NIST Technical Note
NIST TN 2251

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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Abstract

NIST is studying how combustible landscape features around a home burn to better understand their levels of hazard and potential roles in spreading wildland-urban interface (WUI) fires. A series of field experiments was conducted to examine the effects of burning firewood piles on fire spread toward a structure under conditions that may be encountered during a WUI fire. The fire behavior of a variety of firewood species in multiple configurations was studied under various wind conditions. The 62 experiments conducted included long range firebrand travel and fire spread mitigation experiments. Wood species included kiln-dried maple, oak [dried and not dried ("green")] and eastern white pine. Configuration variations included woodpile height, orientation, and elevation on a rack. A wind machine provided a mean wind speed between a nominal 6 m/s and 14 m/s (13 mi/h to 31 mi/h). The woodpiles were ignited by a propane burner on the ground at the end farthest from a small structure located between 0.91 m and 7.32 m (3 ft to 24 ft) downwind of the woodpile. A target mulch bed at the base of the structure evaluated the ability of firebrands produced by the burning woodpile to ignite spot fires that could threaten the structure.

The experiments in this study demonstrated that firewood piles can be rapid sources of spot fire ignitions and can easily spread fire to nearby structures. Rapid fire growth on and substantial flames from the woodpiles were found for all wood species and configurations. Fire behavior was classified as high hazard for igniting spot fires under all wind conditions.

In all cases, spot fire generation was affected by the wind field; the structure created both upward flow (enhanced by buoyancy) and a vortex that deposited firebrands next to the structure. During all experiments, the burning woodpile produced firebrands that ignited spot fires in the target mulch bed. In long range experiments, firebrands from a woodpile caused ignitions over 26 m (85 ft) downwind.

This study of the fire hazard of woodpiles 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; firewood piles; woodpile fires; firebrands; fire spread; structural ignition; structure vulnerability; wildland urban interface fires; wind-driven fires; WUI fires.

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Acknowledgments

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The NIST technicians who contributed their technical expertise and hard labor to ordering supplies for, instrumenting, setting up, carrying out, and cleaning up after the 62 experiments in this study have earned our great appreciation. Many thanks to Phil Deardorff, Laurean Delauter, Tony Chakalis, Steven Fink, and Mike Selepak for their expert assistance to Rik Johnsson and Marco Fernandez in making these experiments happen.

1. Introduction

This report is the second in a series of NIST (The National Institute of Standards and Technology) experiments on fire spread from landscape combustibles to a structure. In the first report, we presented a study on fire spread via flames and firebrands from fences and mulch [1]. In this report, we describe the hazard to a structure due to flames and firebrands from woodpiles. All experiments were performed at the same location as the fence study with a nearly identical experimental setup, instrumentation, and procedure. For the readers' convenience, the sections of this report describing those common aspects are repeated here, with slight adjustments to account for differences between the two experimental series.

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 or grows within a community, its structures and landscape features can add to and may come to dominate the fire sources, magnifying the hazard. Combustible elements in a neighborhood may transform from being the targets of flames and firebrands 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.

NIST has undertaken a long-term project to assess fire hazards in our built environment and develop a mitigation methodology to harden it against firebrand and flame exposures. This report on firewood piles 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 dwellings are adjacent to or intermixed with wildland vegetation A large and growing number of people live in WUI areas in the United States. 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. 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.

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 of damage to the built environment associated with wildfires have increased in time; of the 20 most destructive fires in California history, more than half occurred since 2017 [2]. At the top of this list is the Camp Fire of November 2018, which resulted in 85 fatalities and the destruction of 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 [3]. The second most destructive fire was the Tubbs Fire in Sonoma County in October 2017, which resulted in 22 deaths and over 5 000 destroyed structures. 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. A multiyear Camp Fire case study is currently ongoing, with the fire progression timeline already published [4]. A report on notification, evacuation, and temporary refuge areas (NETRA) will be published soon, with the final report focusing on responder actions and structure survivability.

Firewood piles have been identified as common contributors to the spread of WUI fires within communities. Instances of fires spreading to structures from woodpiles were observed in the Witch Creek Fire [5]. 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, landscape combustibles may ignite nearby objects, including homes, 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 Chapter 7A in the California Building Code; 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[1] (HMM) was developed based on the relationships among fuel layout, fire hazard, and structure hardening [6].

For maximum effectiveness, these efforts would be best served by 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 improve community resilience to these fires. The hazard may be reduced through improvements in materials, building designs, and configurations. Firewood piles present a challenge because they cannot be replaced by a noncombustible alternative. In order to safely retain firewood piles on homeowners' properties in at-risk areas, the potential exposure needs to be understood so that mitigation strategies can be developed.

The goal of this research was to improve our understanding of the mechanisms by which firewood piles can transport fire to a home, with a focus on firebrand ignition of near-building combustibles. 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 influence codes, standards, and best practices 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 (also called embers). In contrast to the large body of knowledge on

[1] The Hazard Mitigation Methodology (HMM) [6] has been developed in a collaboration among NIST, The California Department of Forestry and Fire Protection (CAL FIRE), and the Insurance Institute for Business & Home Safety (IBHS).

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 (with added complexities of local topography such as slope and local weather such as wind and humidity), the wide variety of WUI fuels (vegetative and structural), and the extensive assortment of exterior construction materials and assemblies (with responses affected by particular designs and weathering). The research presented in this report joins other efforts to better understand structure vulnerabilities to fires from nearby firewood piles.

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 additional firebrands and flame radiation exposures to surrounding fuels (targets).

1.2.2. Landscape Feature Fire Studies

Unlike fences, landscape timbers, and retaining walls, woodpiles usually don’t have a linear character and don’t act as connections of burning material to a structure unless they are located close enough to the structure for potential flame contact while burning. It is common, especially where WUI fires are not a concern, for firewood piles to be located near or against residences or auxiliary structures or at the edge of parcels where they may be close to structures on an adjoining lot. In these cases, exposure of nearby combustibles to woodpile flames could be an issue.

Nevertheless, woodpiles do share the firebrand generation aspect of other landscape combustibles such as those mentioned above. The recent NIST study on fences [1] found that: 1. a combustible ground cover such as mulch can generate many firebrands that ignite downwind spot fires and 2. when combined with fences, firebrand production was enhanced. The report [1] listed prior studies of fences and mulch. While much of the study’s results were related to how fire spreads along these features, some also provided insight into how firebrands are generated and ignite downwind spot fires. This was a significant focus of the study on woodpiles described in this report.

1.3. Approach

A series of field experiments on the fire spread behavior of ignited firewood piles has been conducted by NIST. The experiments examined the growth of fire on the woodpile directed toward a structure by the presence of wind at various speeds. A primary purpose of the experiments was to observe and analyze the ability of firebrands generated by the burning woodpiles to ignite spot fires at the base of the structure.

In each of these experiments, a portable, airboat-style wind machine fan was used to direct a wind field with a prescribed speed in the direction of a small shed. A pile of firewood was assembled at a prescribed location between the fan and the shed. The woodpile was ignited with a propane burner at the end near the fan, and the growth of the fire and generation of firebrands were observed. The small shed was used as a target structure for firebrands. A target mulch bed was placed along the base of the wall to observe spot fire ignitions from firebrands. Tree species used as firewood in the experiments included oak, maple, and pine.

Realistic, yet relatively small, firewood piles were used. The findings provide context for the hazard from larger woodpiles but are not necessarily to be extrapolated linearly. Additional limitations of the study are listed in Section 4.2

1.4. Objectives

The overall goal of the work described in this report is to assess the severity of the fire hazard that firewood piles pose to structures. This was accomplished by studying the mechanism of fire spread in the presence of wind as the fire jumped via firebrands from the woodpile to combustible materials at the base of the shed. The main objectives of the experiments were:

- To observe the burning behavior of wind-driven fires on firewood piles;
- To determine whether a burning woodpile produces firebrands capable of igniting downwind combustibles and posing an ignition danger to a nearby structure;
- To understand the generation of firebrands that ignite spot fires that threaten a structure as related to wind speed and separation distance between the woodpile and the structure; and
- To determine the impact of firewood species, height, orientation, elevation, and moisture of firewood on the generation of firebrand-ignited spot fires.

It is anticipated that this work will contribute technical knowledge that will improve guidance for best practices for home landscape features and to support efforts to address the WUI fire problem by hardening structures and creating defensible space. Future reports will include a study of fire spread over landscape timbers and retaining walls. A device is being developed at NIST to provide quantitative data on firebrand flux and size. Research is also anticipated to further explore methods of mitigating the risk posed by burning woodpiles.

2. Experimental Design

To investigate the spread of fire through direct flame impingement or firebrand spotting, a series of outdoor experiments was performed on firewood piles erected in front of a structure in a generated wind field. Figure 1 shows a schematic of the experimental setup. 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 stack of firewood was arranged at a prescribed location between the structure and the wind machine. The firewood pile was located away from the wall of the structure by separation distances ranging from 0.91 m (3 ft) to 7.32 m (24 ft). This range was in contrast to the 0 m (0 ft) to 1.83 m (6 ft) range examined in the fence/mulch study [1]. To study the potential for firebrands to ignite the structure, a target pan of mixed hardwood mulch was positioned at the base of the structure wall. This mulch bed served as a surrogate for any combustible material next to a structure.

The woodpile was ignited with a propane burner to simulate prior ignition via either one or more firebrands or a nearby combustible item that in turn provided flaming exposure to the woodpile. Wind was directed at the woodpile. 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 wood species and configurations were investigated. The following sections will detail the experimental setup, equipment, measurements, conditions, and the parameters explored.

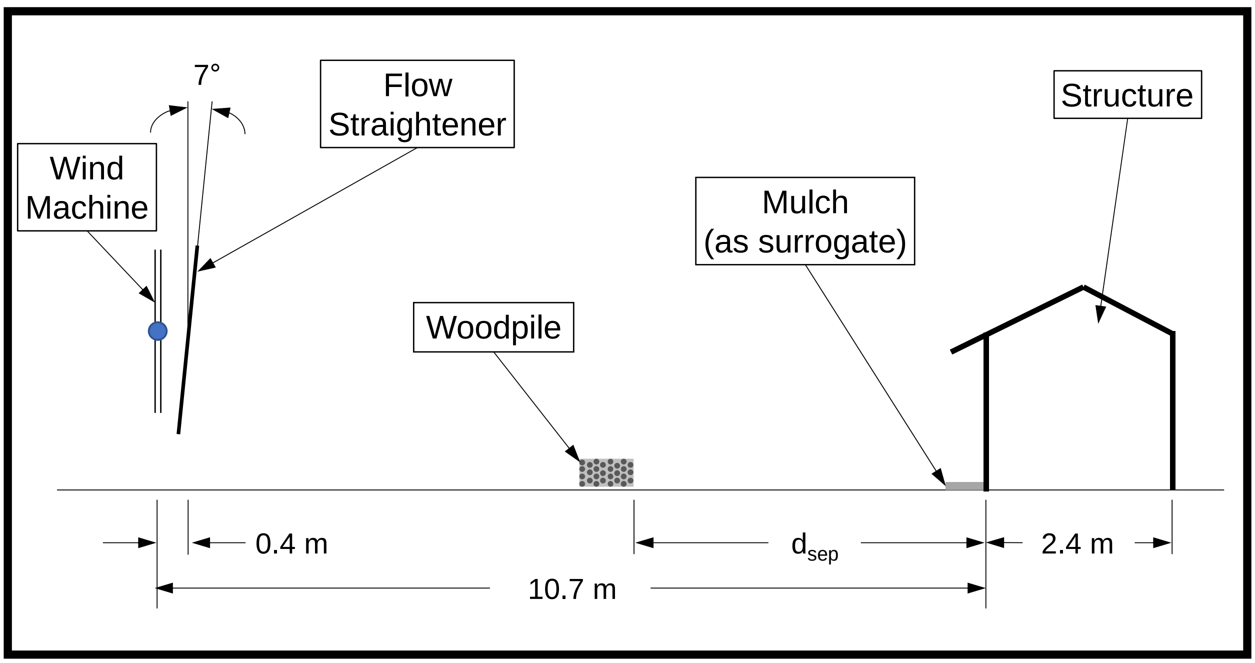

Fig. 1. Major components of the experiment (not to scale).

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 an adjacent 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. 2, marked 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 3.9 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°.

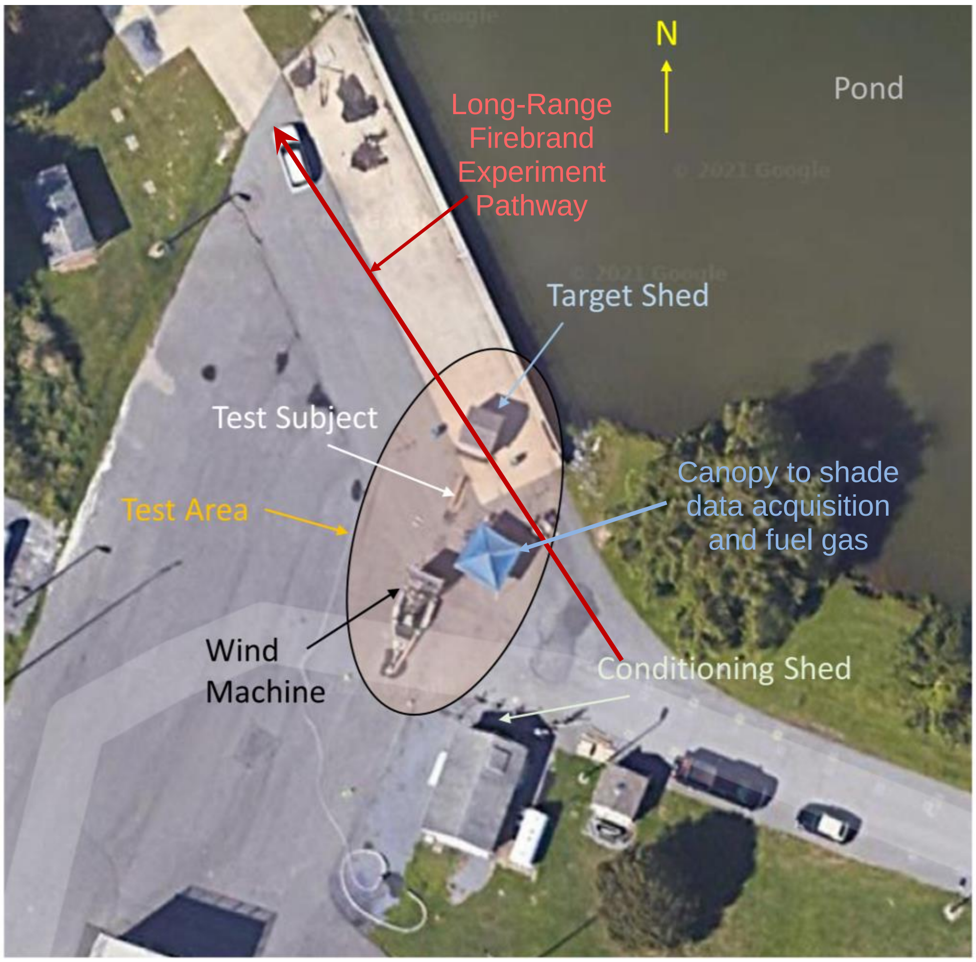

Fig. 2. Aerial view of site used for experiments. Google Earth image with NIST overlay. The red arrow shows the approximate pathway for the long-range firebrand experiments.

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. 3, 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.

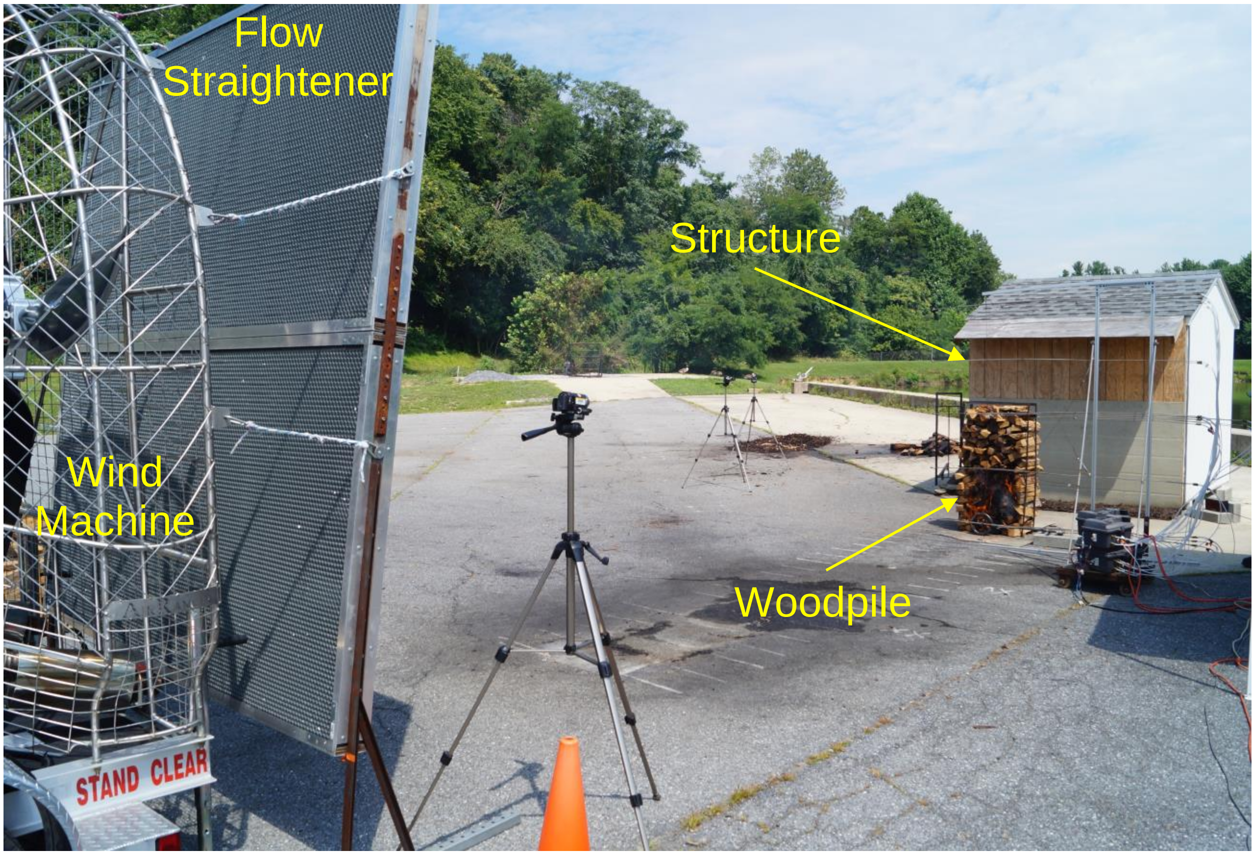

Fig. 3. Photograph of test site showing the wind machine, flow straightener, woodpile, and target shed in an experiment.

