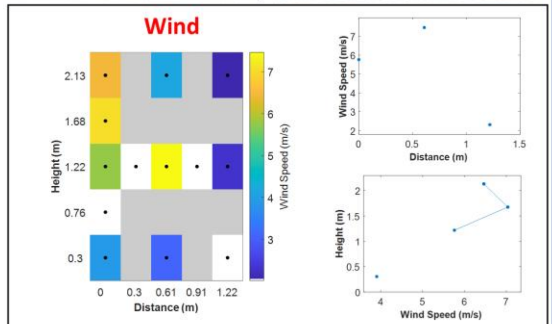
Test # C-18

Fence + Mulch

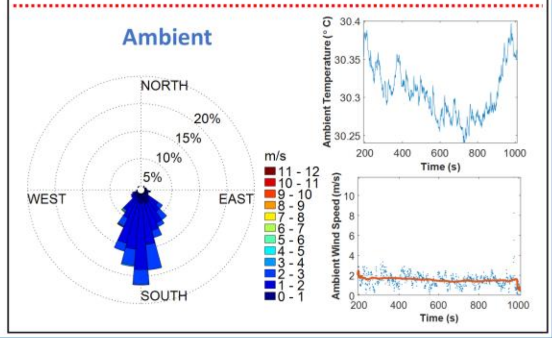
Good Neighbor Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

9/20/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	13:41	0:02
Time to end of fence (min:s)	12:00	0:30
Time to first spot (min:s)	6:10	0:20
Time to spot reaching wall (min:s)	10:05	0:20
Time to flames on wall (min:s)	10:49	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.6	0.5
Ambient wind speed (m/s)	1.54	0.21
Ambient wind direction (°)	177	10
Ambient temperature (°C)	30.3	4.6

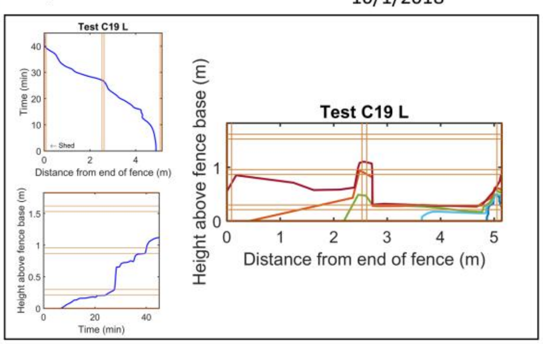


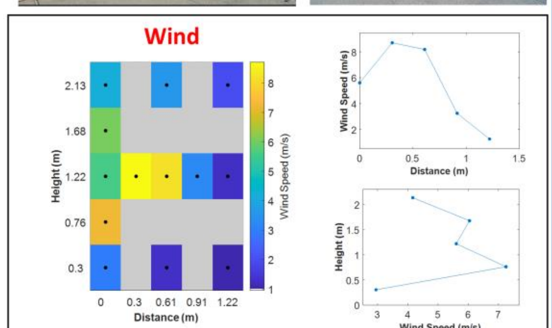
Test # C-19

Fence + Mulch

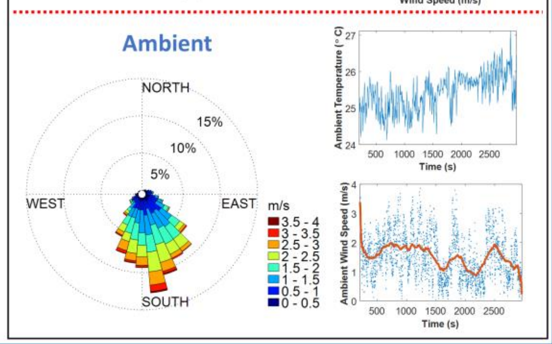
Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Two panels

10/1/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	46:00	0:02
Time to end of fence (min:s)	40:00	1:00
Time to first spot (min:s)	23:17	0:20
Time to spot reaching wall (min:s)	23:17	0:20
Time to flames on wall (min:s)	45:46	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.5	0.4
Ambient wind speed (m/s)	1.51	0.20
Ambient wind direction (°)	166	10
Ambient temperature (°C)	25.4	4.5

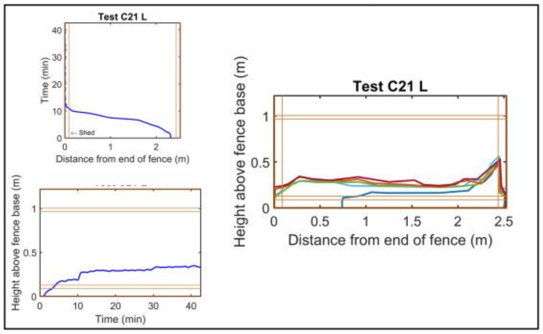


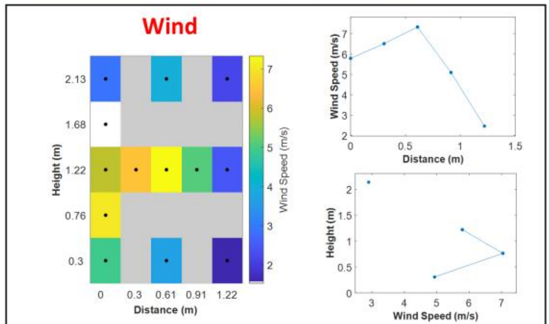
Test # C-21

Fence + Mulch

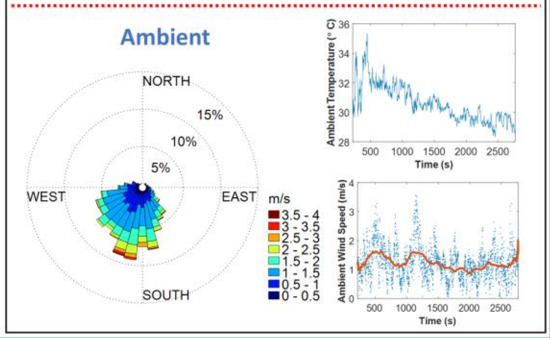

Pine Lattice Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

10/1/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	42:31	0:02
Time to end of fence (min:s)	13:20	0:30
Time to first spot (min:s)	10:58	0:20
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	5.9	0.5
Ambient wind speed (m/s)	1.22	0.20
Ambient wind direction (°)	201	10
Ambient temperature (°C)	30.6	4.6

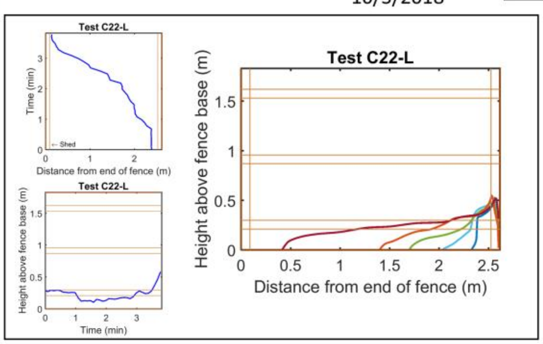


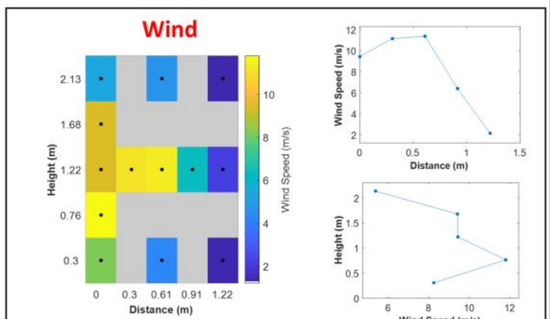
Test # C-22

Fence + Mulch

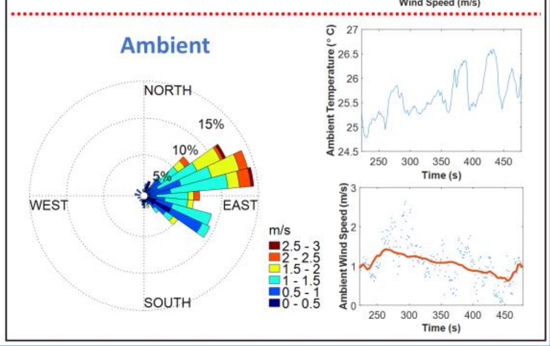

Good Neighbor Fence+ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

10/3/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:26	0:02
Time to end of fence (min:s)	3:30	0:20
Time to first spot (min:s)	1:32	0:20
Time to spot reaching wall (min:s)	2:45	0:20
Time to flames on wall (min:s)	4:20	0:06
Mean wind sp. 4 ctr. probes (m/s)	9.7	0.7
Ambient wind speed (m/s)	1.08	0.21
Ambient wind direction (°)	86	10
Ambient temperature (°C)	25.6	4.5

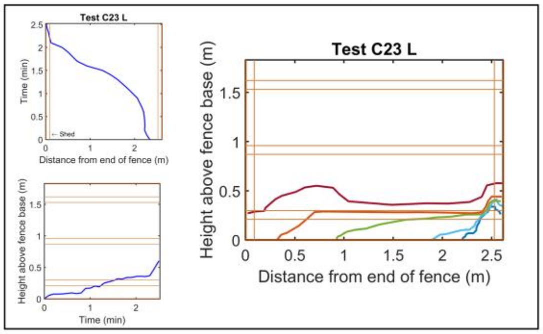


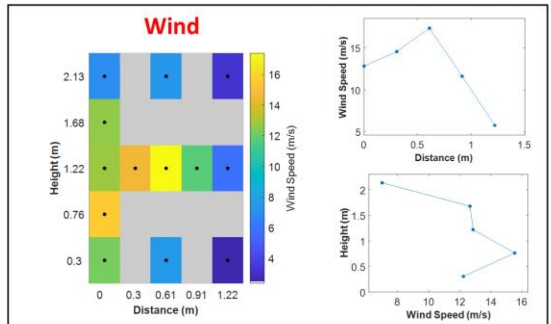
Test # C-23

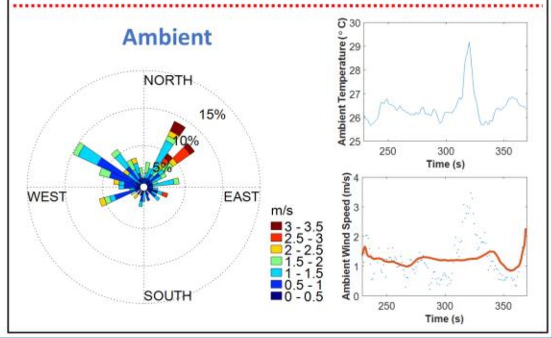
Fence + Mulch

Good Neighbor Fence+ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

10/3/2018







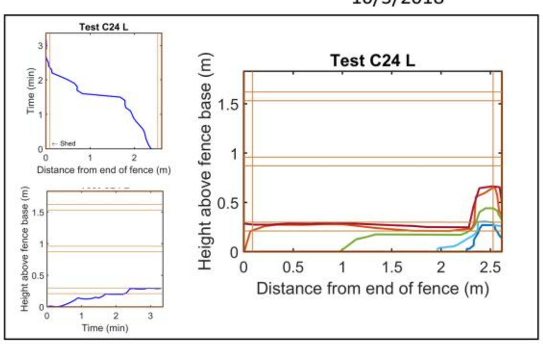
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	2:33	0:02
Time to end of fence (min:s)	2:20	0:20
Time to first spot (min:s)	0:55	0:20
Time to spot reaching wall (min:s)	1:40	0:20
Time to flames on wall (min:s)	1:53	0:06
Mean wind sp. 4 ctr. probes (m/s)	13.3	0.9
Ambient wind speed (m/s)	1.21	0.23
Ambient wind direction (°)	348	10
Ambient temperature (°C)	26.4	4.5