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. 3, with the front plane of the flow straightener positioned 45 cm (18 in) in front of the wind machine fan at the height of the fan center. Since the lowest sweep extent of the wind machine propellers was 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 a woodpile being tested with substantial velocity, the flow straightener was angled downward by approximately 7°. Measurements of the resulting wind field are discussed in Section 2.6.1.

2.3. Target Shed and Mulch Bed

A target shed and mulch bed were used as realistic combustible entities which could be ignited by flames or firebrands from a burning woodpile.

2.3.1. Target Shed

A target shed was used for all experiments except for the one evaluating firebrand travel. 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, potentially resulting in fire spread to the shed wall. The firebrand travel experiment was 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 is visible in the background of Fig. 3. 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 two-by-fours[2] 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 two-by-fours (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. A JamesHardie™ fiber cement siding panel was added to the bottom of the false wall, as shown in Fig. 4, 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.

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. 4 is a metal corner bead protecting the edge of the shed.

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[2] The term “2×4” or “two-by-four” 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 thickness and width (the “dressed” size) after cutting and either surfacing or planing are 3.8 cm by 8.9 cm (1 ½ in by 3 ½ in) [15]. 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).

Fig. 4. Target shed configuration.

2.3.2. Target Mulch Bed

To evaluate whether the woodpile being tested was capable of generating firebrands that could threaten a structure through spot fires, the experiments included a target bed of shredded hardwood mulch placed along the base of the shed wall, as shown in Fig. 5. 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.

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, shown in Fig. 6, 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 bed was prepared by filling the pans with an even layer of mulch and compressing the mulch by foot. 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.

Fig. 5. Target mulch bed and digital timer.

Fig. 6. A photograph of the shredded hardwood mulch used in the target mulch bed.

The mulch used in these experiments was 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 (described in 2.4.2), 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 [7] – 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. 7). 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) [7, 8]. 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. 7. Moisture analyzer used for measuring moisture content of mulch.

2.4. Firewood and Preparation

A standard cord of firewood measures 1.22 m (4 ft) wide by 2.44 m (8 ft) long by 1.22 m (4 ft) high with the width comprising the lengths of three 0.41 m (16 in) logs in line. The volume of a cord is 3.62 m^3 (128 ft^3). The amount of wood selected for each of the woodpile experiments was 1/12 of a cord or 0.302 m^3 (10.7 ft^3). The width of the woodpile used in these experiments was

0.41 m (16 in) wide or 1/3 of a cord’s width. The height of the woodpile was set at either 0.61 m (2 ft) or 1.22 m (4 ft) with the length always being the other amount.

2.4.1. Firewood Rack

A firewood rack (shown in Fig. 8 a and c) was purchased in order to evaluate whether the use of a rack and elevation of the firewood pile made a difference in the generation of firebrands and ignition of spot fires. The rack used was Style Selections model 0669018 with overall dimensions of 243.8 cm (96 in) long, 34.3 cm (13.5 in) wide to support the 0.41 m (16 in) long logs, and 124.5 cm (49 in) high. Only one half of the length of the rack was fully assembled and used in the experiments since the woodpiles were planned to be a maximum of 1.22 m (4 ft) long. The rack was made of powder-coated rectangular cross-section tubular steel. The legs of the rack were 10.2 cm (4 in) long, and the combination of the legs and the height of the horizontal members for log support combined to place the firewood 13.3 cm (5.25 in) off the ground. JamesHardie™ fiber cement panels were used to protect the asphalt pavement under the firewood whether or not a rack was used.

In order to keep the firewood secure and in the correct overall shape and dimensions while stacking the wood, two rectangular frames were fabricated. Each had two opposite sides made of 2.54 cm wide (1 in) and 6.4 mm (1/4 in) thick flat steel bar stock, and the two other opposite sides were made of 2.54 cm (1 in) wide and 4.8 mm (3/16 in) thick steel angle. The frames were attached with wire to the rack uprights. As shown in Fig. 8 a and c, these frames were helpful maintaining the woodpile shape since only half of the rack length was used. Also, the frames were used on the ground when the woodpile elevation was planned for ground level without the rack as shown in Fig. 8 b and d. Without the rack, the frames were essential to maintain the woodpile shape. The width of the angle used to make the rack was considered small enough not to have a significant impact on the wind flow or woodpile burning process.

2.4.2. Firewood Conditioning

The firewood was purchased from local vendors and was seasoned outdoors but not specially dried when it arrived. The firewood was loaded onto pallets [102 cm (40 in) by 122 cm (48 in)] that had vertical wood frames added to hold the wood in place. Each pallet with wood stacked about 0.73 m (2.4 ft) high could hold about 1/6 of a cord of wood (0.604 m^3 or 21.3 ft^3) so approximately two experiments could be supplied by one pallet. The pallets were used to transport the firewood from the drying kiln to the conditioned building, onto the NIST box truck, and off the truck at the test site. A forklift or pallet jack was used to move the pallets.

A commercial drying kiln was erected on the NIST campus for the purpose of drying large quantities of wood materials in preparation for experiments. The kiln, shown in Fig. 9, has interior dimensions of 3.14 m (10.3 ft) high by 2.34 m (7.7 ft) deep by 7.85 m (25.3 ft) wide with large racks for collecting two levels of firewood-loaded pallets. Up to 16 pallets or about 2.7 cords of wood could be dried at once. The kiln operated by circulating hot water of a set temperature through heat exchangers over which a number of fans blow mostly recirculated air. The interior air wet bulb temperature was monitored and the vent opening adjusted to allow a small amount of air exchange to cause more or less rapid drying over about 4 days to 7 days. By varying the vent opening and water and air temperatures, the wood was dried to approximately

7 % to 11 % moisture content, on an oven-dry basis. At that level, it was moved to a space conditioned to 30 % relative humidity, which drove the wood moisture content to about 6.5 %.

Fig. 8. Photos of woodpile configurations (clockwise from top left): (a) short with a rack, (b) short without a rack, (c) tall with a rack, and (d) tall without a rack.

Fig. 9. A photograph of the NIST wood-drying kiln.

Wood moisture content changes were monitored on multiple firewood logs with a Delmhorst BD-2100 conductivity meter. This device measures the electrical conductivity across two uninsulated metal prongs stuck about 5 mm into the surface of the wood. The relative humidity in the kiln and the conditioned building was verified periodically with a handheld HM40 Vaisala Compact Humidity and Temperature Meter.

2.5. Ignition Source

The test subject was ignited by a burner applied at the end of the woodpile farthest from the structure. The Imperial model IMP1273 ring jet burner is shown in Fig. 10. Propane was used for fuel. The ring 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. When the firewood was stacked on a rack, the burner was placed under the rack (see Fig. 10 center photograph); however, when the firewood was stacked directly on the ground, the burner was placed up against the woodpile (see Fig. 10 right photograph).

Fig. 10. Propane burner for igniting woodpiles.

2.6. Measurements

2.6.1. Wind Speed Profiles

The experiments were performed under imposed wind speeds from 6 m/s to 14 m/s (13 mi/h to 31 mi/h) perpendicular to and centered on the target shed wall. In order to measure the wind velocity field, an array of thirteen bidirectional probes was placed 1.22 m (4 ft) upwind of the edge of the woodpile closest to the wind machine. This location was selected to capture the wind field close to the woodpile that was 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 [9]. 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 2.8.2) were used to account for any voltage offsets.

A photograph of the bidirectional probe array in front of a burning woodpile is shown in Fig. 11, and the diagram in Fig. 12 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. 11. Bidirectional probe array.

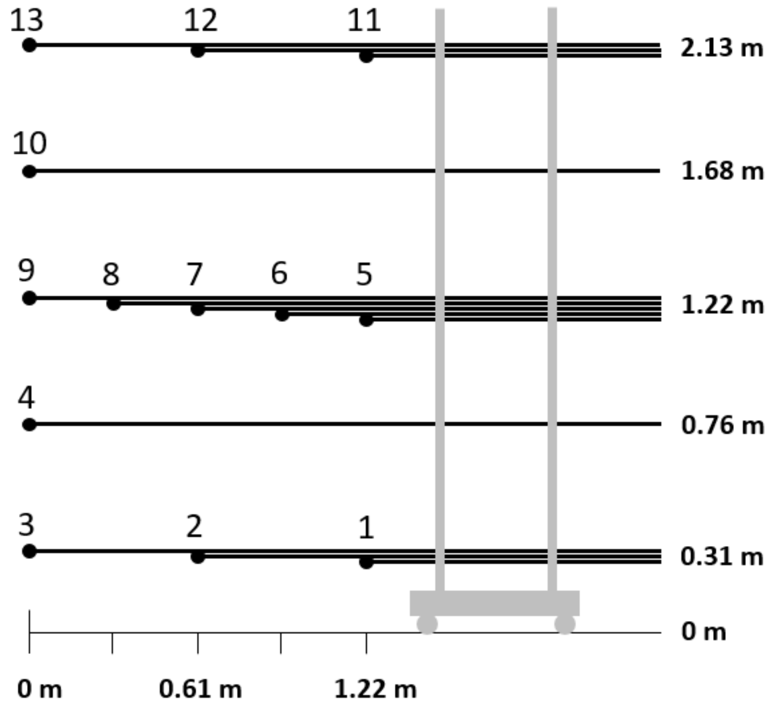

Fig. 12. Diagram of the bidirectional probe array used to measure the velocity field.

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 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 windward side of the woodpile and at least 2.74 m (9 ft) upwind from the shed, the effects of these objects on the measured wind field are minimal.

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 because the top probe was much higher than the woodpile and its output would not be representative of the winds near it.

2.6.2. 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.

2.7. Data Acquisition

2.7.1. 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 woodpile, 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.

2.7.2. Digital Video and Photographic Records

A minimum of four high-definition video cameras, Sony model HDR CX-350, were placed around the woodpile and target mulch bed to capture the fire and spotting behavior. Two cameras located on opposite sides of the woodpile (pointing perpendicular to the wind direction) included the woodpile, shed wall, and target 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 woodpile next to the wind machine flow straightener, including the woodpile, shed, and target mulch pan in their views. For most experiments with separation distances greater than 3.66 m (12 ft), a fifth camera was placed on the left side of the experiment near the target mulch bed to more closely capture the record of spot fire ignitions. Fig. 13 is a top view schematic of the experimental setup showing the relative positions of the video cameras.

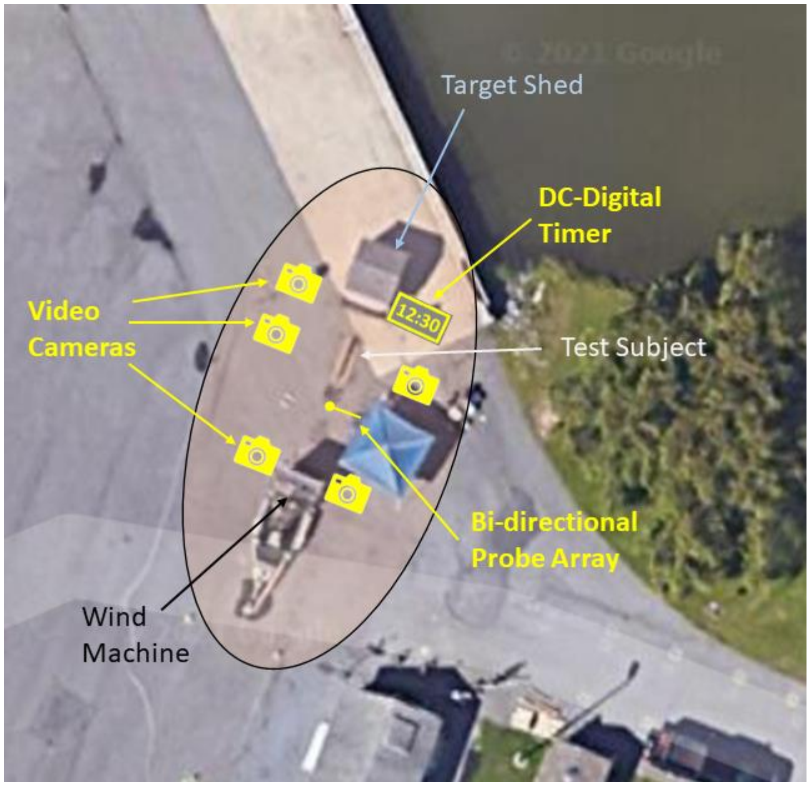

Fig. 13. Top view schematic of experimental setup showing placements of video cameras, timer, and bidirectional probe array. Google Earth image with NIST overlay.

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 woodpile position). The timer, visible in Fig. 5 and Fig. 11, was started nearly simultaneously (within a few seconds) of burner ignition. 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.

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

2.8. Experimental Procedures

2.8.1. 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 wind machine 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 was 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 forestalled by difficulties with handling tools, vaporizing propane, and drying the wet ground after fire extinguishment.

2.8.2. Preparation

Preparation for a typical experiment began with clearing the test area of debris. A JamesHardie™ fiber cement panel was placed at the approximate woodpile location to protect the asphalt pavement from the fire. The firewood rack (if being used) was placed in the planned orientation and at the prescribed distance from the shed and centered along the shed/wind machine centerline axis. If the rack was being used, rectangular frames made of angle (see description in section 2.4.1) were attached with wire to the rack in the shape of the planned woodpile. If the rack was not being used, the frames were still used directly on the ground to maintain the woodpile shape while stacking and during the experiment.

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 woodpile. The ring burner was connected to a rotameter and the propane gas cylinder and positioned under (for tests using the rack) or in front of the woodpile, with the torch heads directed at the center of the bottommost windward logs. The propane cylinder was opened and the burner line charged to adjust the burner flow, 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 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.

2.8.3. Operations

The following procedure was typical, although some minor aspects varied for some tests. The burner propane plumbing was initially charged, and the required flow was set with a rotameter and pressurized propane from the gas cylinder. After that, the ¼-turn shut-off valve nearest the burner was closed to allow instantaneous supply of gas during ignition by reopening that valve. 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 a countdown was performed and the propane cylinder was opened. At 1 min, the ignition torch was held near the burner torches until they were all ignited. The ring burner torches ignited within 1 s of the application of the ignition torch, ignition was declared, 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. This is in contrast to the procedure used for fences and mulch when the timer was synchronized with initiation of the wind machine. The time for burner ignition was recorded. For most experiments, the burner was sustained for 3 min on the woodpile in order to produce a self-sustaining fire (i.e., one that would not self-extinguish in the wind). Photographs of the woodpile fire were usually taken shortly after ignition.

Fig. 14. Ignition of woodpile by ring burner.

After the 3 min of burner operation, a countdown to starting the wind machine was performed. The wind speed was adjusted by setting the tachometer to 32π rad/s (950 rpm) for low wind [a nominal 6 m/s (13 mi/h)], 50π rad/s (1500 rpm) for medium wind [a nominal 10 m/s (22 mi/h)], and 67π rad/s (2000 rpm) for high wind [a nominal 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 propane valve was closed, and the burner was removed to protect it from the fire.

In addition to the continuous videos recorded on fixed cameras, photographs were taken from many angles and fields of view during the experiment. The photographs included overall views encompassing the entire woodpile and shed, 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; this occurred for every experiment. At the end of the test, the fires were extinguished with a water hose and post-fire photographs were taken.

2.9. Research Scope

This section describes the range of conditions that were investigated for this experimental series on firewood pile fires.

2.9.1. Parameter Summary

From May 2017 through September 2020, sixty-two field experiments were conducted on firewood piles. Woodpiles varied by firewood species, height, orientation, elevation, and moisture content. Conditions varied were separation distance from the target shed and wind speed. The parameters and numbers of tests conducted under each condition are listed in Table 1 through Table 6. The distributions of the parameters in these experiments are shown visually in Fig. 15.

Table 1. Distribution of woodpile experiments by Nominal Wind Speed

Nominal Wind Speed	Number of Experiments
6 m/s (13.5 mph)	19
10 m/s (22.5 mph)	21
14 m/s (31 mph)	22
Total	62

Table 2. Distribution of woodpile experiments by Separation Distance

Separation Distance	Number of Experiments
0.91 m (3 ft)	2
1.83 m (6 ft)	24
3.66 m (12 ft)	12
5.49 m (18 ft)	11
6.71 m to 7.32 m (22 ft to 24 ft)	12
>15 m (50 ft)	1
Total	62

Table 3. Distribution of woodpile experiments by Wood Type

Wood Type	Number of Experiments
Dry Oak	45
Moist Oak	3
Maple	10
Eastern White Pine	4
Total	62

Table 4. Distribution of woodpile experiments by Woodpile Height

Woodpile Height	Number of Experiments
Tall	53
Low	9
Total	62

Table 5. Distribution of woodpile experiments by Woodpile Orientation to Wind

Woodpile Orientation to Wind	Number of Experiments
Ends of logs	30
Sides of logs	32
Total	62

Table 6. Distribution of woodpile experiments by Woodpile Elevation

Woodpile Elevation	Number of Experiments
Rack	53
No rack	9
Total	62

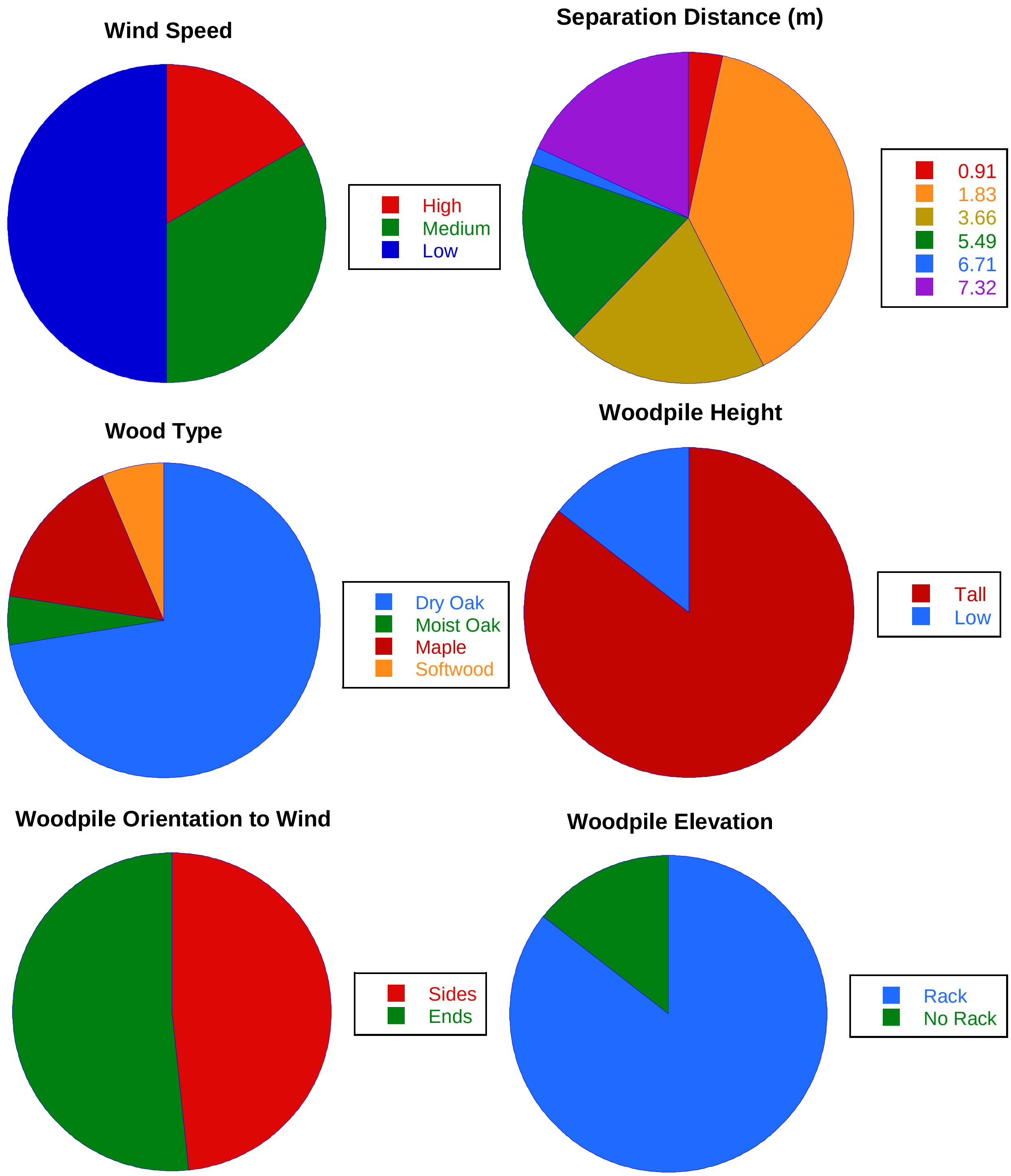

Fig. 15. Distribution of 62 experiments by wind speed, separation distance, wood type, woodpile height, woodpile orientation, and woodpile elevation.

2.9.2. Separation Distance from Structure

When the shed was present, experiments were performed at separation distances between the shed wall and the nearest end of the woodpile ranging from 0.91 m to 7.32 m (3 ft to 24 ft) including: 0.91 m (3 ft), 1.83 m (6 ft), 3.66 m (12 ft), 5.49 m (18 ft), 6.71 m (22 ft), and 7.32 m (24 ft). Fig. 16 shows diagrams of two examples of the six separation distances (SD) showing the woodpile, bidirectional probe array, and bed of shredded hardwood mulch which served as the target for spot fires. Fig. 17 is a photo of a 0.91 m (3 ft) separation experiment.

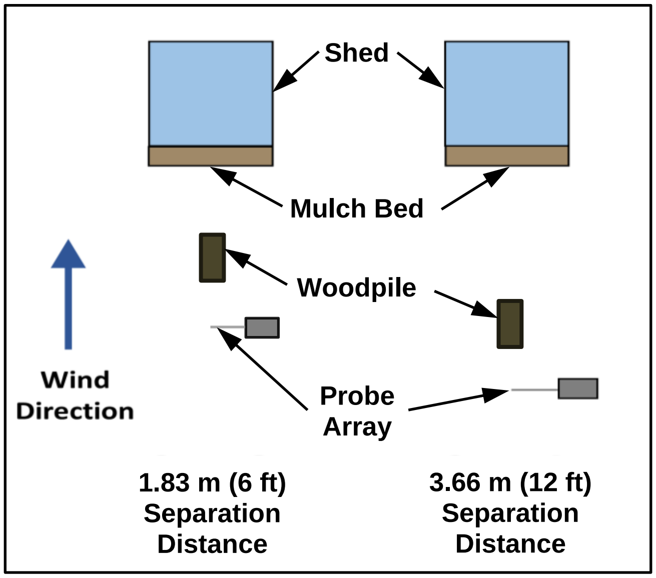

Fig. 16. Two example experimental configurations showing overhead views of woodpiles and probe arrays with the target shredded hardwood mulch bed at the structure's base.

Fig. 17. A 0.91 m (3 ft) separation distance oak logs experiment in a tall, sides, elevated configuration, within 30 s of wind initiation.

The position of the bidirectional probe array was always 1.22 m (4 ft) from the front or windward surface of the woodpile. The distance of the wind machine from the shed was 10.67 m (35 ft) in every experiment.

For the firebrand travel experiment, the shed was removed, and the distance was measured from the end of woodpile farthest from the wind machine fan to the leading edge of the target mulch bed. The long separation distances for these experiments were intended to determine the distance over which firebrands were able to ignite spot fires in a mulch bed.

2.9.3. 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 a 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.

All experiments were performed with the shed wall perpendicular to the imposed wind direction.

2.9.4. Tree Species

Three varieties of firewood were tested to determine if there were any differences in the hazard produced. Oak (*Quercus sp.*) and maple (*Acer sp.*) were selected as typical hardwoods. Neither was provided with any more specificity regarding exact species. Although softwoods are less commonly used for firewood, a supply of eastern white pine (*Pinus strobus*) was procured and tested.

2.9.5. Woodpile Height

The height and length of the woodpile were varied while keeping the volume the same to determine any effect of height on fire behavior. The woodpiles were either “tall” at 0.61 m (2 ft) high (1/2 cord height) and 1.22 m (4 ft) long (1/2 cord length) as shown in Fig. 8 c and d or “short” at 1.22 m (4 ft) high (full cord height) by 0.61 m (2 ft) long (1/4 cord length) as shown in Fig. 8 a and b.

When stacking the logs, an attempt was made to keep the dimensions of the woodpile close to the targets, although the shapes and sizes of the logs varied widely. Based on measurements of a sample of logs, it is reasonable to estimate that each woodpile dimension, on average, had a total combined uncertainty of about ±2 cm relative to the target dimensions, while individual log lengths varied by as much as about ±5 cm.

2.9.6. Woodpile Elevation

Often, firewood piles are stored on racks to provide containment for the logs, allow better air circulation around the woodpile, and prevent moisture and rot from affecting the logs near the bottom of the woodpile. A rack was selected with storage dimensions for one row of logs 1.22 m (4 ft) high and 1.22 m (4 ft) long that could accommodate 1/6 of a cord. The rack was made of steel and was 34.3 cm (13.5 in) wide with 10.2 cm (4 in) long legs.

Two 1.22 m (4 ft) by 0.61 m (2 ft) rectangular frames were constructed from 1.9 cm (0.75 in) steel angle and attached with wire to the vertical and horizontal rack members to hold the firewood on the rack in the intended shape. When used for a short woodpile as shown in Fig. 8 a, the frames extended the length of the rack and were filled to a height of 0.61 m (2 ft) off the top of the rack base where the bottom logs were laid. For the tall woodpile shown in Fig. 8 c, the frame contained the wood in the front half of the rack's length and extended the height to 1.22 m (4 ft).

2.9.7. Woodpile Orientation

Woodpiles have quite different structures when viewed towards the log ends versus towards the log sides. Looking towards the log ends, there are numerous, fairly straight air passages of various sizes through the woodpile between the logs. When viewing the log sides, the woodpile presents more like a wall; there are no straight paths for air to pass through the woodpile easily. The orientation of the woodpile to the imposed wind was varied between "ends" and "sides" in order to investigate any difference this made in the woodpile fire and its propensity to generate firebrands and ignite spot fires. Examples of ends configuration are shown by Fig. 8 a, b, and c, and examples of sides configuration are shown in Fig. 8 d, Fig. 11, and Fig. 17.

2.9.8. Moisture Content

A very limited set of experiments compared kiln-dried oak firewood to undried oak that had been sitting outside. Refer to Wood Type category in Table 3 for more information.

2.10. Video Analysis

The primary data to be collected from each experiment was 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 the target mulch bed spot fires more closely, 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, wind machine engine startup and shutdown, and the start of suppression. The frame rate was 29.97 frames/s.

The analyses for the timing of spot fires in the target mulch bed and flames reaching the target shed wall were performed on videos from the left and right cameras. When the fifth video camera was employed from the left to focus on the mulch bed, its record was much easier to use to observe the timing for phenomena instead of the left camera which captured the woodpile as well.

2.10.1. Event Timing

All four or five 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 primary event used for synchronization of the videos and referencing the timing of spot fires and flames was Fan On. Fan On marked the zero time for all analyses, and typically occurred 3 min after the propane ring burner was ignited. Time zero was simply determined aurally from when the wind machine engine started (“caught” after “turning over”) which is a distinct sound immediately after the sound of the starter and “cranking”. The is easily determined within 1 s for combined expanded uncertainty.

As a backup reference for timing in case there was an issue with the audio or when multiple videos were used to capture an experiment, the initiation of the digital timer described in Section 2.7.2 and its continued operation were visible from the camera on the left side. For the woodpile experiments, the timer was started with the ignition of the burner. The time to ignite the burner typically took less than 2 s since the ring burner ignited easily.

The timing of spot fires was measured for all of the experiments. Three simple timing measures were recorded for each experiment:

(1) the time at which the first spot fire ignited within the target mulch bed (first ignition in the mulch bed),

(2) the ignition time for the spot fire which would be the first to put flames against the wall, and

(3) the time at which sustained flames were first observed at the wall.

The rationale for determining these events is the following. Flames on the wall indicate the time at which a combustible wall could be ignited by a spot fire. The spot fire that resulted in flames on the wall is interesting because its ignition is the beginning of the chain of events that leads to the wall flames and puts the wall and structure at risk. Finally, the first spot fire, while not the one that leads to wall flames, puts the mulch bed and any other combustibles in or near the mulch bed at risk. Also calculated from these times was the length of the period between the beginning of the spot fire leading to wall flames and the time of the flames reaching the wall.

The right and left video recordings were used to identify both the first spot fire ignited and the first spot fire resulting in flames on the wall. Ignition was detected when the first visible puff of smoke at a location was distinguishable from the surroundings. The spot fires were tracked back in time to determine the ignition time. Only spot fires that continued (did not self-extinguish) were counted. Spot fires that self-extinguished produced a small amount of smoke for a short time but did not grow or spread. These short-lived spot fires could not cause the ignition of other combustibles. Sometimes, the first spot fire was also the one that was the first to impinge on the wall.

The time of flames on the wall was determined as when flames began to lick the wall either continuously or more than two times within 5 s. This criterion was used to eliminate situations when there was a brief single flame that did not persist sufficiently to ignite the surface if it were combustible.

While timing was determined from video recordings from both sides, the earliest times (usually from the camera view closest to the spot fire or flames) were selected as the actual time of the event. The maximum expanded combined uncertainties for the times to spot fires and flames on the wall were estimated at less than 4 s and time between spot fire ignition and flames at less than 5 s. Calculation of these uncertainties took into account rounding errors to the nearest second and assessment of the difficulty of precisely determining the initiation time of smoke and flame from the videos.

2.11. Wind Field Description and Analysis

The fence/mulch report [1] provided an in-depth description of the wind field generated by the wind machine from both measurement/analysis and modeling perspectives. It explained the functionality and output of the software programs used to analyze and visualize the velocity measurements. In summary, for the fence/mulch experiments, the flow field was not uniform, but the velocities were within 20 % of the average with the lowest speeds at probe nearest the ground and in the center where there is an area of lower wind speeds surrounded by higher ones, roughly in the shape of a doughnut due to the fan hub. The woodpile experiment separation distances overlapped the region described by the fence/mulch report but also extended much closer to the fan and further from the shed. As expected, the flow field was even less uniform at separation distances closer to the fan. Wind speeds at the lowest probe position were sometimes less than half the magnitude of those higher up in the array.

Appendix C.2 in the fence/mulch report [1] shows mean velocity profiles measured during experiments at four distances from the wind machine. The positions of the probe array corresponded to separation distances between the end of the fence or mulch bed and the shed of 0 m to 1.8 m (0 ft to 6 ft). In this study, the separation distance between the woodpile and the shed ranges from 3 ft to 24 ft. Appendix B includes a description of the wind speed analysis and average plots for those distances. The resulting pseudocolor plots show that for separation distances closer to the shed and further from the fan, the velocity profile is reasonably uniform over the central region of the wind field in the region occupied by the woodpile. The center velocity is somewhat lower than the assigned wind speed and increased with distance along the mulch bed toward the shed due to the angled flow straightener. The lowest probe generally experienced the lowest velocities, and for the furthest separation distance, the velocities were on the order of 1/3 of the maximum. Despite the lower velocities at the lowest probe position, the wind field did extend to the ground sufficiently to push the fire plume forward and cause fast fire spread horizontally and vertically when the wind machine was turned on.

The fence/mulch report also described the flow simulations using the Fire Dynamics Simulator (FDS) [10] computational fluid dynamics software that were generated to help understand the interaction of the wind with the structure and burning objects. With the wind perpendicular to the wall, a vortex is formed in front of the shed that causes a counterflow at the ground. Firebrands that enter the wind higher in the flow field are deposited closer to the shed wall, while those that enter lower are resisted by the counterflow and may be deposited at the front edge or side edges of the target mulch bed. Unlike the fence and mulch experiments, woodpiles present a significant wind blockage which may interact with and significantly change the flow patterns between the woodpile and shed. These differences were not modeled.

A cross-flow was added to the FDS model of the experimental setup to determine what levels of ambient wind speeds could be tolerated during experiments without significantly affecting the overall wind field and firebrand pathways. The modeling results informed the wind restrictions described in Section 2.8.1.

3. Experimental Results

The set of 62 experiments described in this report represents a survey of the effects of certain firewood piles on the spread of fire to a structure, given various wind speeds and separation distances. The wind was perpendicular to the shed wall for these experiments. The focus of this study was on spot fires ignited by firebrands. Three wood species in multiple woodpile configurations were evaluated under a range of conditions; the parameters were described in Section 2.9. The three mitigation experiments and one firebrand travel experiment are treated separately from the other 58 experiments, and the spot fire data for those four experiments is excluded from the following plots.

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 because 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, rather than on quantitative results. The existence of trends could point to potential mitigation strategies. All experiments under every combination of parameters resulted in spot fires that spread to the structure, but any conditions under which the spotting process was particularly slow would be interesting for mitigation purposes.

Wind speed was varied between 3 levels, and separation distance between the woodpile and shed was varied by 6 levels. The effects of wind speed and separation distance are shown first. The effects of firewood species, woodpile height, woodpile elevation, woodpile orientation, and firewood moisture content are then described. The graphs for the variables beyond wind and separation distance are plotted versus both wind speed and separation distance to show whether there were any discernable trends with either of those independent variables.

Wind speeds used for the results plots were calculated from the 4 lowest vertical bidirectional probe locations on the experiment centerline because the top (5th) probe was nearly 1 m above the woodpile and the wind speed there did not pertain to the lower wind's interaction with the woodpiles. Uncertainty for the average wind speed takes into account the uncertainty of the bidirectional probe pressure transducer measurement, the uncertainty in the correlation of the probe response to pressure, the uncertainty in the ambient temperature measurement, and the variation in the actual wind. The maximum combined expanded uncertainty on the values used for average wind speed was ±15 %.

Separation distances have a combined expanded uncertainty of ± 2 cm, which took into account measurement error and the uneven horizontal position of the vertical face of the woodpile facing the shed wall. For the lowest separation distance of 0.91 m, this represents a 2 % uncertainty. For the largest separation distance of 7.31 m, the uncertainty is 0.3 %.

As described in Section 2.10.1, the combined expanded uncertainty for the timing of spot fires and flames on the wall was less than 4 s. The uncertainty for the time between the wall spot fire and flames on the wall was less than 5 s.

3.1. Effect of Wind Speed

Wind speed had a strong effect on spot fire ignitions for some wind conditions. Figure 18 shows the time to the first spot fire plotted versus wind speed. with the separation distances differentiated by symbols. At the low wind speed, the timing ranged from less than 30 s to over 34 min, with many cases spread between the extremes. For the medium wind speed, the range was much tighter, from less than 30 s to nearly 3 min. The high wind speed produced times only slightly shorter than the medium wind speed. Wind speeds over 7 m/s dramatically decreased the time for the first spot fire ignition in the target mulch bed. The plot shows that at the low wind speed, the much higher times were associated with the three longest separation distances and the times below 4 min were associated with all of the short separation distances plus some of the longer ones. No distinction was seen between separation distances among the spot fire timing for medium or high wind speeds. Figure 19 is the corresponding plot for the time of the ignition of the spot fire that first reaches the shed wall. It shows the same characteristics as for the first spot fire with the same decrease in timing above the low wind speed.

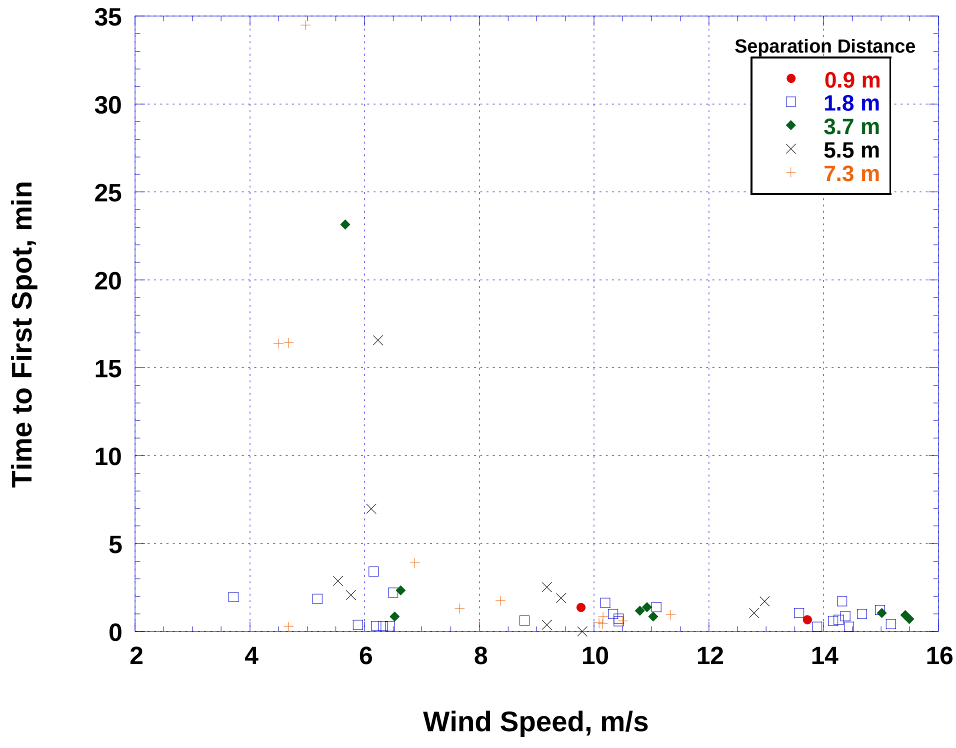

Fig. 18. Time to first spot fire plotted as a function of wind speed for all woodpile experiments with separation distance differentiated.