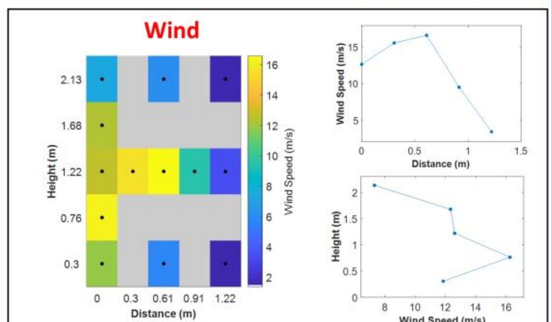
Test # C-24

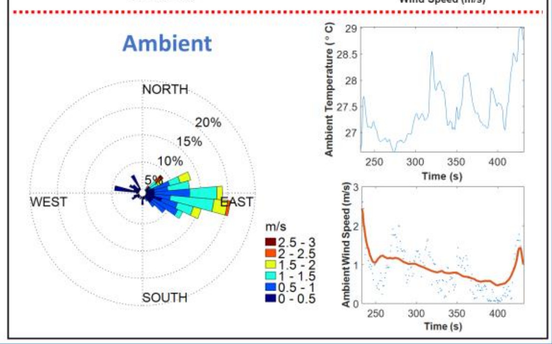
Fence + Mulch

Old Western Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)

10/3/2018







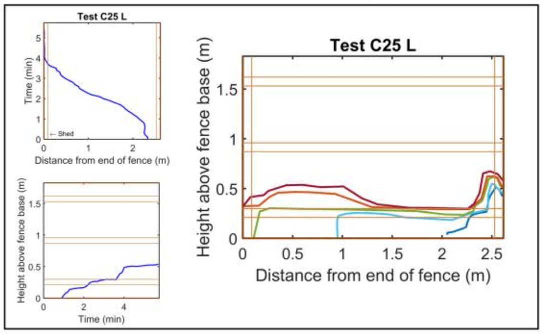
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:33	0:02
Time to end of fence (min:s)	2:35	0:10
Time to first spot (min:s)	0:49	0:20
Time to spot reaching wall (min:s)	0:49	0:20
Time to flames on wall (min:s)	3:05	0:06
Mean wind sp. 4 ctr. probes (m/s)	13.3	0.9
Ambient wind speed (m/s)	0.84	0.21
Ambient wind direction (°)	94	10
Ambient temperature (°C)	27.4	4.5

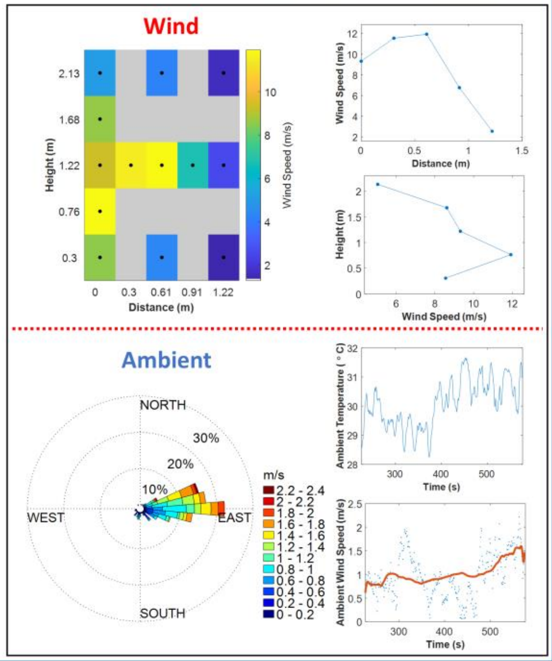
Test # C-25

Fence + Mulch

Old Western Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)

10/3/2018





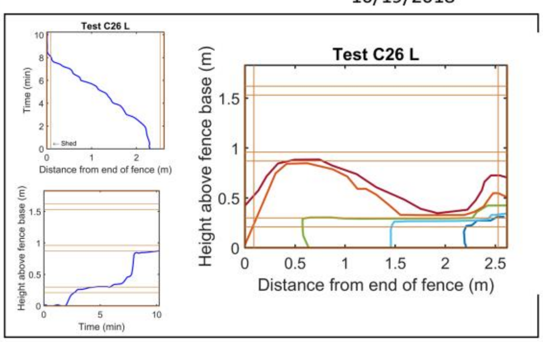
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:00	0:02
Time to end of fence (min:s)	3:55	0:10
Time to first spot (min:s)	1:59	0:20
Time to spot reaching wall (min:s)	4:38	0:20
Time to flames on wall (min:s)	5:19	0:06
Mean wind sp. 4 ctr. probes (m/s)	9.6	0.7
Ambient wind speed (m/s)	0.97	0.21
Ambient wind direction (°)	94	10
Ambient temperature (°C)	30.1	4.5

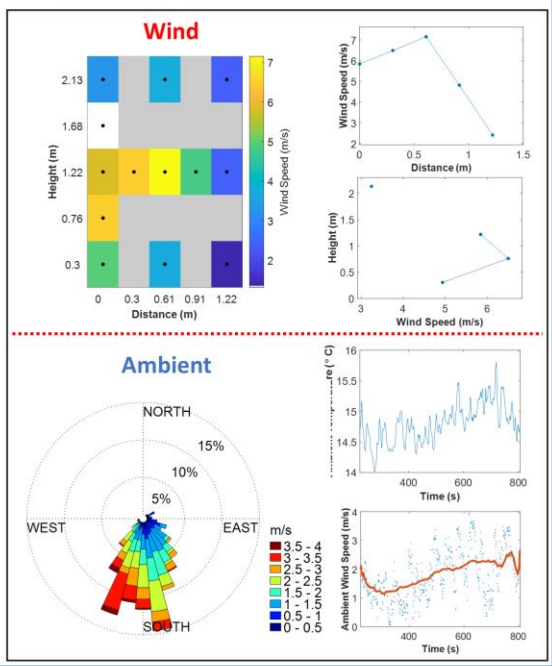
Test # C-26

Fence + Mulch

Old Western Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

10/19/2018





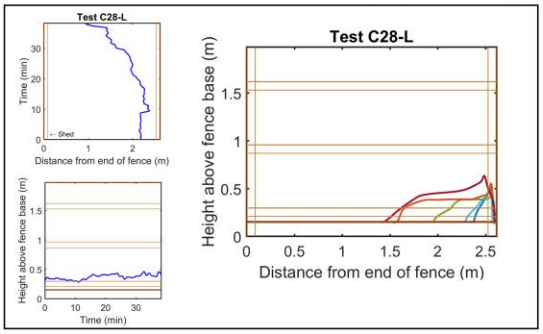
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	9:55	0:02
Time to end of fence (min:s)	8:20	0:20
Time to first spot (min:s)	4:13	0:20
Time to spot reaching wall (min:s)	6:55	0:20
Time to flames on wall (min:s)	8:24	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.8	0.5
Ambient wind speed (m/s)	1.81	0.21
Ambient wind direction (°)	173	10
Ambient temperature (°C)	14.8	4.4

Test # C-28

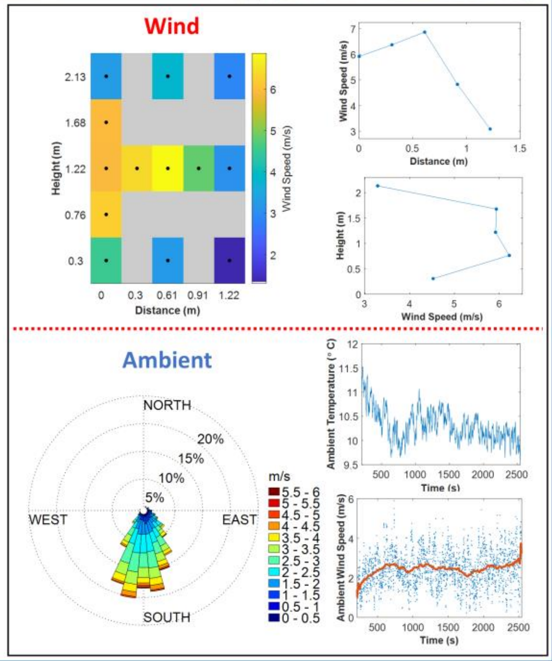
Fence + Mulch

Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence elevation: 15.2 cm (6 in)

10/22/2018



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	38:56	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	3:39	0:20
Time to spot reaching wall (min:s)	3:39	0:20
Time to flames on wall (min:s)	5:32	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.7	0.4
Ambient wind speed (m/s)	2.45	0.20
Ambient wind direction (°)	174	10
Ambient temperature (°C)	10.3	4.4