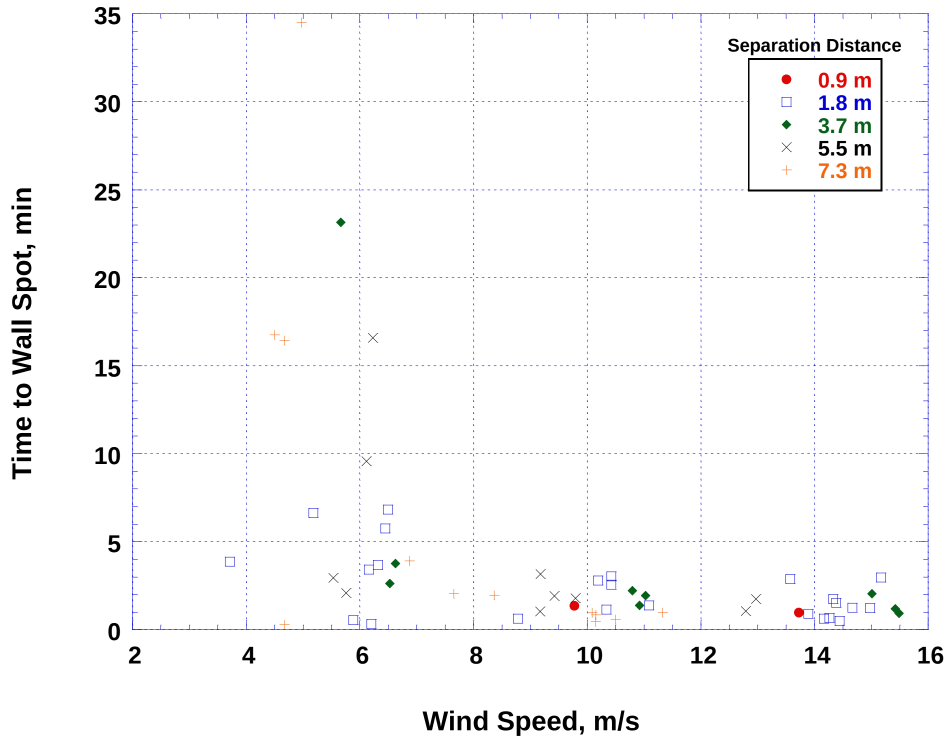

Fig. 19. Time to spot fire that first reaches the wall plotted as a function of wind speed for all woodpile experiments with separation distance differentiated.

Figure 20 shows the time for flames to reach the wall versus wind speed with separation distance differentiated. It is similar to the previous two plots but with some differences. The timing ranges were wider since time for the spot fires to spread after ignition was included. For low wind speed, the range was from less than 2 min to almost 45 min. For medium wind speed, the range was about 1 min to 5 min, and for the high wind speed, the range was less than 1 min to 4 min. While the times were longer, the trend was the same as for the spot fire ignitions. Only low wind speeds under 7 m/s resulted in prolonged flame spread to the shed, but fast flame spread was still possible at those speeds. Another difference shown is that at the low wind speed, there was not a clear trend among the three largest separation distances with the range for the longest separation distance encompassing points from the next closer distances. For time to flames on the wall, even one of the times for a 1.83 m (6 ft) separation experiment was in the middle of the range for the longer separation distances.

Figure 21 shows the plot of the time for the wall spot fire to spread to the wall after its ignition versus wind speed. For low wind speed conditions, the maximum time for the spot fire to grow to the wall was 15:15 (min:s). For medium and high wind speeds, the maxima were 1:55 and 1:05, respectively. The plot also shows that the separation distances had some but not a consistent effect on the timing since one of the 1.83 m (6 ft) separation experiments with low wind had the longest length of time between ignition and flames on the wall. Low wind speed allowed for more impact by the separation distance, although spot fires could still ignite and spread over a range of speeds for all distances.

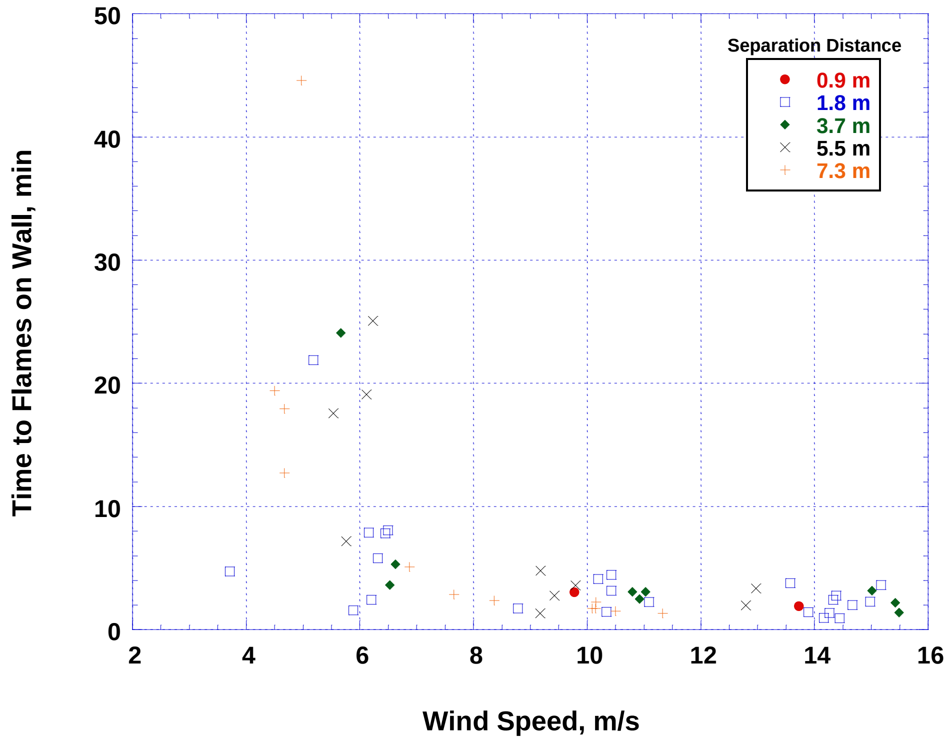

Fig. 20. Time to flames on wall plotted as a function of wind speed for all woodpile experiments with separation distance differentiated.

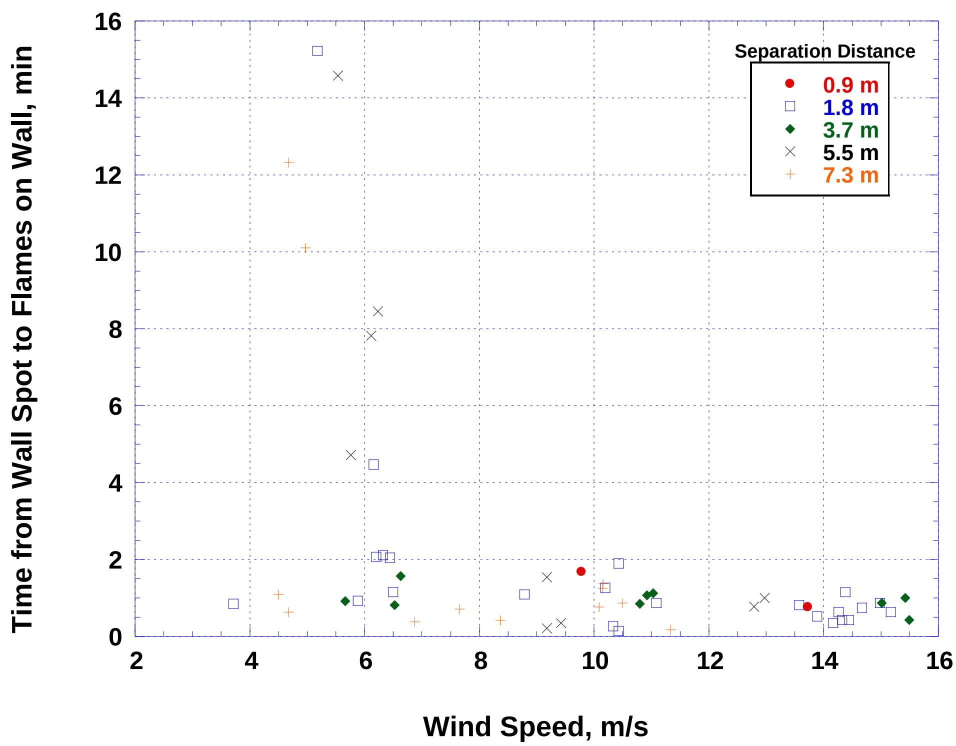

Fig. 21. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for all woodpile experiments with separation distance differentiated.

3.2. Effects of Separation Distance

Separation distance was expected to have a strong influence on spot fire ignitions since it is intuitive that the further a source of firebrands is from a target the harder it would be for them to reach the target and for some of them to ignite spot fires. The results were less conclusive than for the trend with wind speed. Figure 22 shows the time to the first spot fire plotted versus separation distance with the wind speed differentiated between low, medium, and high. At the 0.91 m (3 ft) and 1.83 m (6 ft) separation distances, the timing ranged from less than 30 s to about 3.5 min. For the larger separation distances, the majority of ignitions were still clustered at 4 min or less, but there were 1 to 3 tests at each separation distance, 3.66 m (12 ft), 5.49 m (18 ft), and 7.32 m (24 ft), for which the ignitions were greater in the 5 min to 35 min range. A case could be made that the amount of scatter, or at least the number of long ignitions, increased slightly with separation distance, but it also can be said that the separation distance had little effect on the minimum ignition time or the proportion of ignitions under 4 min.

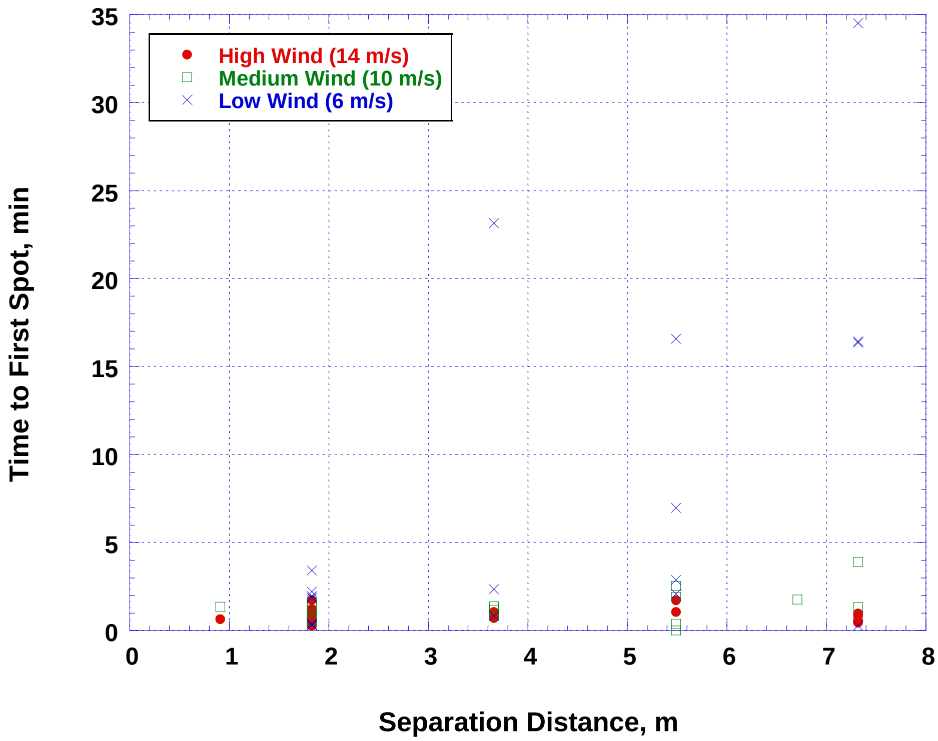

Fig. 22. Time to first spot fire plotted as a function of separation distance for all woodpile experiments with wind speed differentiated.

Figure 23 shows the corresponding plot for the time to the spot fire which first reached the shed wall. It was very similar to the first spot fire plot with the same general concentration of spot ignitions at 4 min or lower and the same slight increase in the number of longer ignitions as separation distance increased. A significant fraction, 46 %, of the spot fires that led to flames on the wall were also the first spot fire. Also of note, only a small fraction of spot fires reached the wall during the test time frame since flow conditions were not conducive for spot fires to spread forward at all locations. This was the likely source of the slight additional spread of times that can be seen, especially at the low separation distance.

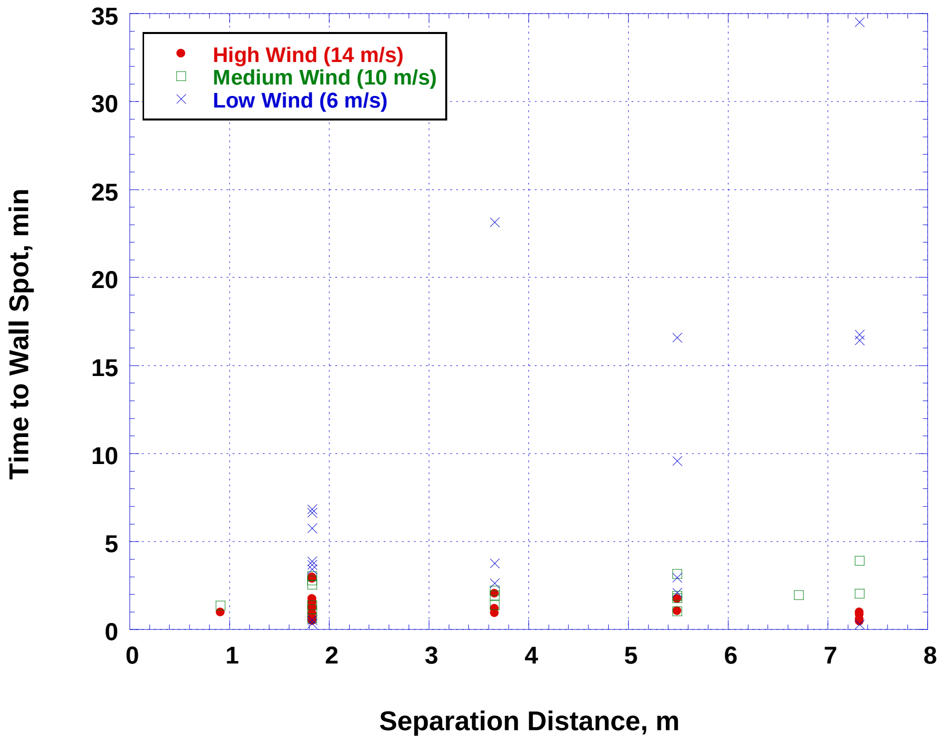

Fig. 23. Time to spot fire that first reaches the wall plotted as a function of separation distance for all woodpile experiments with wind speed differentiated.

Figure 24 shows the plot of the time for the wall spot fire to reach the wall versus separation distance. The majority of experiments at any separation distance found flames on the wall in 8 min or less. At all the separation distances with at least three experiments, there was at least one time to flames on the wall of 12 min or more. Distances of 1.83 m (6 ft) and 3.66 m (12 ft) had single instances of 22 min and 24 min, respectively. The 5.49 m (18 ft) distance had three instances between 17 min and 25 min, and 7.32 m (24 ft) had four instances between 12 min and 45 min. While again, the times to flames on the wall were clustered at under 8 min, about 16 % of tests had times over 12 min, and the frequency of these increased with separation distance.

Figure 25 shows the plot of the time for the wall spot fire to spread to the wall after its ignition versus separation distance. The times from ignition to flames on the wall for all of the experiments performed at 3.66 m (12 ft) separation were less than 2 min. 1.83 m (6 ft) separation had some instances around 2 min and one at about 4.5 min. 5.49 m (18 ft) and 7.32 m (24 ft) separation distances saw more spread of the times from spot ignition to flames with maxima of about 15 min and 12 min, respectively.

The timing for spot fire ignitions and flames reaching the wall of the shed only had limited influence from separation distance. For spot fire plots in Fig. 22 and Fig. 23 and for all separation distances, all of the spot fire ignition times greater than 5 min were for the low wind speed condition. In Fig. 24, all of the times to flames on wall greater than about 5 min were also for low wind speed. Figure 25 shows that for all experiments, all durations greater than 2 min between flames on the wall and ignition of that spot fire occurred under low wind. Greater separation distance between the woodpile and shed caused spot fires and flames to be delayed under low winds but had no discernable impact on spot fire phenomena under higher winds.

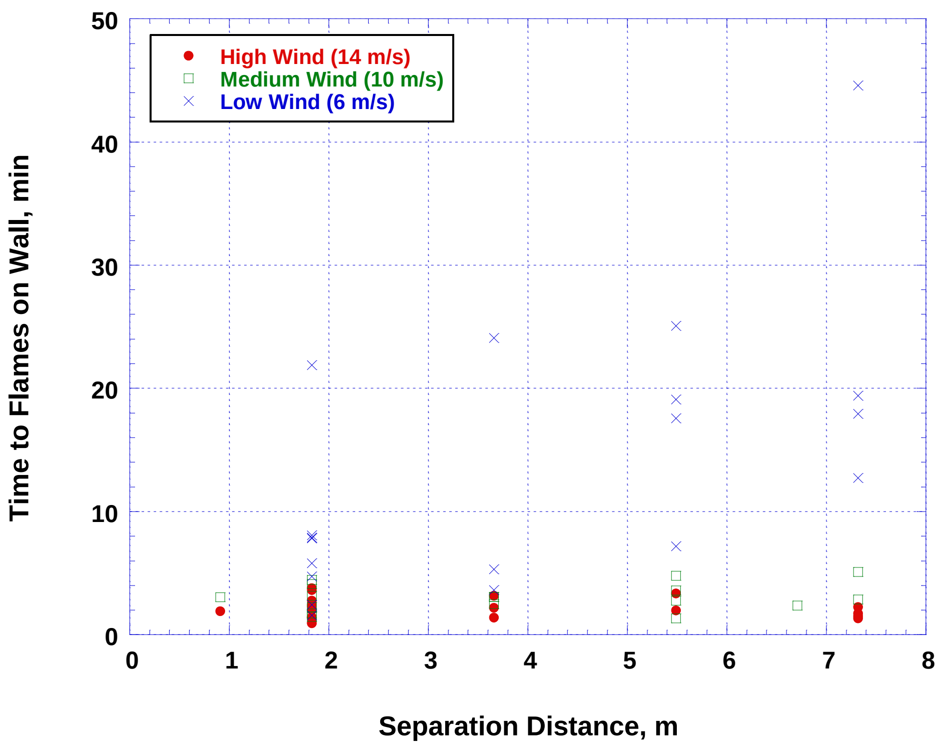

Fig. 24. Time to flames on wall plotted as a function of separation distance for all woodpile experiments with wind speed differentiated.