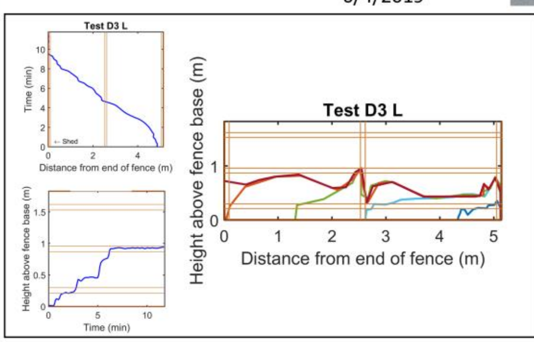


Test # D-3

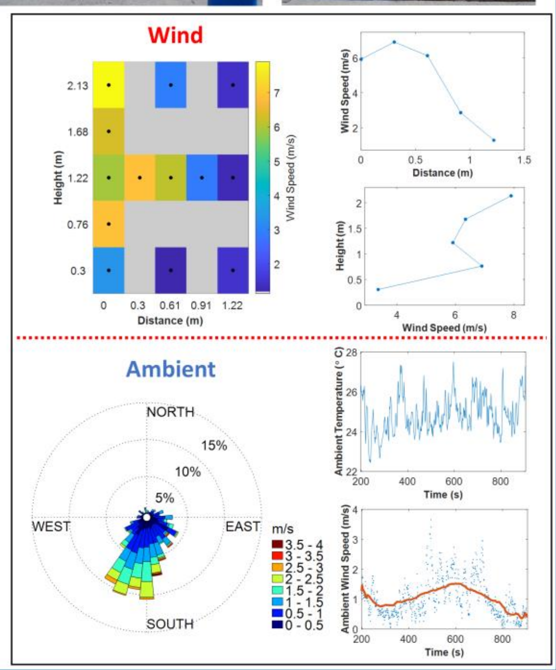
Fence + Mulch

Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Two panel lengths, no shed

6/4/2019



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:57	0:02
Time to end of fence (min:s)	9:30	0:10
Time to first spot (min:s)	N/A	
Time to spot reaching wall (min:s)	N/A	
Time to flames on wall (min:s)	N/A	
Mean wind sp. 4 ctr. probes (m/s)	5.2	0.4
Ambient wind speed (m/s)	1.04	0.21
Ambient wind direction (°)	176	10
Ambient temperature (°C)	24.9	4.5



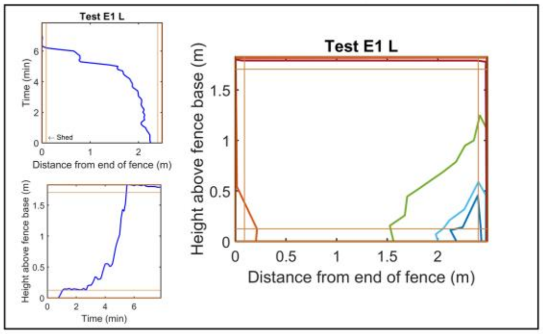
Test # E-1

Fence + Mulch

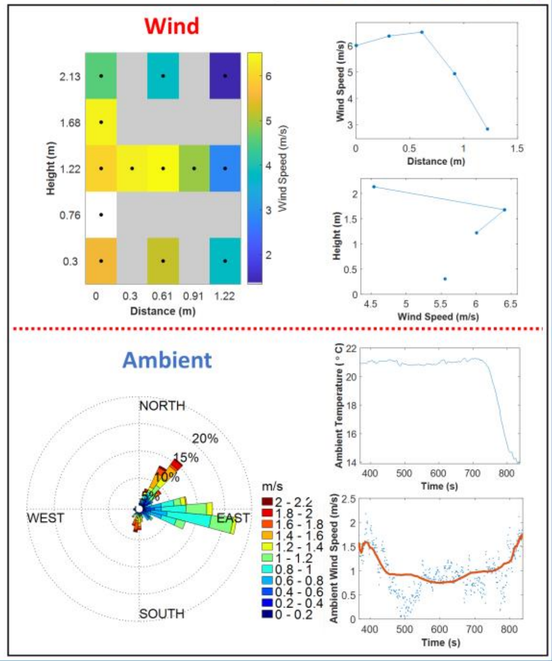
Wood-Plastic Composite (WPC1) Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)

9/25/2020





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	7:53	0:02
Time to end of fence (min:s)	6:15	0:10
Time to first spot (min:s)	6:44	0:20
Time to spot reaching wall (min:s)	6:44	0:20
Time to flames on wall (min:s)	7:08	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.5
Ambient wind speed (m/s)	0.95	0.20
Ambient wind direction (°)	88	10
Ambient temperature (°C)	20.1	4.4



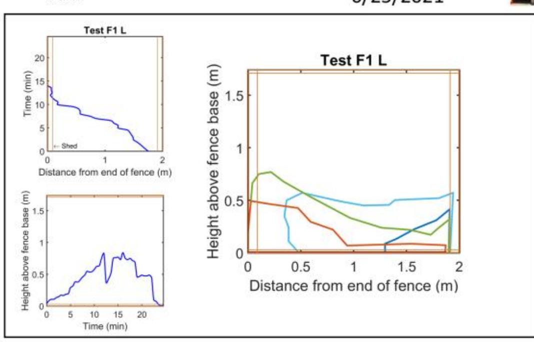
Test # F-1

Fence + Mulch

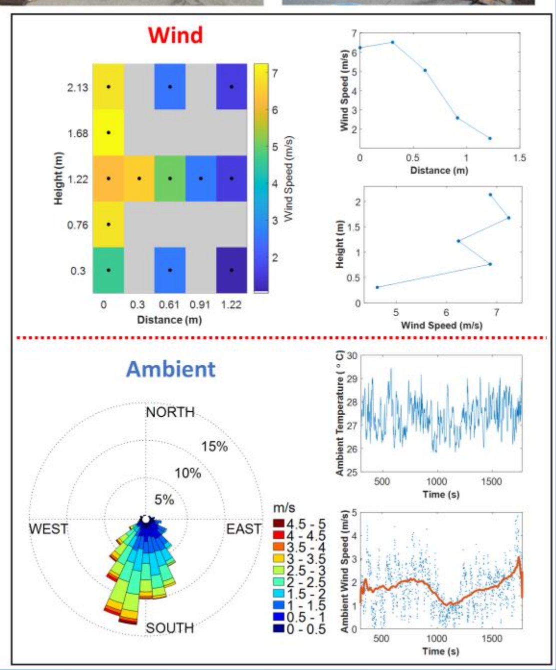
Wood-Plastic Composite (WPC2) Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Note: Horizontal boards slip down as they burn.

6/25/2021



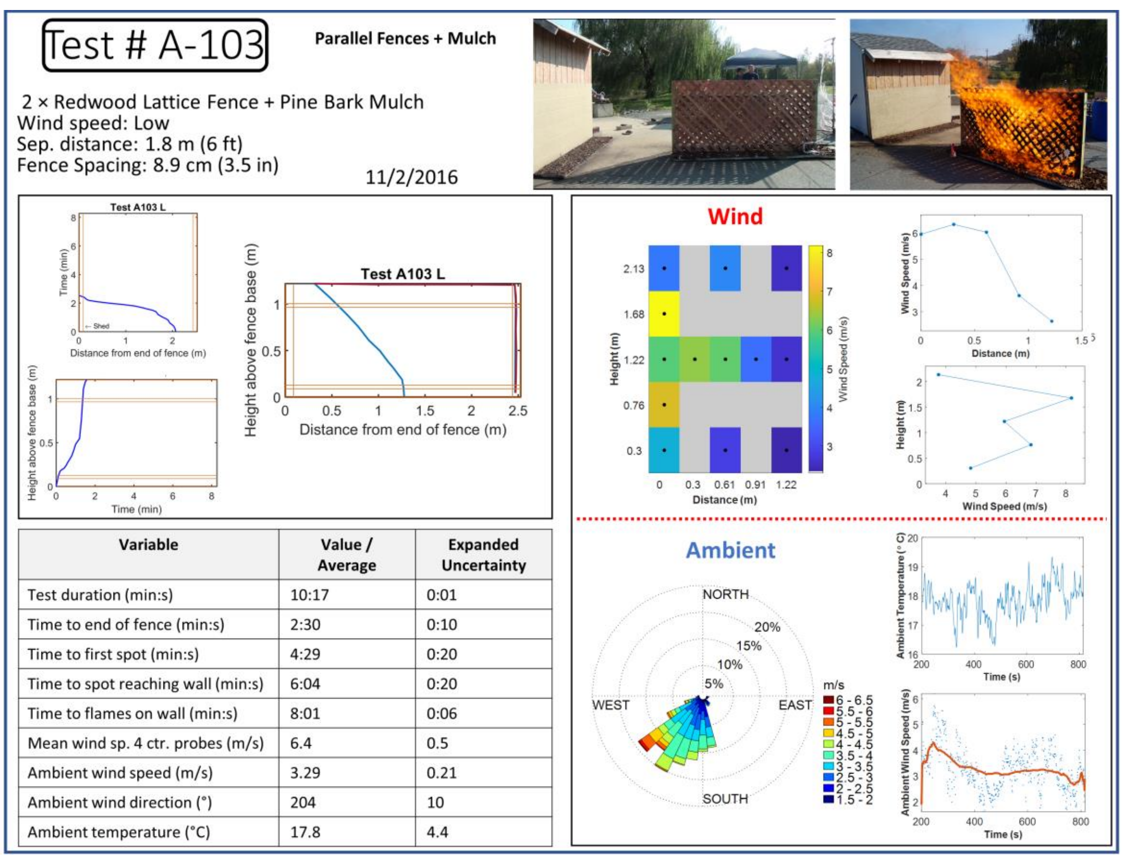


Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	24:37	0:02
Time to end of fence (min:s)	14:00	0:20
Time to first spot (min:s)	19:46	0:20
Time to spot reaching wall (min:s)	20:10	0:20
Time to flames on wall (min:s)	21:08	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	1.742	0.915
Ambient wind direction (°)	182	10
Ambient temperature (°C)	27.4	4.5



Appendix I. Case Details: Parallel Fences

This appendix provides the data from all experimental cases in which fence panels were mounted parallel to each other, with or without mulch beneath. The data includes a description of the experiment, photographs from before and during, flame spread plots, critical times, and ambient and applied winds. The data for each experiment can be read as described in Appendix E.



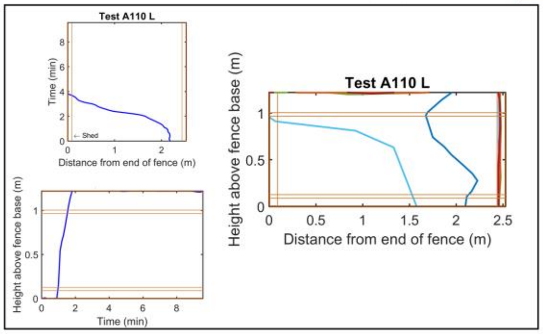
Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	10:17	0:01
Time to end of fence (min:s)	2:30	0:10
Time to first spot (min:s)	4:29	0:20
Time to spot reaching wall (min:s)	6:04	0:20
Time to flames on wall (min:s)	8:01	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.5
Ambient wind speed (m/s)	3.29	0.21
Ambient wind direction (°)	204	10
Ambient temperature (°C)	17.8	4.4

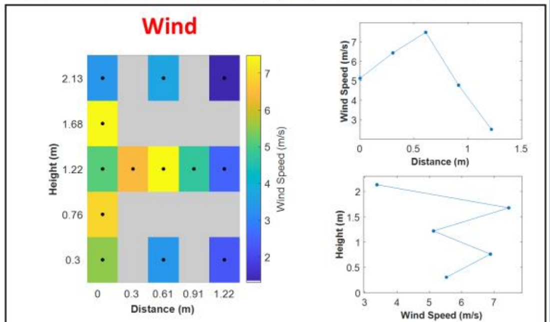
Test # A-110

Parallel Fences. No Mulch

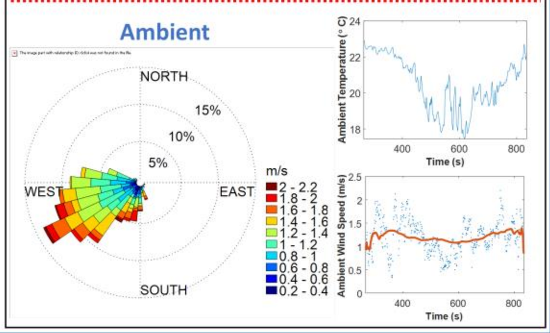
2 × Redwood Lattice Fence
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

11/18/2016





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	9:38	0:02
Time to end of fence (min:s)	3:45	0:10
Time to first spot (min:s)	5:14	0:20
Time to spot reaching wall (min:s)	6:58	0:20
Time to flames on wall (min:s)	8:55	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	1.21	0.20
Ambient wind direction (°)	238	10
Ambient temperature (°C)	20.5	4.4

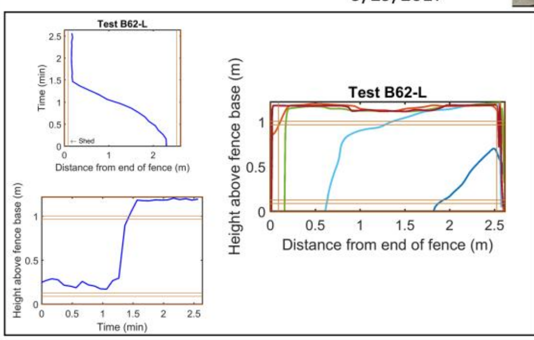


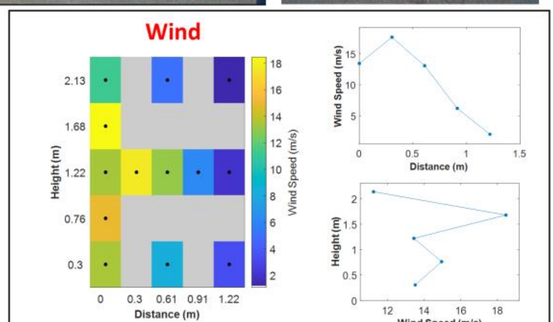
Test # B-62

Parallel Fences + Mulch

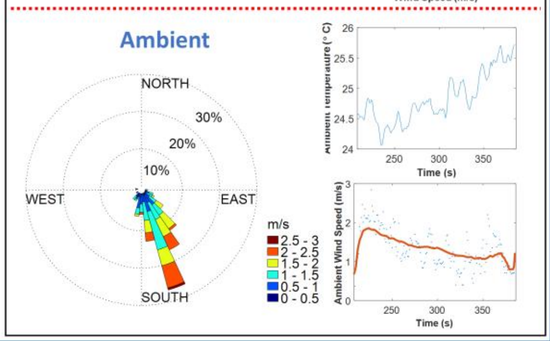
2 × Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: High
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

9/29/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:05	0:02
Time to end of fence (min:s)	1:25	0:10
Time to first spot (min:s)	1:46	0:20
Time to spot reaching wall (min:s)	1:52	0:20
Time to flames on wall (min:s)	2:44	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.1	1.1
Ambient wind speed (m/s)	1.33	0.21
Ambient wind direction (°)	159	10
Ambient temperature (°C)	24.8	4.5

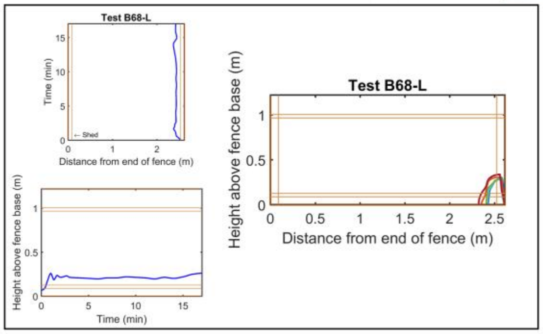


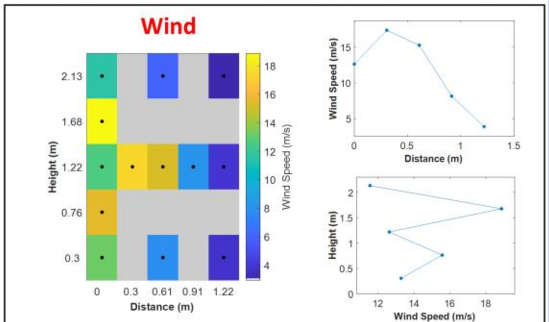
Test # B-68

Parallel Fences. No Mulch

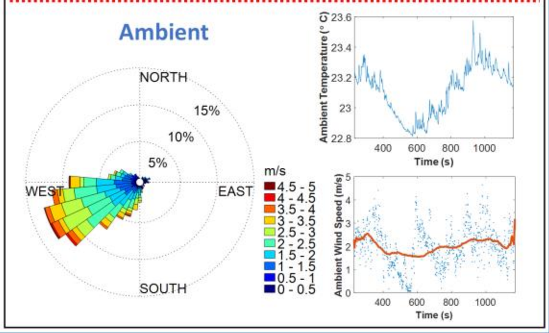
2 × Redwood Lattice Fence
Wind speed: High
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

10/4/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	15:48	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	13:53	0:20
Time to spot reaching wall (min:s)	13:53	0:20
Time to flames on wall (min:s)	14:58	0:06
Mean wind sp. 4 ctr. probes (m/s)	15.1	1.1
Ambient wind speed (m/s)	1.99	0.21
Ambient wind direction (°)	243	10
Ambient temperature (°C)	23.1	4.6

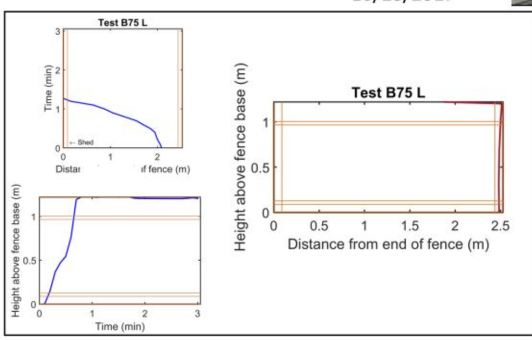


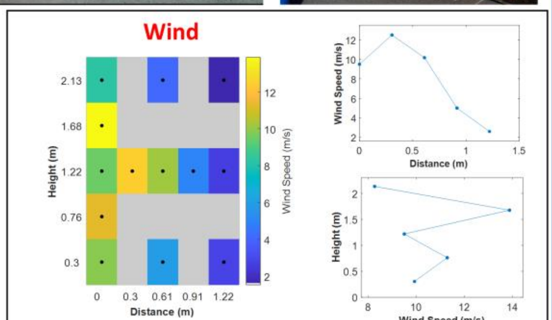
Test # B-75

Parallel Fences + Mulch

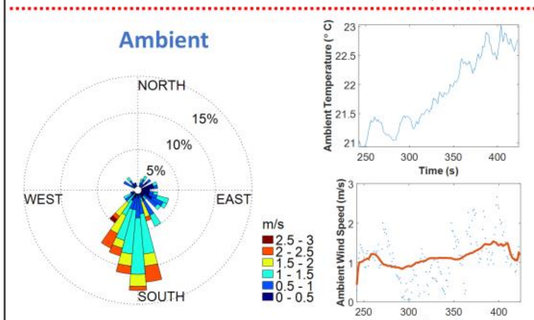
2 × Redwood Lattice Fence + Shredded Hardwood Mulch
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

10/18/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:10	0:02
Time to end of fence (min:s)	1:15	0:10
Time to first spot (min:s)	1:40	0:20
Time to spot reaching wall (min:s)	1:40	0:20
Time to flames on wall (min:s)	2:30	0:06
Mean wind sp. 4 ctr. probes (m/s)	11.1	0.8
Ambient wind speed (m/s)	1.11	0.22
Ambient wind direction (°)	173	10
Ambient temperature (°C)	21.9	4.4