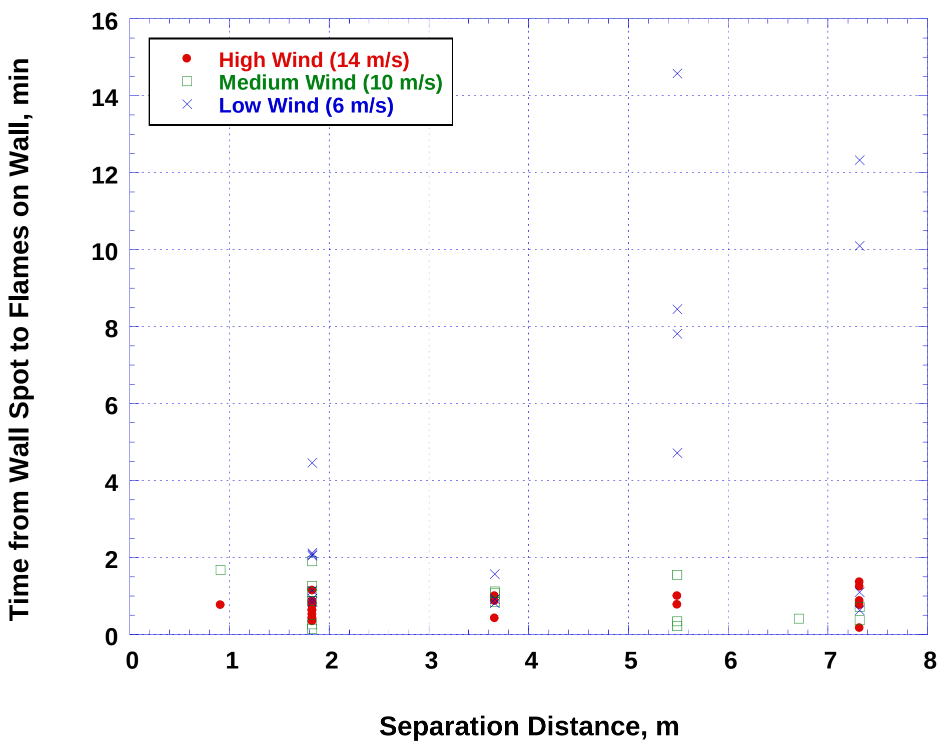

Fig. 25. Time between ignition of wall spot fire and flames on wall plotted as a function of separation distance for all woodpile experiments with wind speed differentiated.

3.3. Effects of Firewood Species

This section explores the effects of firewood species on the timing of the ignition of spot fires and for flames reaching the shed wall. The sets of timing graphs are plotted versus both wind speed and separation distance to see whether there were any trends with either.

Figure 26 shows the first spot fire time versus wind speed. At medium and high wind speeds, many of the oak times were in the 1.5 min to 3 min range while all of the maple and softwood times were below 1.5 min. At low wind speed, it appears that there was a substantially larger fraction of maple experiments that took longer than oak for the first spot fire to ignite. The same qualitative situations were true for the time for ignition of the spot that first put flames on the wall in Fig. 27.

For Fig. 28 and the time to flames, maple still seemed to require longer in general than oak for flames to reach the wall under low wind conditions, but oak and maple were indistinguishable at medium and high wind speeds. Softwood still seemed to be generally faster for spot fires to reach the shed wall under medium and high wind speeds. This same description holds for the time between ignition and flames for the wall spot ignition plotted in Fig. 29.

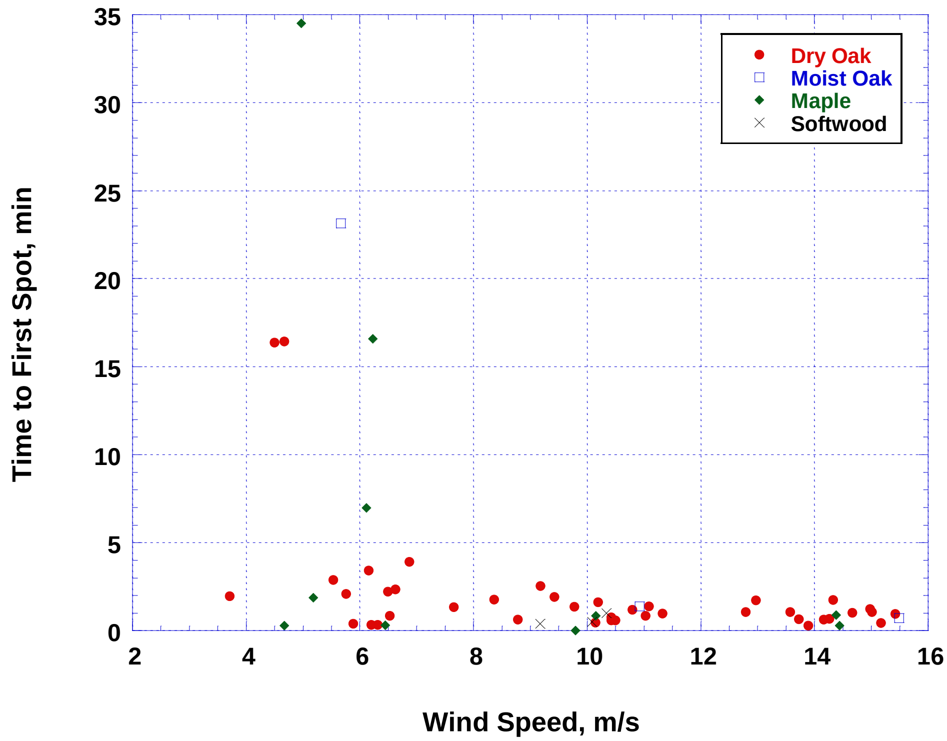

Fig. 26. Time to first spot fire plotted as a function of wind speed for all woodpile experiments with firewood type differentiated.

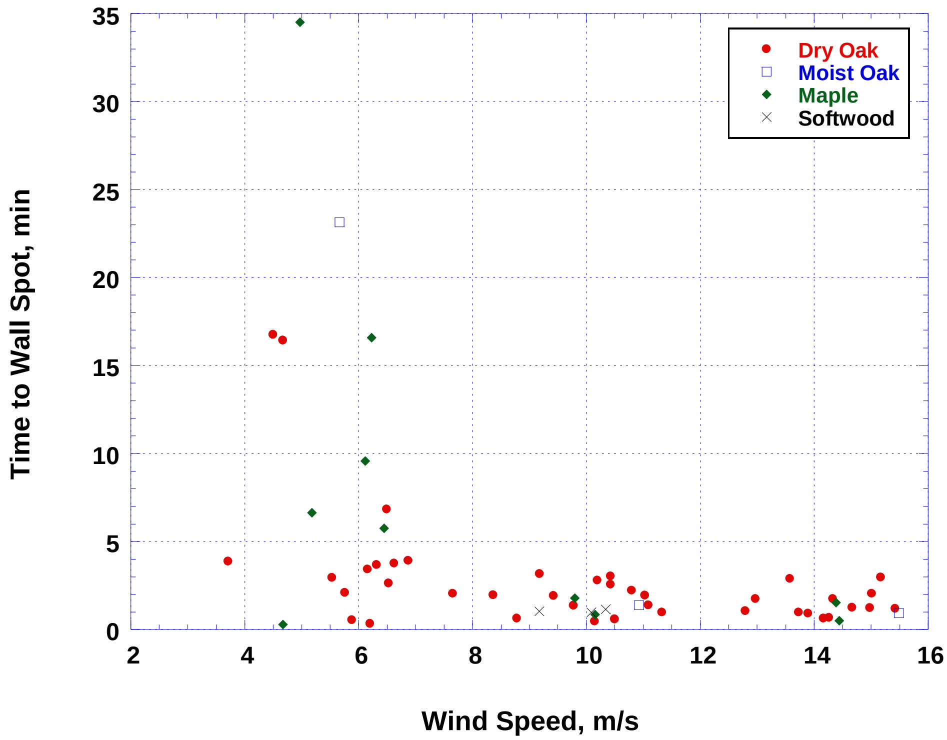

Fig. 27. Time to spot fire that first reaches the wall plotted as a function of wind speed for all woodpile experiments with firewood type differentiated.

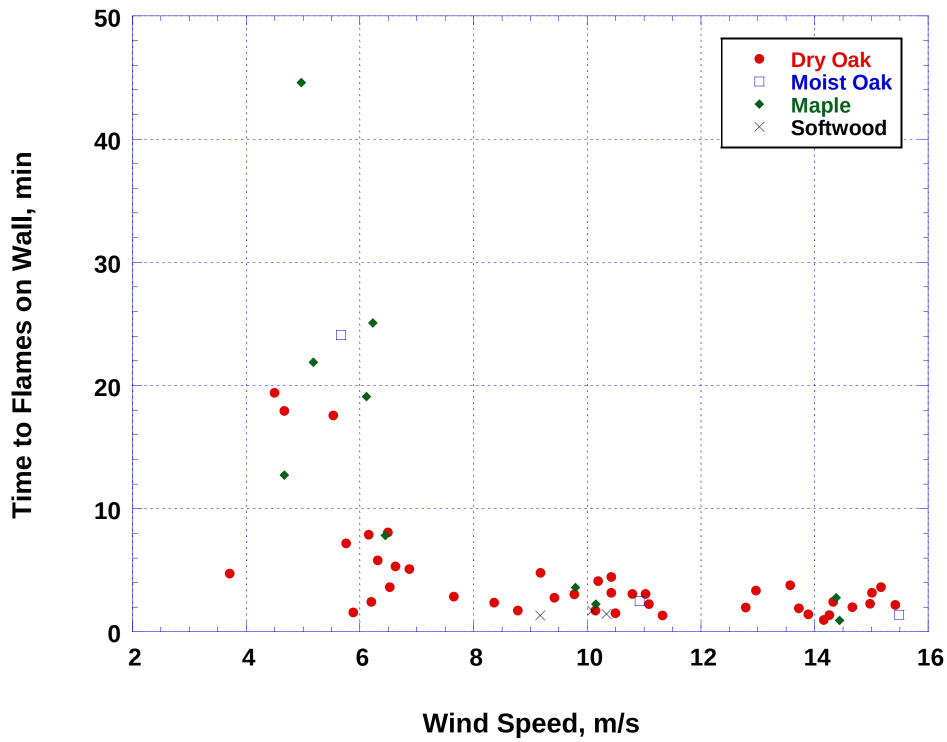

Fig. 28. Time to flames on wall plotted as a function of wind speed for all woodpile experiments with firewood type differentiated.

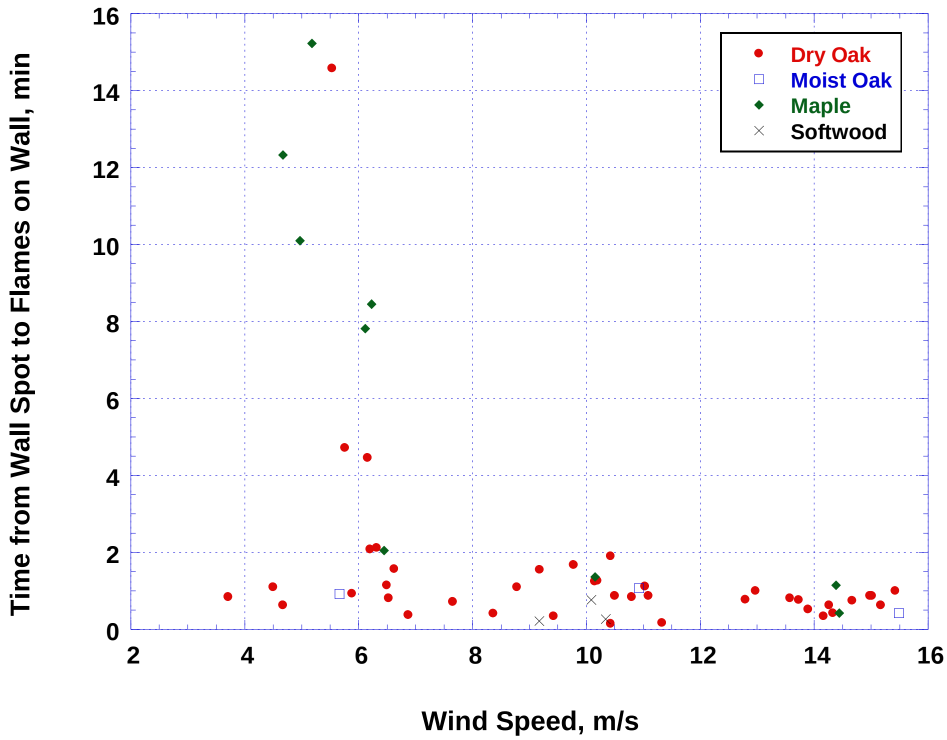

Fig. 29. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for all woodpile experiments with firewood type differentiated.

Figures 30 through 33 are the set of timing plots for different species of firewood plotted versus separation distance. For the spot fire ignition times in Fig. 29, Fig. 30 and Fig. 31, one possible distinction between wood species is that the maple produced more examples of longer ignition times at the longest separation distances of 5.49 m (18 ft) and 7.32 m (24 ft). Softwood was only evaluated at long separation distances, but it always produced fast fire spot ignitions. The same wood species distinctions carry over to the time for flames on the wall in Fig. 32 and the time between spot fire ignition and flames on the wall in Fig. 33.

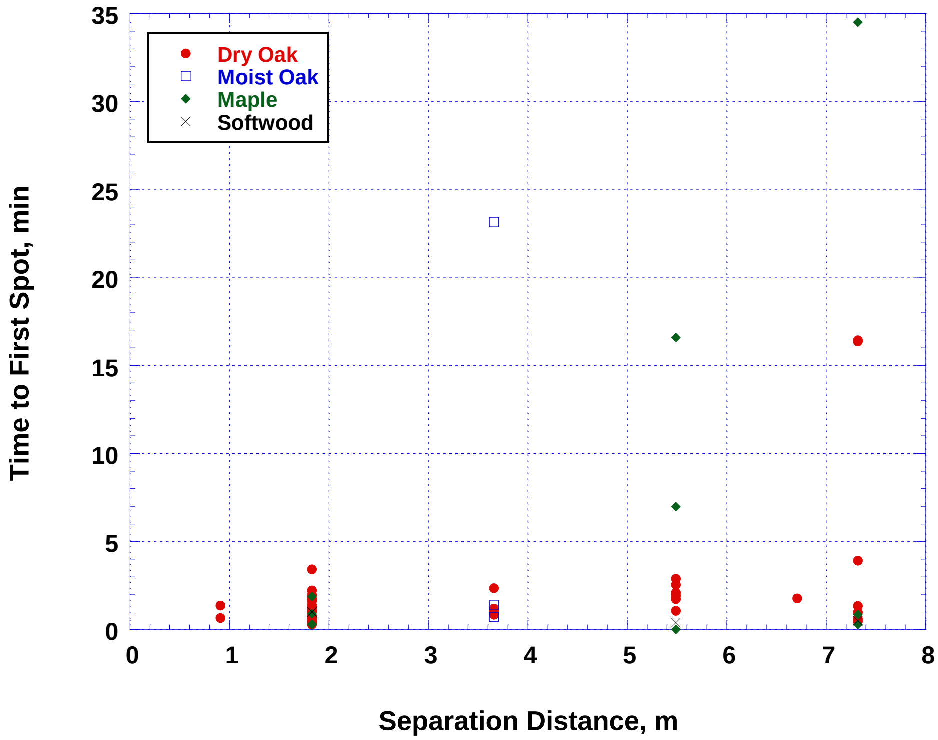

Fig. 30. Time to first spot fire plotted as a function of separation distance for all woodpile experiments with firewood type differentiated.

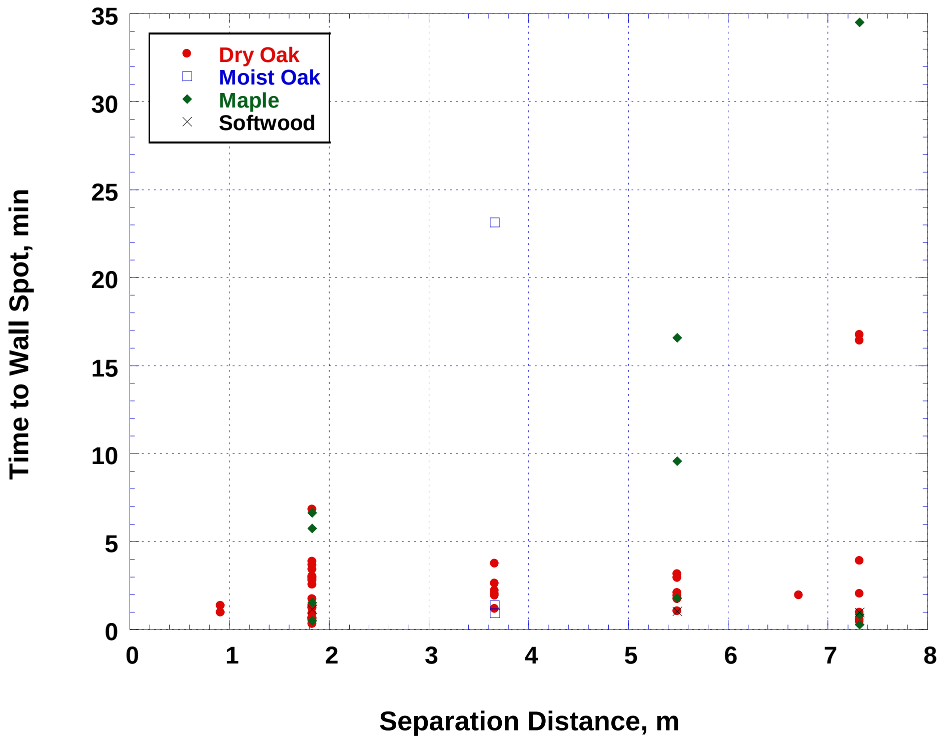

Fig. 31. Time to spot fire that first reaches the wall plotted as a function of separation distance for all woodpile experiments with firewood type differentiated.