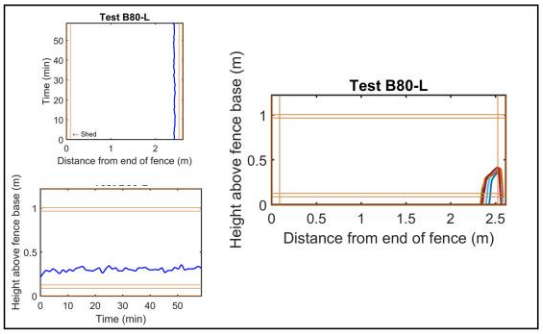


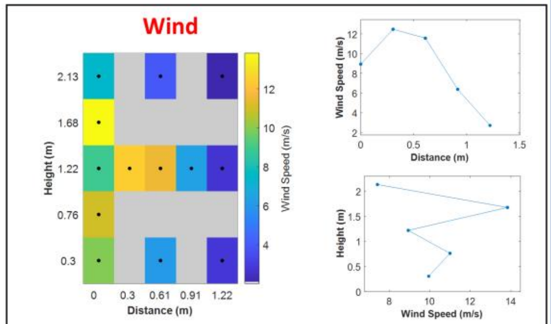
Test # B-80

Parallel Fences. No Mulch

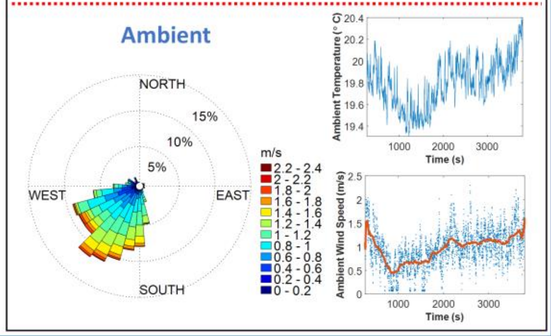
2 x Redwood Lattice Fence
Wind speed: Medium
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

11/3/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	58:56	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	54:04	0:20
Time to spot reaching wall (min:s)	54:04	0:20
Time to flames on wall (min:s)	57:44	0:06
Mean wind sp. 4 ctr. probes (m/s)	10.9	0.8
Ambient wind speed (m/s)	0.96	0.20
Ambient wind direction (°)	220	10
Ambient temperature (°C)	19.8	4.4

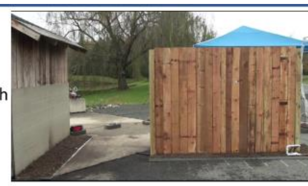


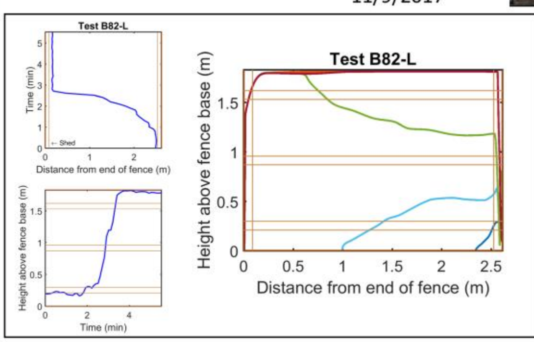
Test # B-82

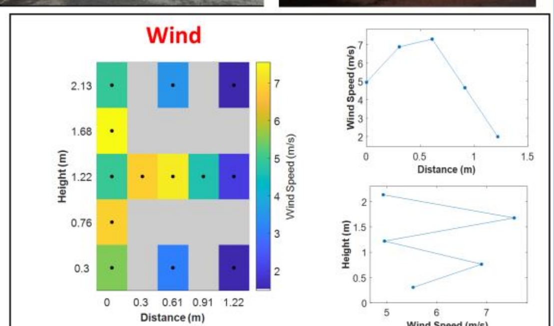
Parallel Fences + Mulch

2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 20.3 cm (8 in)

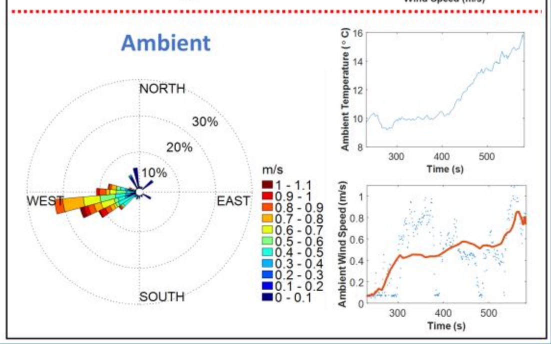
11/9/2017







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	5:54	0:02
Time to end of fence (min:s)	2:40	0:10
Time to first spot (min:s)	3:46	0:20
Time to spot reaching wall (min:s)	5:32	0:20
Time to flames on wall (min:s)	5:32	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	0.48	0.20
Ambient wind direction (°)	263	10
Ambient temperature (°C)	11.5	4.4

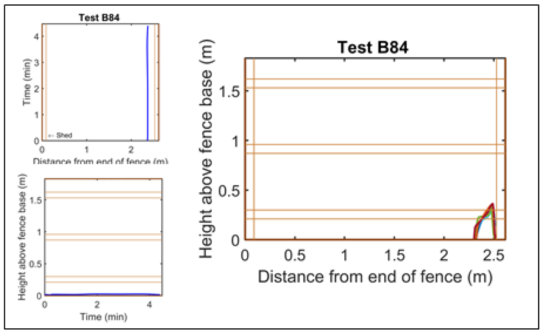


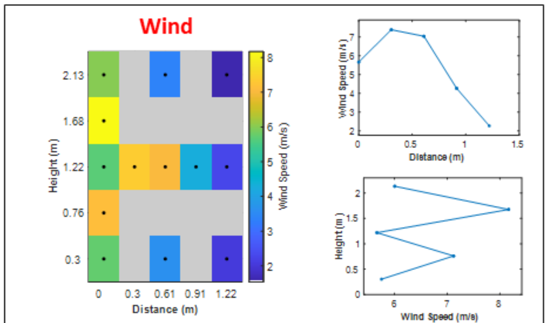
Test # B-84

Parallel Fences. No Mulch

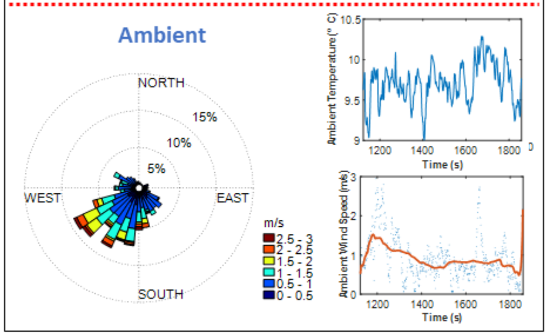
2 × Western Red Cedar Privacy Fence
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 15 cm (6 in)

11/15/2017





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	15:04	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	6.7	0.5
Ambient wind speed (m/s)	0.92	0.20
Ambient wind direction (°)	211	10
Ambient temperature (°C)	9.7	4.4

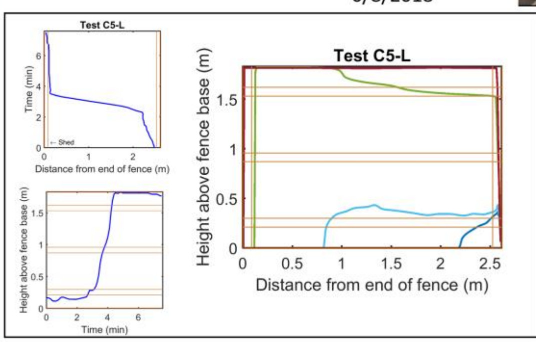


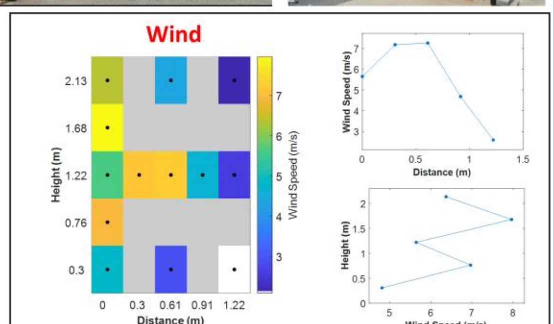
Test # C-5

Parallel Fences + Mulch

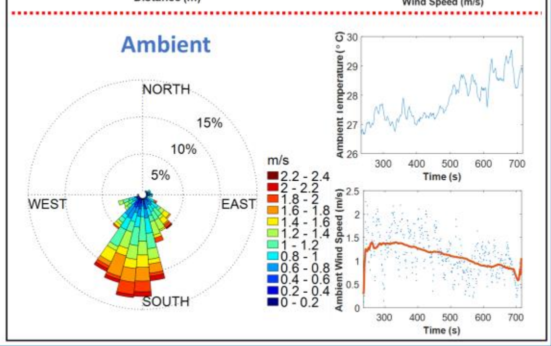
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 30.5 cm (12 in)

6/8/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	8:06	0:02
Time to end of fence (min:s)	3:16	0:10
Time to first spot (min:s)	3:31	0:20
Time to spot reaching wall (min:s)	4:28	0:20
Time to flames on wall (min:s)	5:02	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.5
Ambient wind speed (m/s)	1.13	0.20
Ambient wind direction (°)	183	10
Ambient temperature (°C)	27.8	4.5

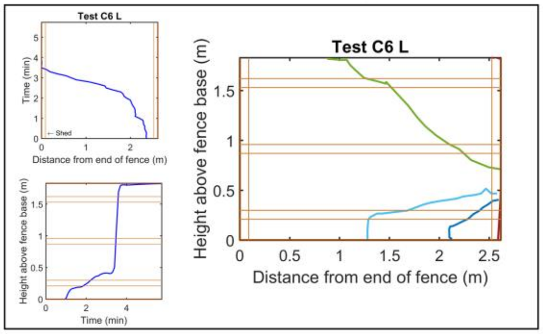


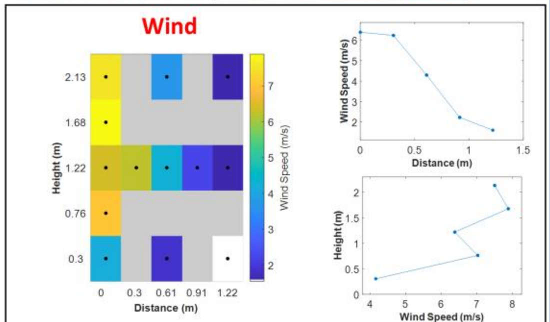
Test # C-6

Parallel Fences + Mulch

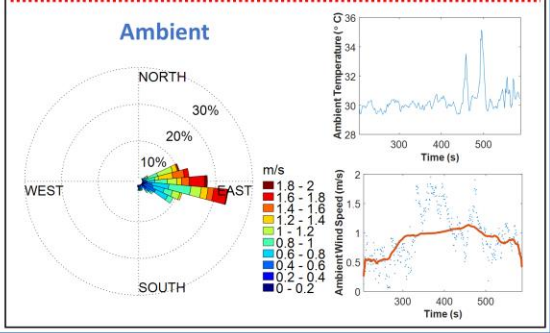
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 45.7 cm (18 in)

6/8/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:27	0:02
Time to end of fence (min:s)	3:30	0:10
Time to first spot (min:s)	3:31	0:20
Time to spot reaching wall (min:s)	4:18	0:20
Time to flames on wall (min:s)	4:31	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.4	0.5
Ambient wind speed (m/s)	0.95	0.20
Ambient wind direction (°)	100	10
Ambient temperature (°C)	30.3	4.6

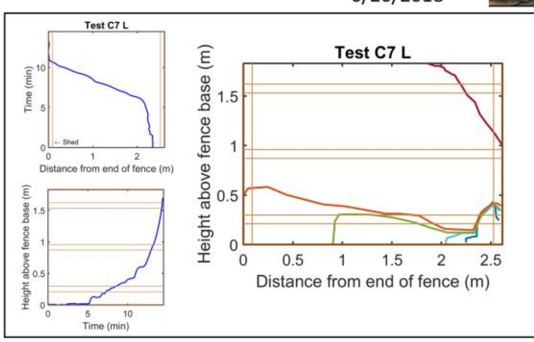


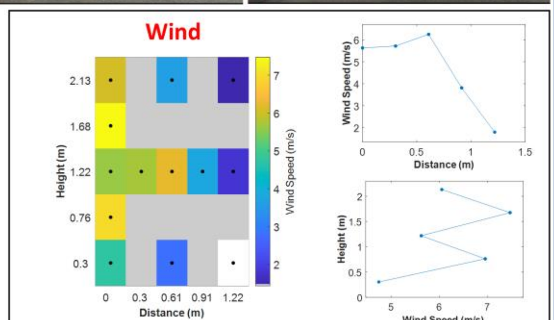
Test # C-7

Parallel Fences + Mulch

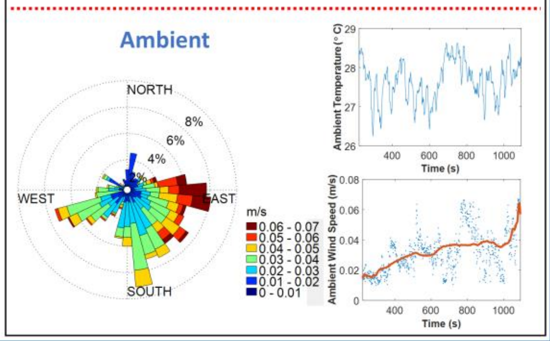
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 61 cm (24 in)

6/20/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:35	0:02
Time to end of fence (min:s)	10:50	0:10
Time to first spot (min:s)	11:21	0:20
Time to spot reaching wall (min:s)	12:39	0:20
Time to flames on wall (min:s)	13:04	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	0.03	0.20
Ambient wind direction (°)	154	10
Ambient temperature (°C)	27.7	4.5

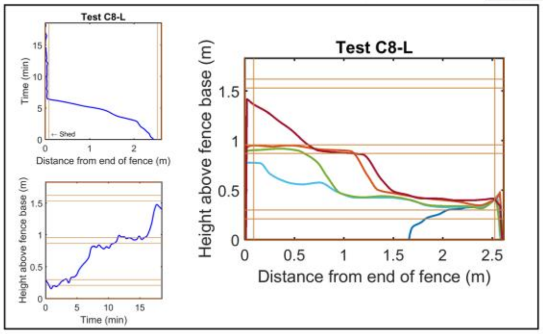


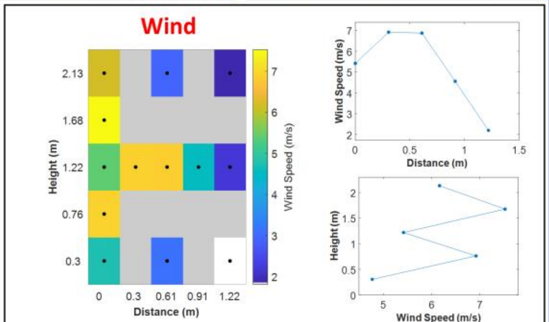
Test # C-8

Parallel Fences + Mulch

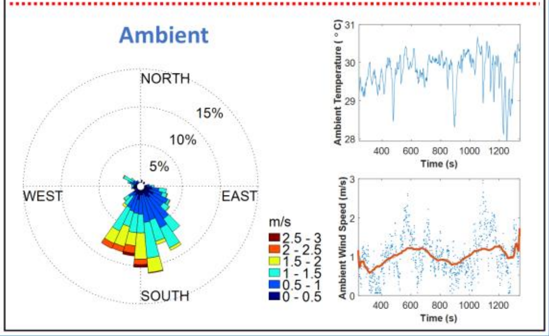
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 91.4 cm (36 in)

7/5/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	19:10	0:02
Time to end of fence (min:s)	7:50	0:10
Time to first spot (min:s)	9:51	0:20
Time to spot reaching wall (min:s)	10:33	0:20
Time to flames on wall (min:s)	13:10	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	1.01	0.20
Ambient wind direction (°)	173	10
Ambient temperature (°C)	29.8	4.5

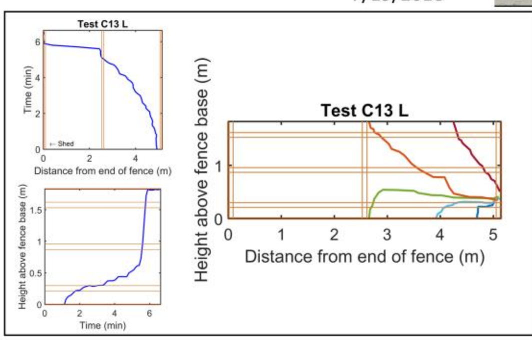


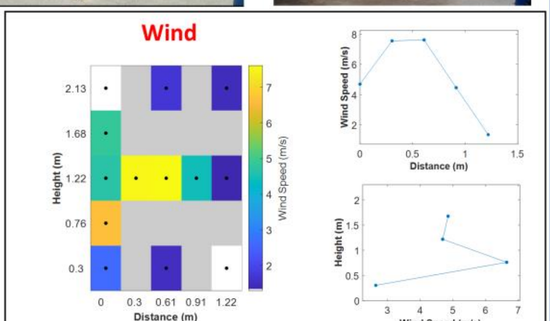
Test # C-13

Parallel Fences + Mulch

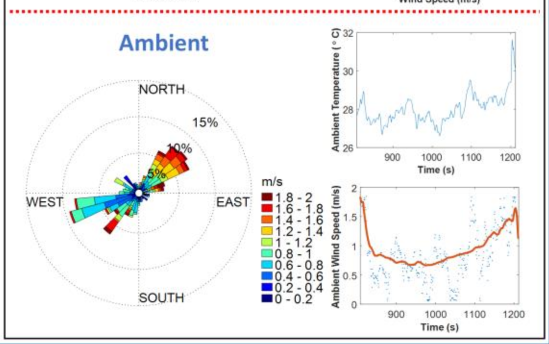
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 91.4 cm (36 in)
Double panel length

7/19/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:47	0:02
Time to end of fence (min:s)	5:40	0:10
Time to first spot (min:s)	5:59	0:20
Time to spot reaching wall (min:s)	5:59	0:20
Time to flames on wall (min:s)	6:17	0:06
Mean wind sp. 4 ctr. probes (m/s)	4.7	0.3
Ambient wind speed (m/s)	0.85	0.21
Ambient wind direction (°)	292	10
Ambient temperature (°C)	28.0	4.5

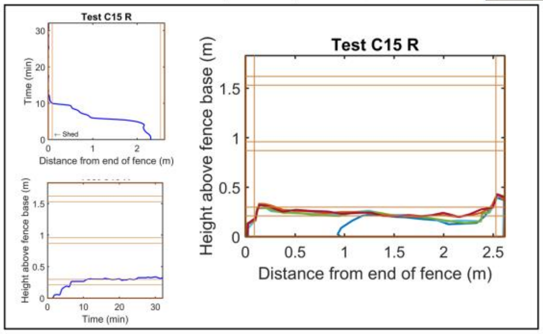


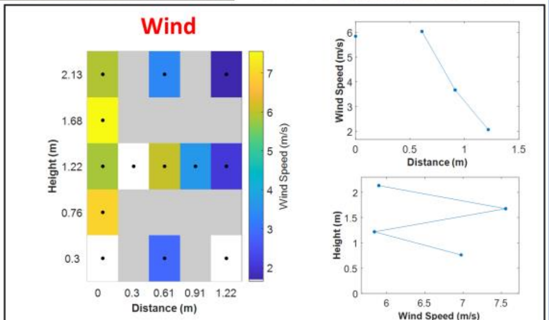
Test # C-15

Parallel Fences + Mulch

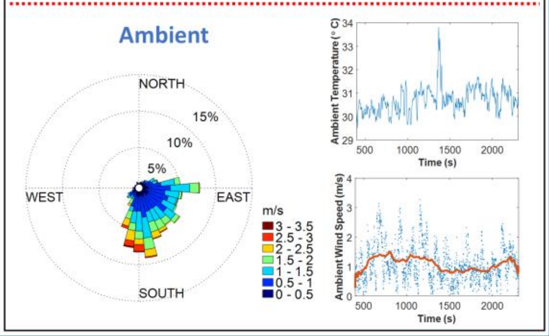
Western Red Cedar Privacy Fence / Cement Board
+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 45.7 cm (18 in)
Note: Plots are from R camera (WRC side)

8/10/2018



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	31:48	0:02
Time to end of fence (min:s)	11:20	0:20
Time to first spot (min:s)	10:51	0:20
Time to spot reaching wall (min:s)	28:37	0:20
Time to flames on wall (min:s)	31:50	0:06
Mean wind sp. 4 ctr. probes (m/s)	7.0	1.0
Ambient wind speed (m/s)	1.09	0.20
Ambient wind direction (°)	144	10
Ambient temperature (°C)	30.7	4.6