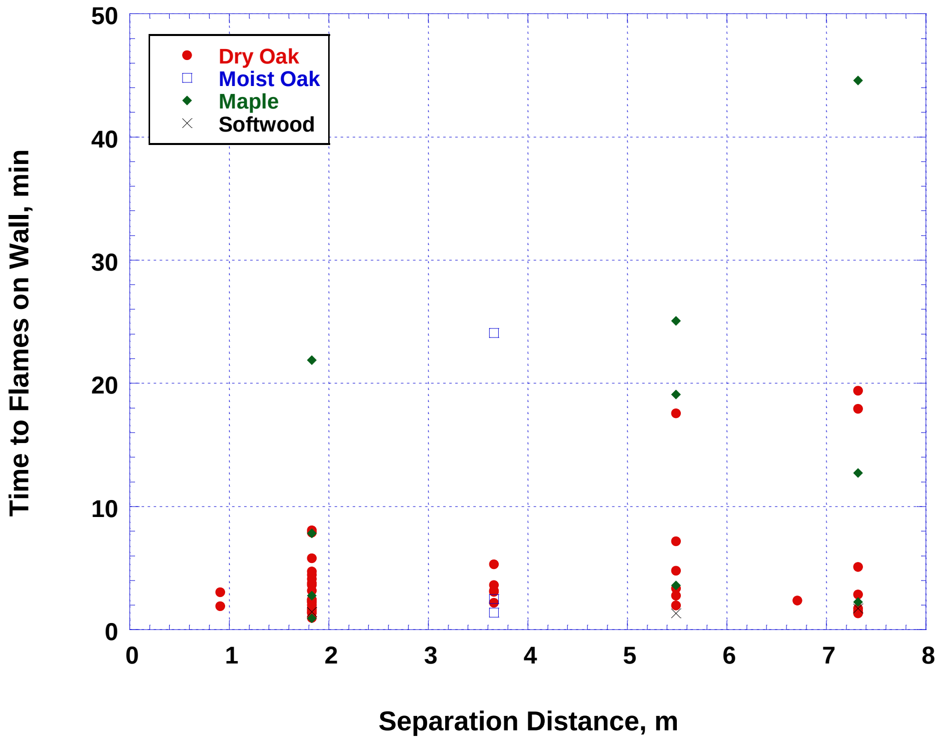

Fig. 32. Time to flames on wall plotted as a function of separation distance for all woodpile experiments with firewood type differentiated.

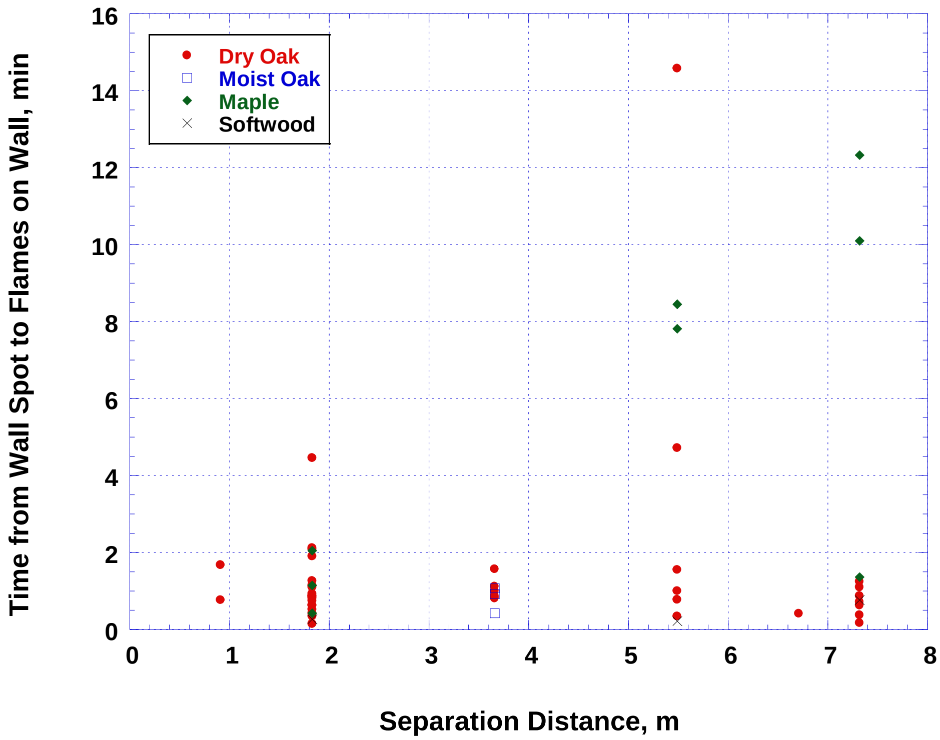

Fig. 33. Time between ignition of wall spot fire and flames on wall plotted as a function of separation distance for all woodpile experiments with firewood type differentiated.

3.4. Effects of Firewood Moisture

Rather than repeat or add figures here, please refer to Fig. 26 through 29 for this analysis related to wind speed. In those plots of firewood types, the moist oak is represented by open blue squares, while the dry oak is represented by solid red circles. For both time to first spot in Fig. 26 and time to wall spot in Fig. 27, at the low wind speed the moist oak had a 40 % longer ignition time than any of the dry oaks. For medium and high wind speeds, there is no clear difference between ignition times for the dry or moist oak firewood. For time to flames on the wall in Fig. 28, the moist oak time is over 20 % higher than the longest time for dry oak. For the time between wall spot ignition and flames on the wall shown in Fig. 29, the times for moist oak are in the middle of times for dry oak. Again, this make sense because all of the spot fires that lead to flames on the wall should not be affected by the characteristics of their source when it is of the same material. Both wet and dry oak will have been dried completely when converted to firebrands.

All of the moist oak experiments were performed at 3.66 m (12 ft). Figures 30 through 33 are the set of ignition and flame times plotted versus separation distance with the firewood type differentiated in the plots. While one moist oak experiment exhibited the longest first spot, wall spot, and time to flames on the wall by about 20 min each over the rest of the data, the other two experiments produced timing that was mingled with the results of dry oak. The experiment that produced the long timings was also at the low wind speed which was discussed earlier as the condition that seemed to enhance any difference due to wood moisture.

3.5. Effects of Woodpile Height

This section explores the effects of the height of the firewood pile on the timing of the ignition of spot fires and for flames reaching the shed wall. Fig. 34 shows examples of tall and short woodpile experiments configured similarly and under the same low wind conditions. The sets of timing graphs were plotted versus both wind speed and separation distance to investigate trends.

Fig. 34. Photographs of tall (left) and short (right) dry oak woodpile experiments configured as ends with racks at 1.83 m (6 ft) separation and low winds.

Figures 35 through 38 are the set of ignition and flame times plotted versus wind speed with the woodpile height differentiated in the plots. At medium and high wind speeds, the spot fire ignition times, time to flames on the wall, and time between wall spot ignition and flames did not show noticeable differences due to woodpile height. At low wind speeds, there may have been a tendency for the short woodpile to generate somewhat faster times to ignition and flames than the tall woodpile. Since only two short woodpile experiments were performed at the low wind speed condition, there was not enough data to determine if this difference was due to a general effect of woodpile height. If it was, we could speculate one possibility that it could be due to the greater wind blockage caused by the taller woodpile which would cause some firebrands generated to drop to the ground behind the woodpile rather than continue forward to the target mulch bed.

Figures 39 through 42 are the set of ignition and flames times plotted versus separation distance. It is apparent from the plots that all of the short woodpile experiments were conducted at the 0.91 m (3 ft) or 1.83 m (6 ft) separation distances. There are no obvious distinctions between the woodpile heights on any of the timing plots.

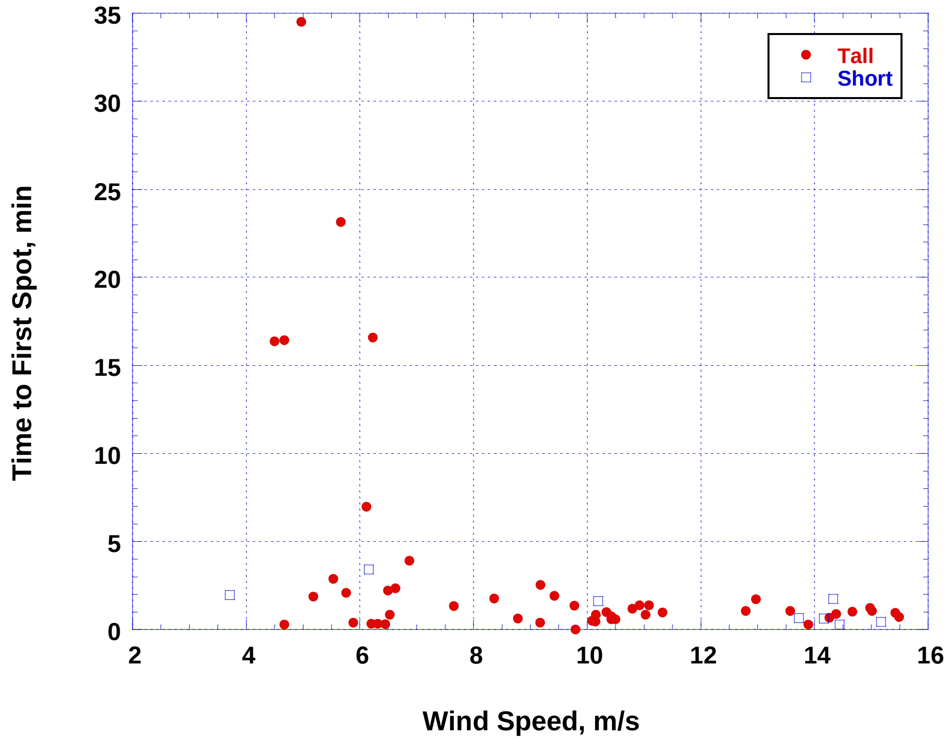

Fig. 35. Time to first spot fire plotted as a function of wind speed for all woodpile experiments with woodpile height differentiated.

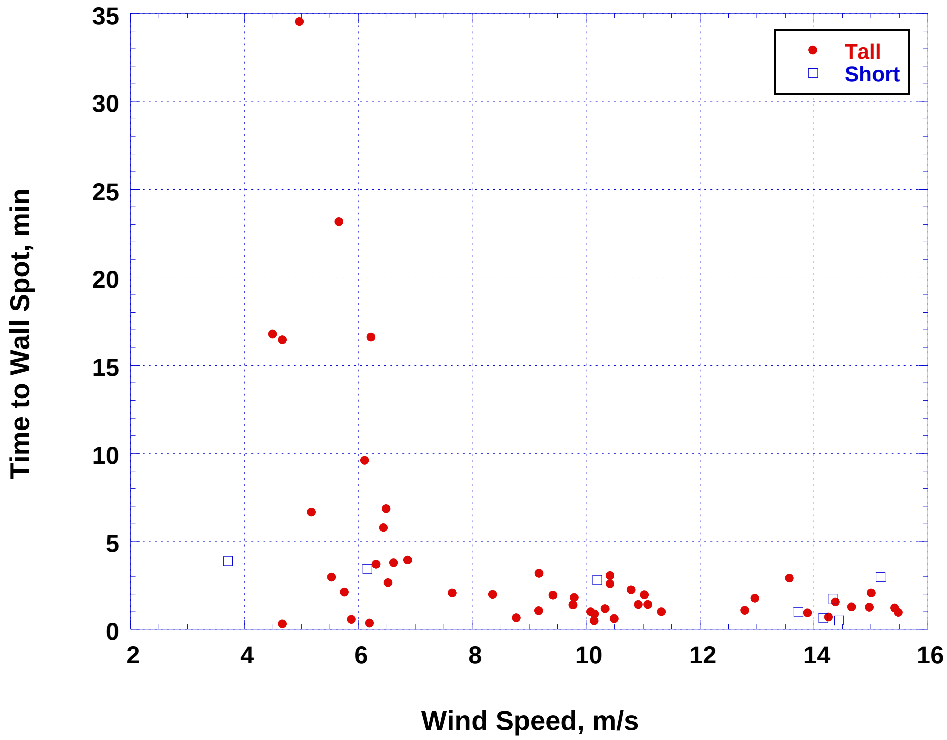

Fig. 36. Time to spot fire that first reaches the wall plotted as a function of wind speed for all woodpile experiments with woodpile height differentiated.

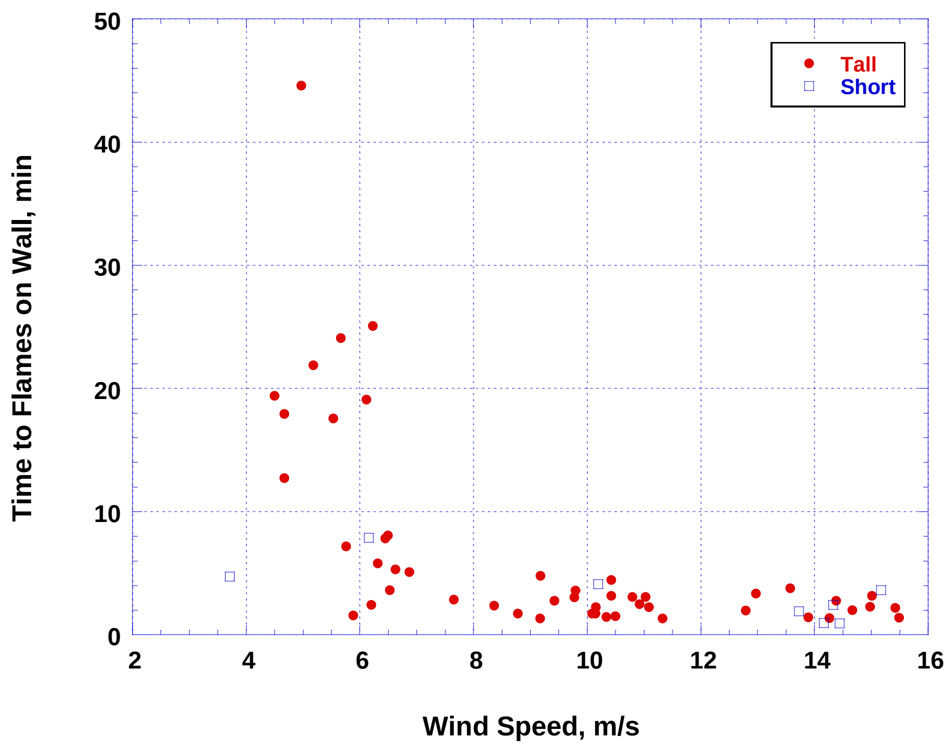

Fig. 37. Time to flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile height differentiated.

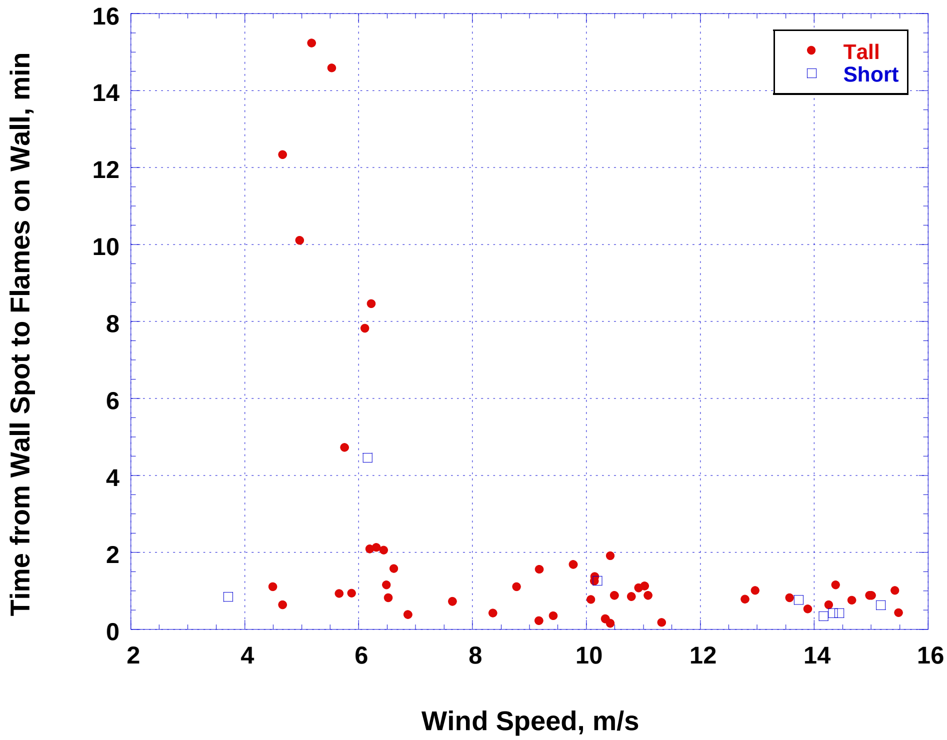

Fig. 38. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile height differentiated.

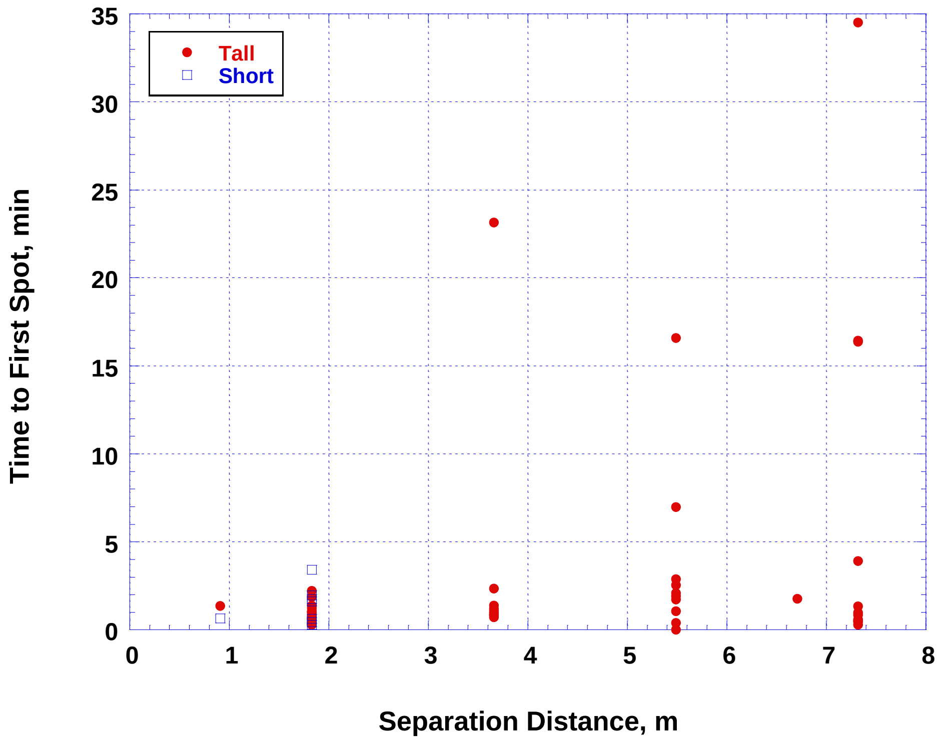

Fig. 39. Time to first spot fire plotted as a function of separation distance for all woodpile experiments with woodpile height differentiated.

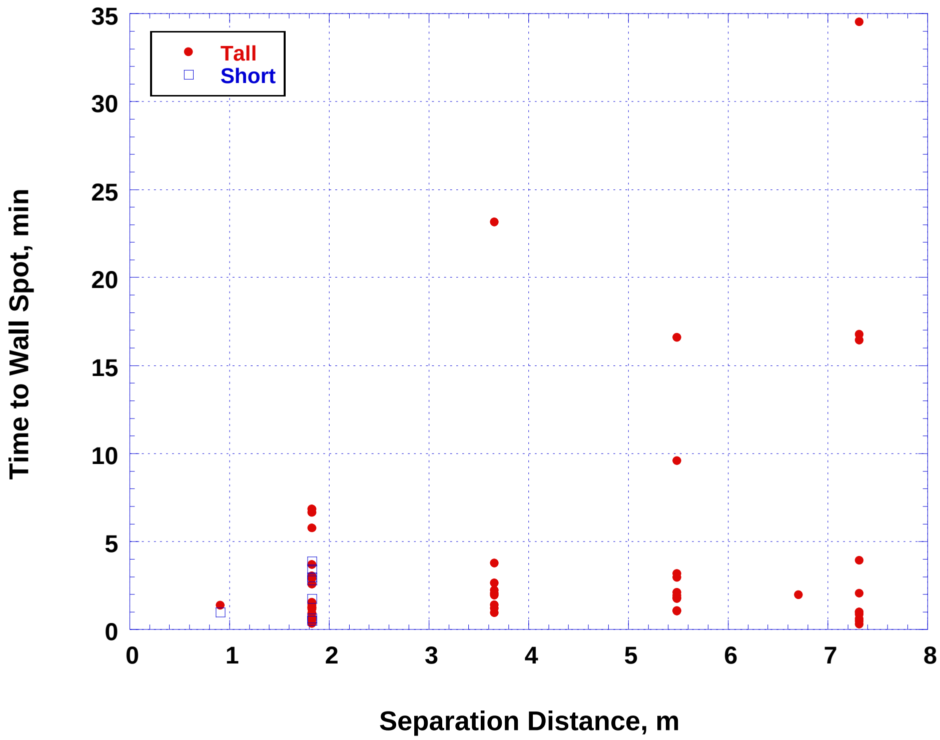

Fig. 40. Time to spot fire that first reaches the wall plotted as a function of separation distance for all woodpile experiments with woodpile height differentiated.

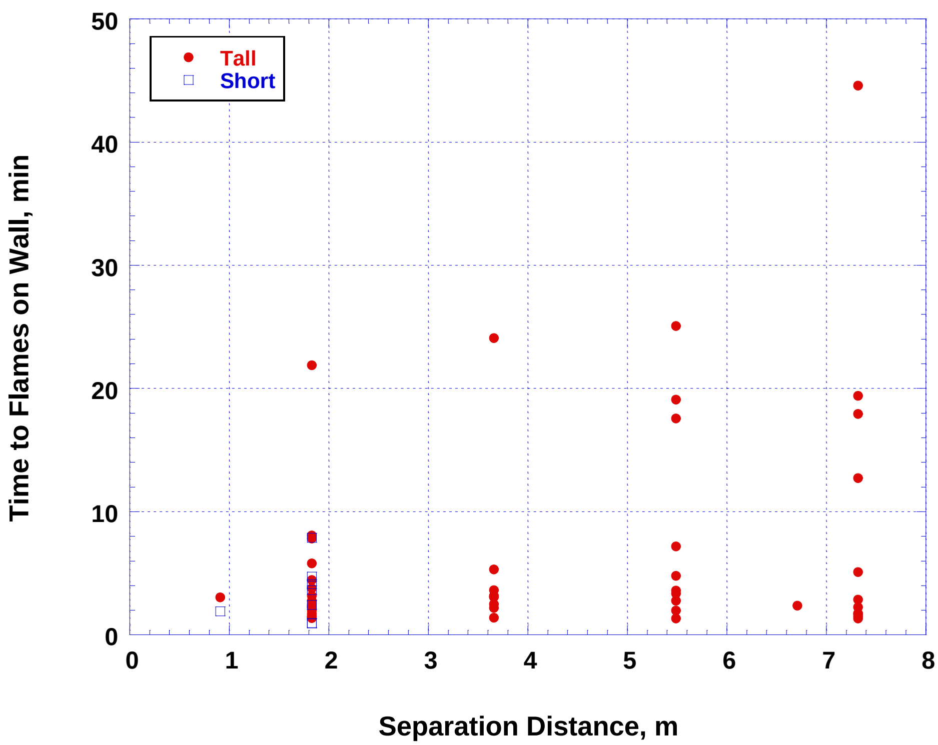

Fig. 41. Time to flames on wall plotted as a function of separation distance for all woodpile experiments with woodpile height differentiated.

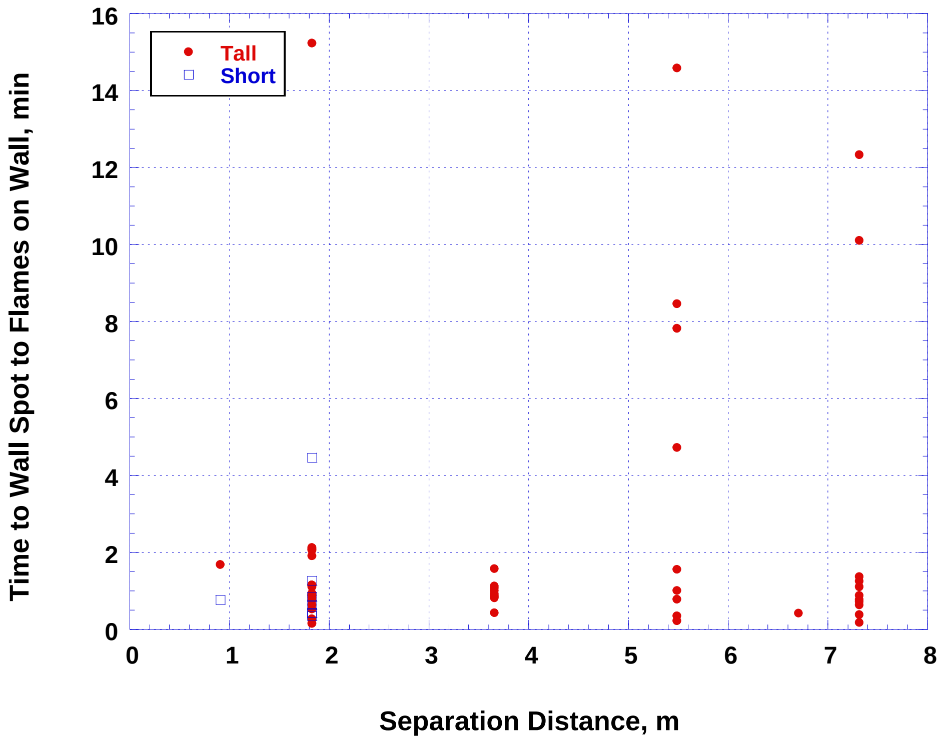

Fig. 42. Time between ignition of wall spot fire and flames on wall plotted as a function of separation distance for all woodpile experiments with woodpile height differentiated.

3.6. Effects of Woodpile Orientation

This section explores the effects of the orientation of the firewood pile on the timing of the ignition of spot fires and for flames reaching the shed wall. Orientation is described as "ends" if the log central axes are in line with the wind and "sides" if the log axes are perpendicular to the wind. Figure 43 shows examples of sides and ends woodpile experiments otherwise configured the same and under the same low wind conditions. Flame extensions downwind of burning woodpiles in the sides orientation did tend to be longer than those for woodpiles in the ends configuration. For the ends configuration, the air spaces between logs were aligned with the wind which allowed penetration of wind and flames through the woodpile, while woodpiles in the sides orientation essentially blocked the wind. The sets of timing graphs are plotted versus both wind speed and separation distance to look for trends.

Figures 44 through 47 are the set of ignition and flame times plotted versus wind speed with the woodpile orientation differentiated in the plots. At medium and high wind speeds, the spot fire ignition times and time to flames on the wall do not show noticeable differences due to woodpile orientation. At low wind speeds, there seem to be more long times to spot ignitions and flames for woodpiles with the ends facing the wind than for those with the sides facing the wind. Since there are only about four data points showing this difference, it is not clear if it is a significant trend. In Fig. 47, for the time from wall spot ignition to flames on the wall, even at the low wind condition there is no distinction between the two orientations. This makes sense, since once a spot fire is ignited, it should not behave differently due to its generation unless the generation process has influence over the firebrand landing in a more or less favorable location. This result indicated that for spot fires that reached the wall, the time of their growth from ignition was not influenced by woodpile orientation.

Fig. 43. Photographs of sides (left) and ends (right) dry oak woodpile experiments configured as tall with racks at 1.83 m (6 ft) separation and low winds.

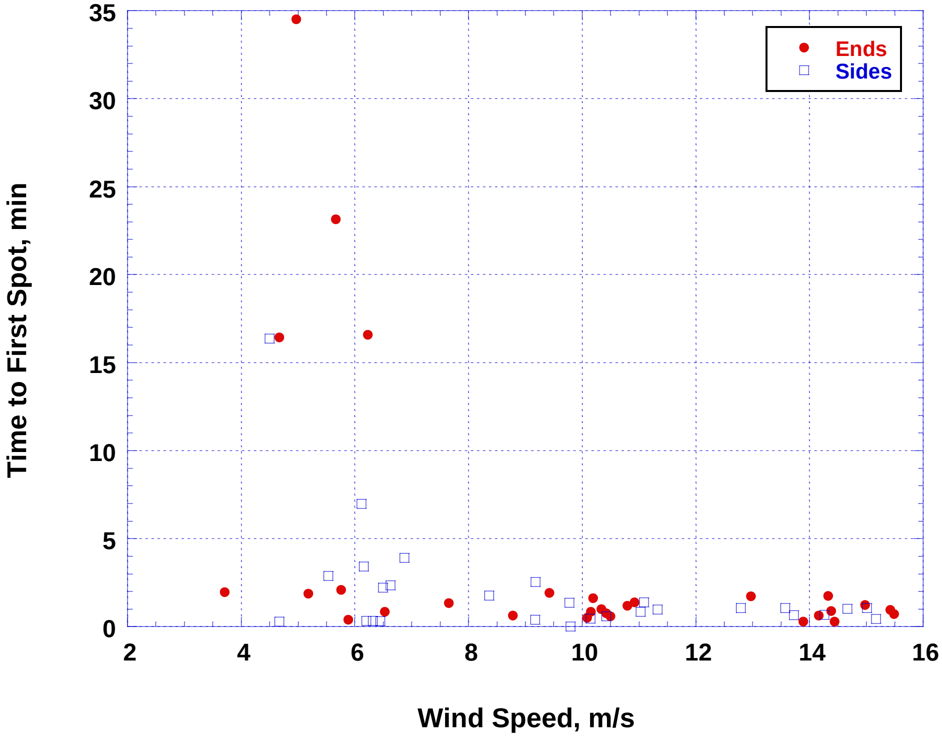

Fig. 44. Time to first spot fire plotted as a function of wind speed for all woodpile experiments with woodpile orientation differentiated.

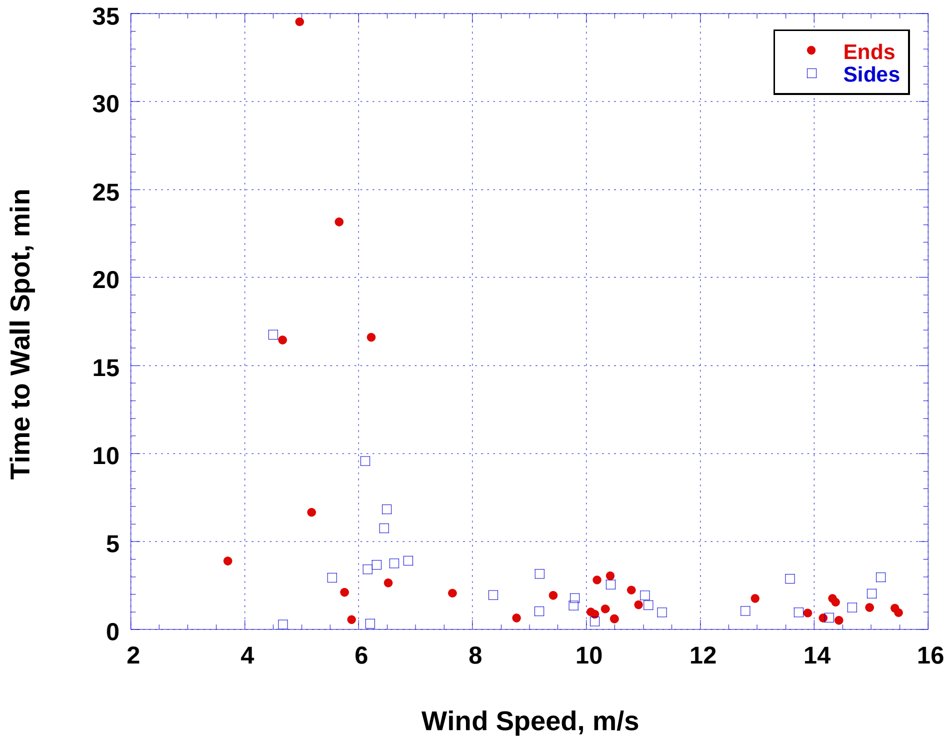

Fig. 45. Time to spot fire that first reaches the wall plotted as a function of wind speed for all woodpile experiments with woodpile orientation differentiated.

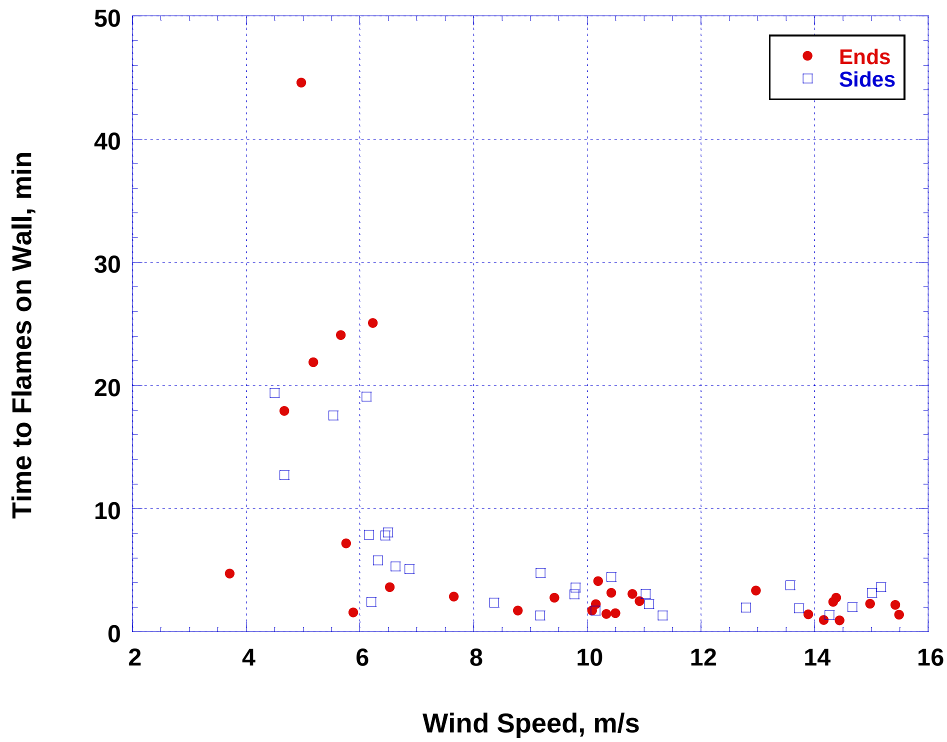

Fig. 46. Time to flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile orientation differentiated.

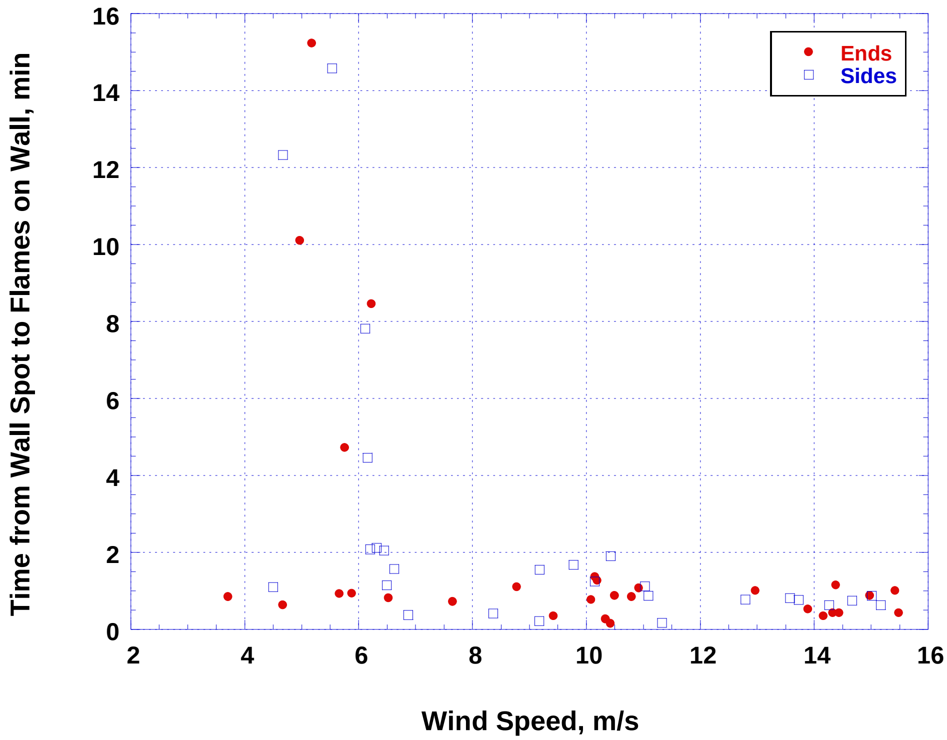

Fig. 47. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile orientation differentiated.