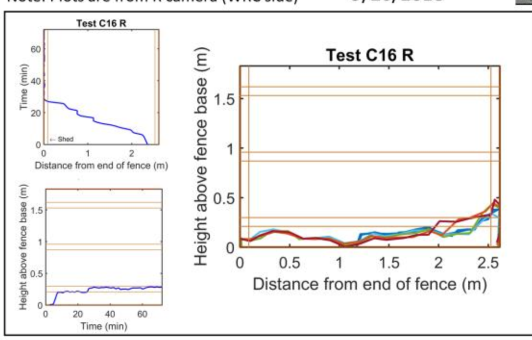


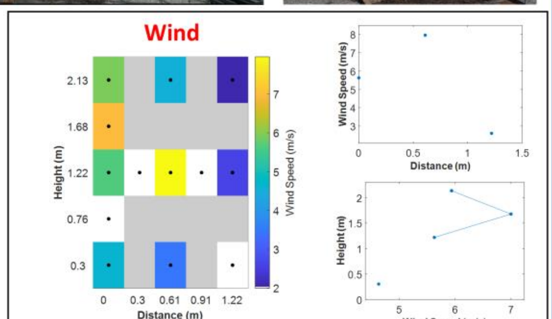
Test # C-16

Parallel Fences + Mulch

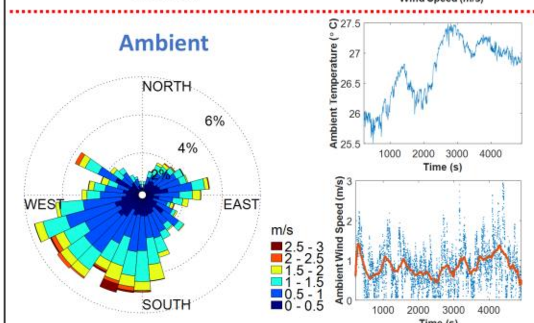
Western Red Cedar Privacy Fence / Vinyl Fence
+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 45.7 cm (18 in)
Note: Plots are from R camera (WRC side)

9/20/2018



Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	78:11	0:02
Time to end of fence (min:s)	28:20	0:20
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	5.8	0.5
Ambient wind speed (m/s)	0.85	0.20
Ambient wind direction (°)	206	10
Ambient temperature (°C)	26.7	4.5

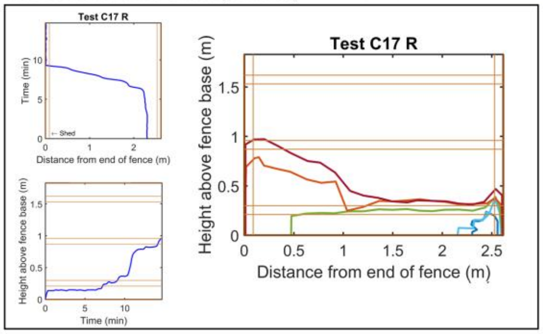


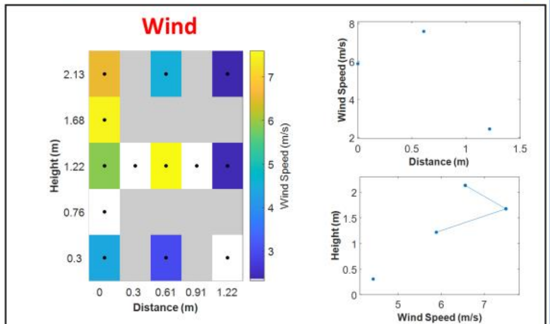
Test # C-17

Parallel Fences + Mulch

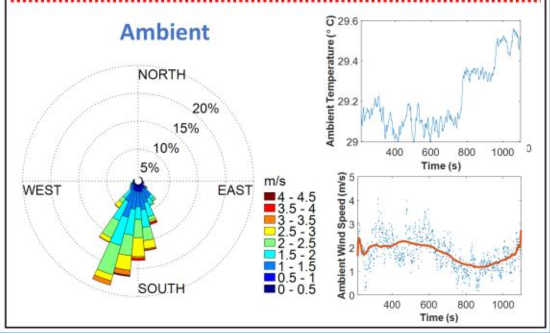
Western Red Cedar Privacy Fence / Pine Lattice
+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 45.7 cm (18 in)
Note: Plots are from R camera (WRC side)

9/20/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	14:45	0:02
Time to end of fence (min:s)	9:20	0:20
Time to first spot (min:s)	10:23	0:20
Time to spot reaching wall (min:s)	12:17	0:20
Time to flames on wall (min:s)	14:09	0:06
Mean wind sp. 4 ctr. probes (m/s)	5.9	0.5
Ambient wind speed (m/s)	1.75	0.21
Ambient wind direction (°)	186	10
Ambient temperature (°C)	29.2	4.5

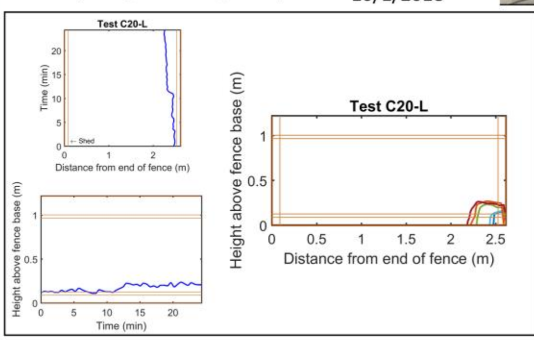


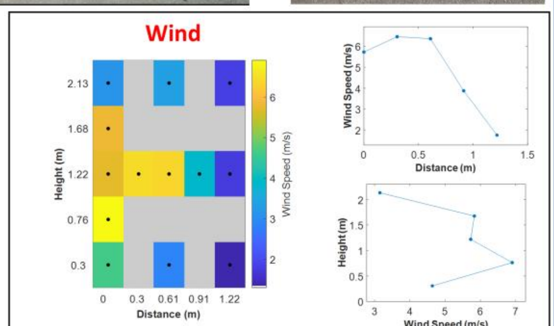
Test # C-20

Parallel Fences. No Mulch

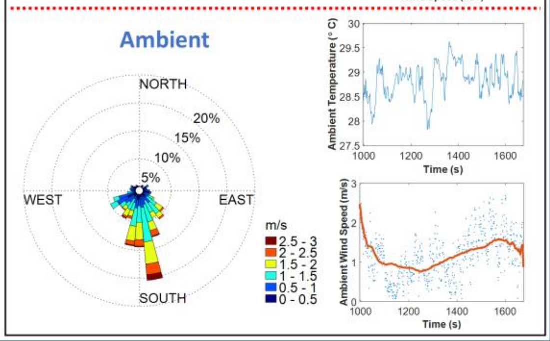
2 × Pine Lattice Fence
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

10/1/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	24:36	0:02
Time to end of fence (min:s)	--	--
Time to first spot (min:s)	--	--
Time to spot reaching wall (min:s)	--	--
Time to flames on wall (min:s)	--	--
Mean wind sp. 4 ctr. probes (m/s)	5.8	0.4
Ambient wind speed (m/s)	1.15	0.20
Ambient wind direction (°)	181	10
Ambient temperature (°C)	28.8	4.5

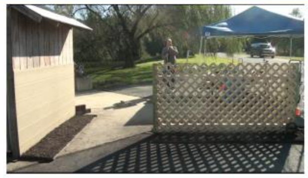


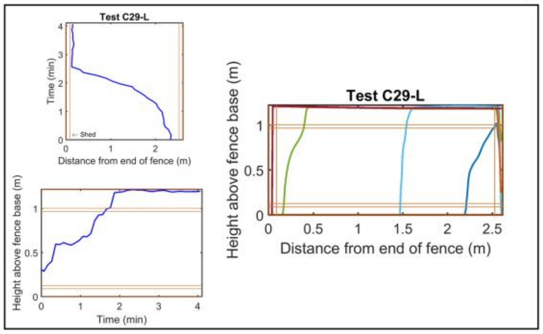
Test # C-29

Parallel Fences + Mulch

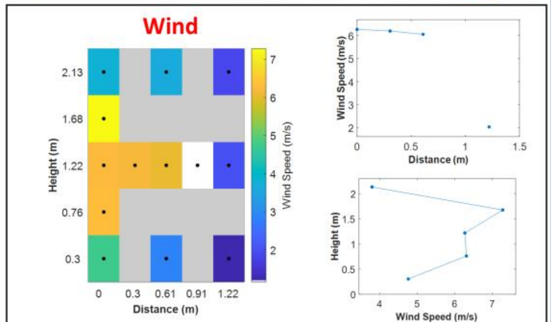
2 × Pine Lattice Fence + Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence Spacing: 8.9 cm (3.5 in)

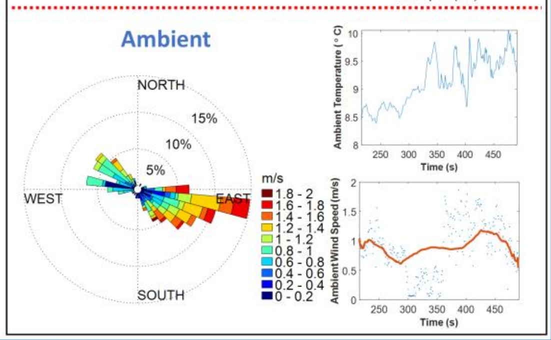
10/25/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	4:40	0:02
Time to end of fence (min:s)	2:35	0:10
Time to first spot (min:s)	1:04	0:20
Time to spot reaching wall (min:s)	2:01	0:20
Time to flames on wall (min:s)	3:01	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	0.88	0.21
Ambient wind direction (°)	120	10
Ambient temperature (°C)	9.1	4.4



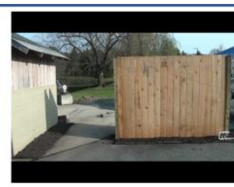


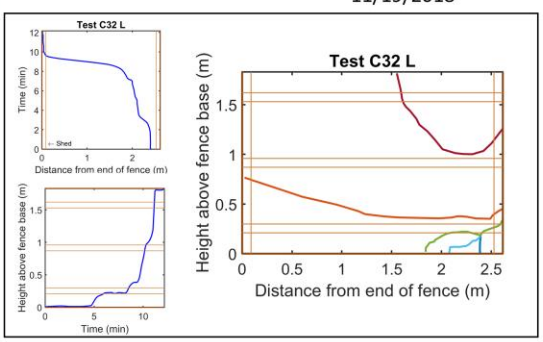
Test # C-32

Parallel Fences + Mulch

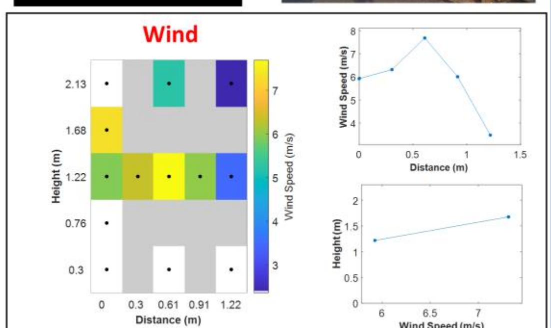
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 30.5 cm (12 in)

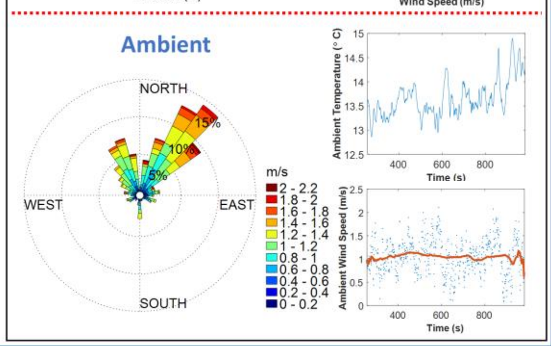
11/19/2018





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	12:23	0:02
Time to end of fence (min:s)	9:50	0:20
Time to first spot (min:s)	10:20	0:20
Time to spot reaching wall (min:s)	11:43	0:20
Time to flames on wall (min:s)	12:24	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.6	0.7
Ambient wind speed (m/s)	1.05	0.20
Ambient wind direction (°)	15	10
Ambient temperature (°C)	13.6	4.4





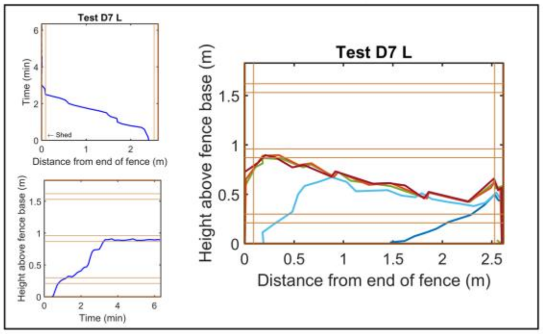
Test # D-7

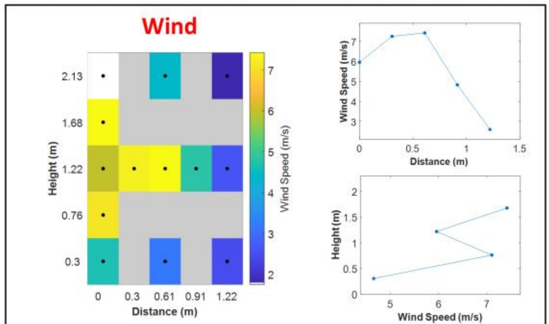
Parallel Fences + Mulch

Western Red Cedar Privacy Fence / Cement Board
+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 30.5 cm (12 in)

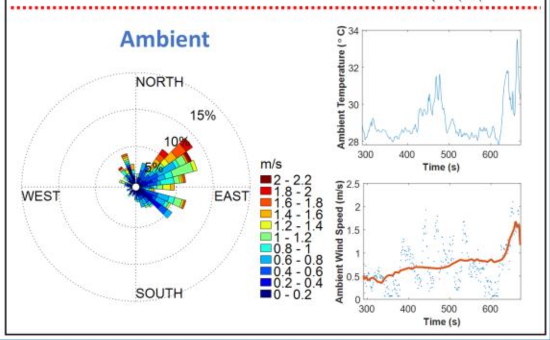
7/26/2019







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	6:25	0:02
Time to end of fence (min:s)	3:00	0:10
Time to first spot (min:s)	4:27	0:20
Time to spot reaching wall (min:s)	4:27	0:20
Time to flames on wall (min:s)	4:52	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.3	0.4
Ambient wind speed (m/s)	0.73	0.21
Ambient wind direction (°)	71	10
Ambient temperature (°C)	29.0	4.5



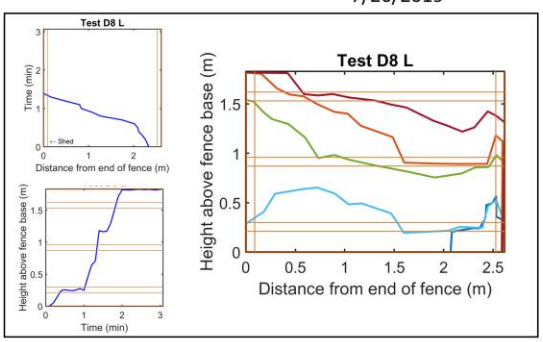
Test # D-8

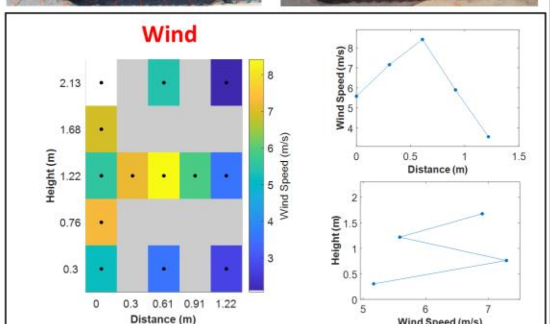
Parallel Fences + Mulch

Western Red Cedar Privacy Fence / Pine Lattice
+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 30.5 cm (12 in)

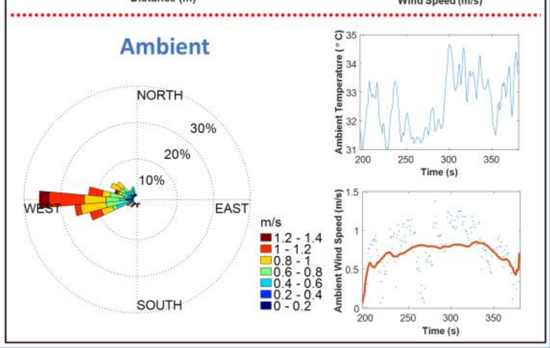
7/26/2019







Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	3:08	0:02
Time to end of fence (min:s)	1:20	0:10
Time to first spot (min:s)	1:22	0:20
Time to spot reaching wall (min:s)	2:11	0:20
Time to flames on wall (min:s)	2:37	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.2	0.4
Ambient wind speed (m/s)	0.77	0.20
Ambient wind direction (°)	273	10
Ambient temperature (°C)	32.6	4.6

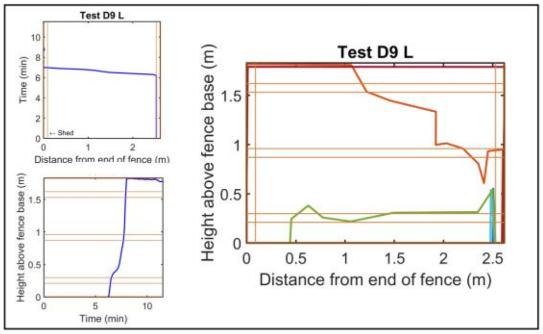


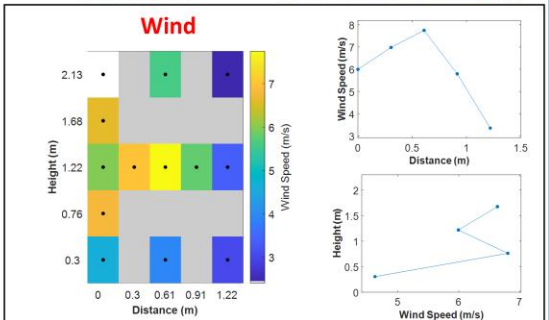
Test # D-9

Parallel Fences + Mulch

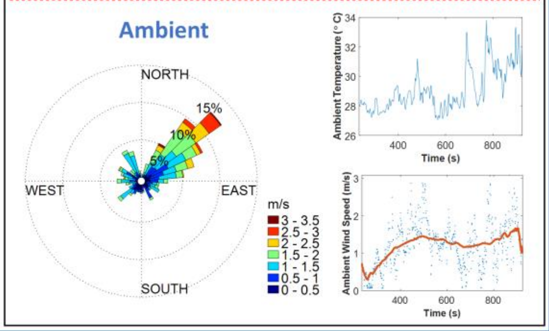
2 × Western Red Cedar Privacy Fence+ Shredded Hardwood Mulch
Wind speed: Low
Sep. distance: 1.8 m (6 ft)
Fence spacing: 30.5 cm (12 in)
Note: R/L camera views of half of fence closest to ignition site are blocked

8/1/2019





Variable	Value / Average	Expanded Uncertainty
Test duration (min:s)	11:34	0:02
Time to end of fence (min:s)	7:10	0:10
Time to first spot (min:s)	8:56	0:20
Time to spot reaching wall (min:s)	8:56	0:20
Time to flames on wall (min:s)	9:28	0:06
Mean wind sp. 4 ctr. probes (m/s)	6.0	0.4
Ambient wind speed (m/s)	1.22	0.21
Ambient wind direction (°)	46	10
Ambient temperature (°C)	29.1	4.5



Appendix J. Change Log

In December 2022, the following changes were made to the report:

- Acknowledgments – Added appreciations for the contributions of Captain Kathleen Harne, Erica Kuligowski, and Nelson Bryner.
- Executive Summary, p. 11, Section 6.1.5 Low Hazard Configurations, p. 194 – Specified that fences "in contact with the ground" can trap and accumulate windblown debris along their length.
- Section 1.1 Motivation, p. 17 – Corrected "defensive space" to "defensible space."
- Section 5.1 Hazardous Scenarios – Rewrote sentence describing fences acting as a ladder fuel to improve clarity.
- References – Deleted references not cited in the text.