Figures 48 through 51 are the set of ignition and flame times plotted versus separation distance with the woodpile orientation differentiated in the plots. There are no clear distinctions between timing of spot fires and flames for different woodpile orientations. For the first and wall spot fire ignitions at 3.66 m (12 ft) or larger separation distances, the longest times to ignition (all more than 15 min) are each for the ends orientation. For all of the main separation distances (those with more than two data points), the longest time to flames on the wall (all more than 20 min) are also for the ends orientation. Although this may indicate a possible difference, the number of data points is too small to be statistically significant, and the rest of the data for faster (under 10 min) ignitions and flames show no pattern between woodpile orientation and separation distance.

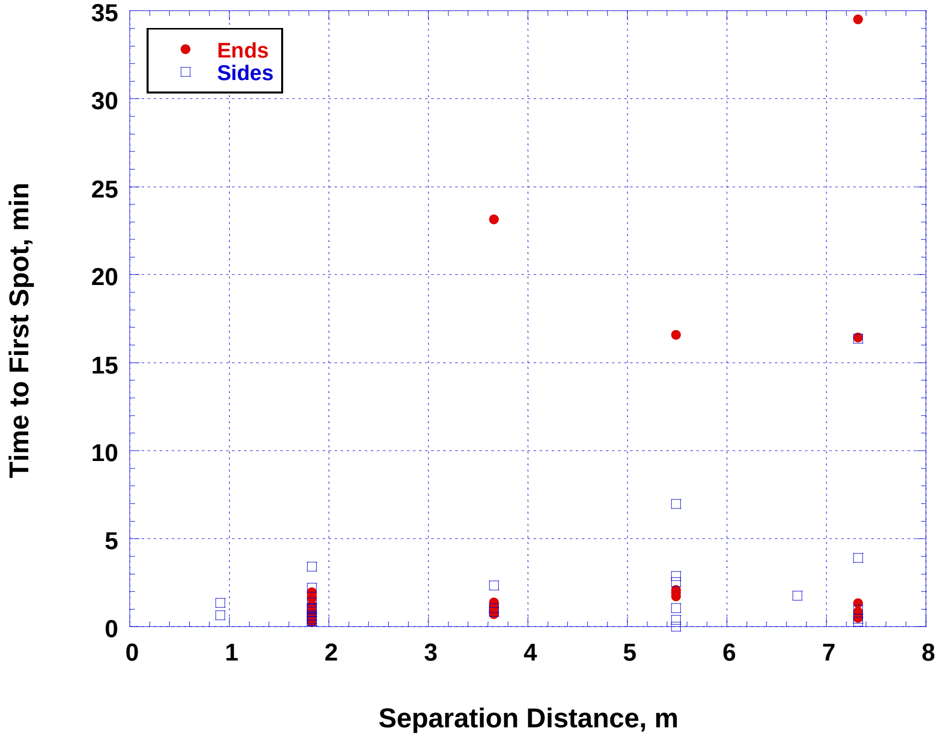

Fig. 48. Time to first spot fire plotted as a function of separation distance for all woodpile experiments with woodpile orientation differentiated.

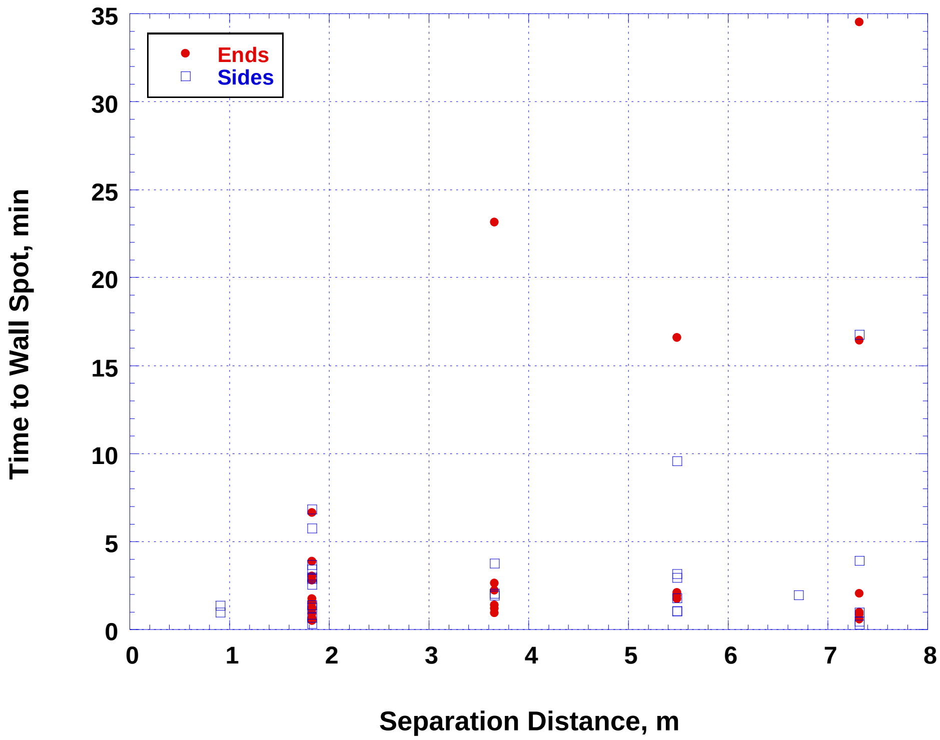

Fig. 49. Time to spot fire that first reaches the wall plotted as a function of separation distance for all woodpile experiments with woodpile orientation differentiated.

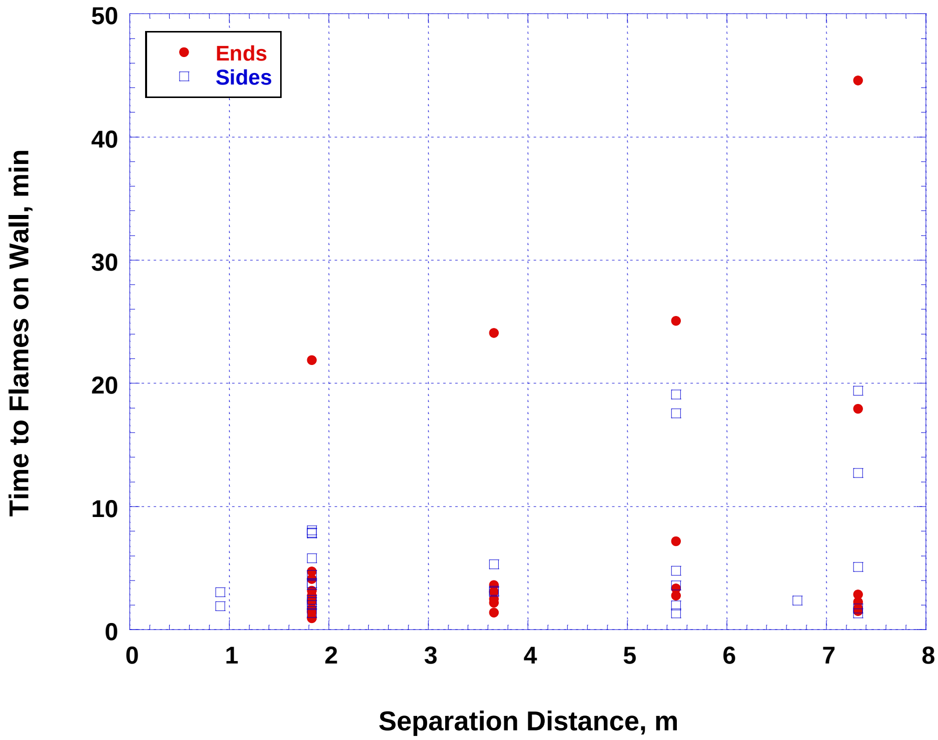

Fig. 50. Time to flames on wall plotted as a function of separation distance for all woodpile experiments with woodpile orientation differentiated.

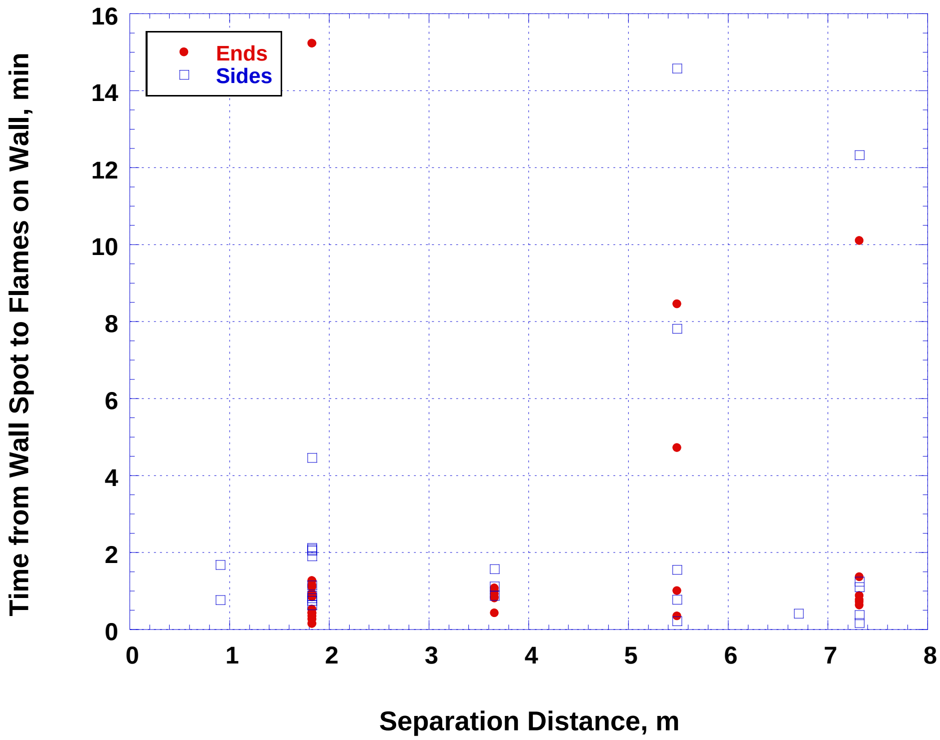

Fig. 51. Time between ignition of wall spot fire and flames on wall plotted as a function of separation distance for all woodpile experiments with woodpile orientation differentiated.

3.7. Effects of Woodpile Elevation

This section explores the effects of the elevation of the firewood pile on the timing of the ignition of spot fires and for flames reaching the shed wall. Elevation was determined by whether the woodpile was placed on a rack or directly on the ground. In these plots elevation is referred to as either “rack” or “no rack”. Figure 52 shows examples of no-rack and with-rack woodpile experiments otherwise configured the same and under the same low wind conditions. The sets of timing graphs are plotted versus both wind speed and separation distance to look for trends.

Fig. 52. Photographs of no-rack (left) and with-rack (right) dry oak woodpile experiments configured as ends and tall at 1.83 m (6 ft) separation and low winds.

Figures 53 through 56 are the set of ignition and flame times plotted versus wind speed with the woodpile elevation differentiated in the plots. At medium and high wind speeds, the spot fire ignition times and time to flames on the wall do not show noticeable differences due to woodpile elevation. At low wind speeds, the two woodpiles with no rack had very fast times to ignition compared to almost all of the woodpiles on racks. Since there are only two data points, this may not be significant. The two no-rack experiments also had the wall spot fire as the same as the first spot fire so no additional information is gained by a second spot fire’s behavior. Even though there were only two experiments, the low wind condition with no rack also generated the fastest times to flames on the wall and relatively fast times between wall spot ignition and flames.

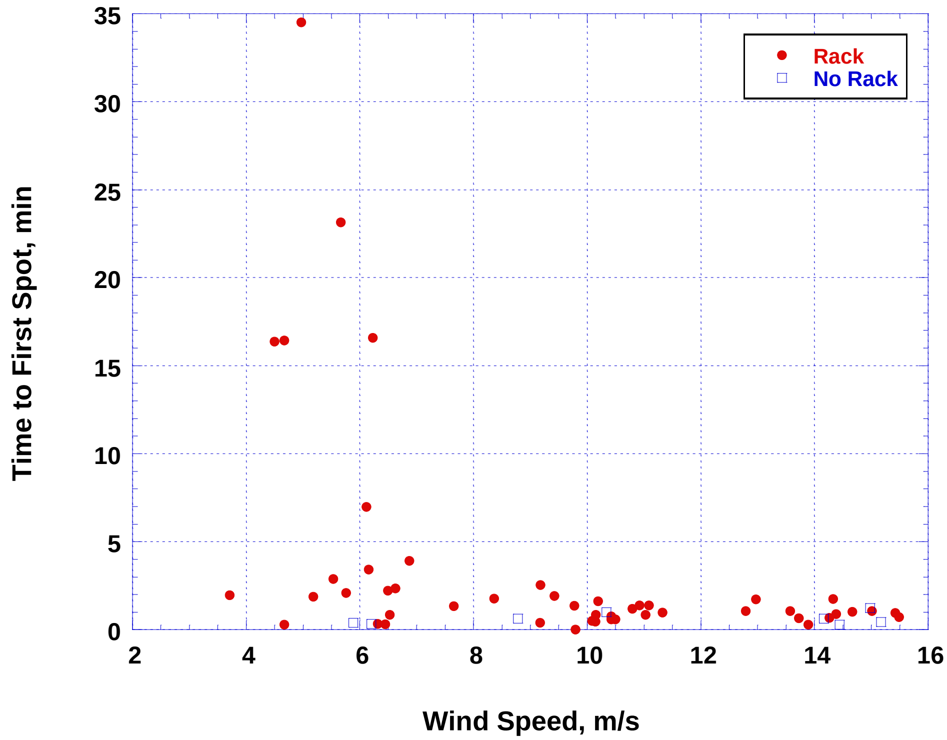

Fig. 53. Time to first spot fire plotted as a function of wind speed for all woodpile experiments with woodpile elevation differentiated.

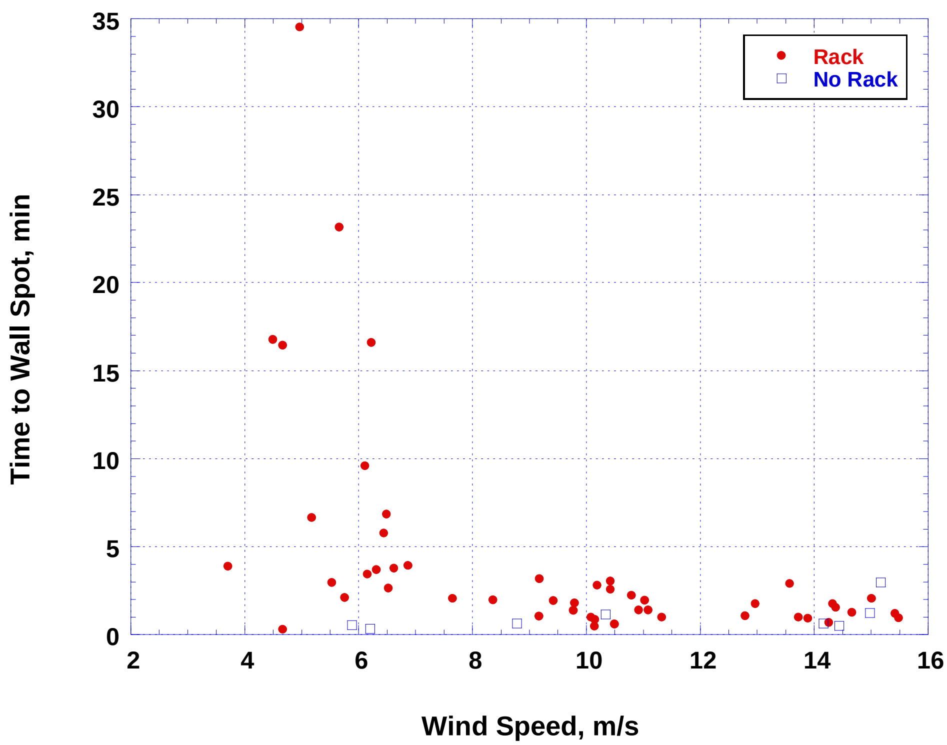

Fig. 54. Time to spot fire that first reaches the wall plotted as a function of wind speed for all woodpile experiments with woodpile elevation differentiated.

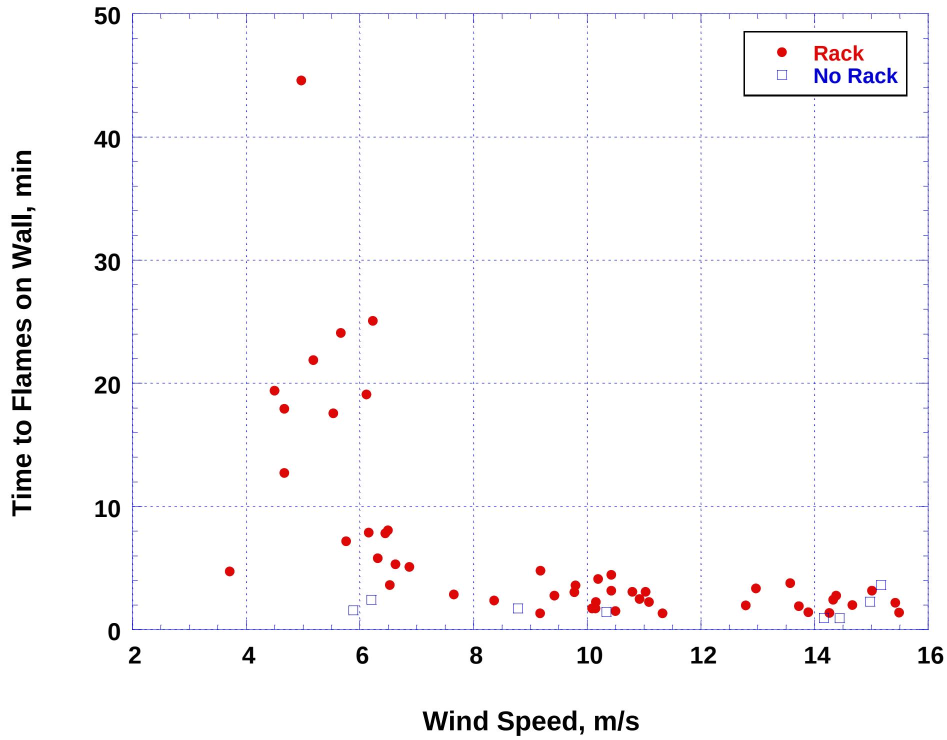

Fig. 55. Time to flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile elevation differentiated.

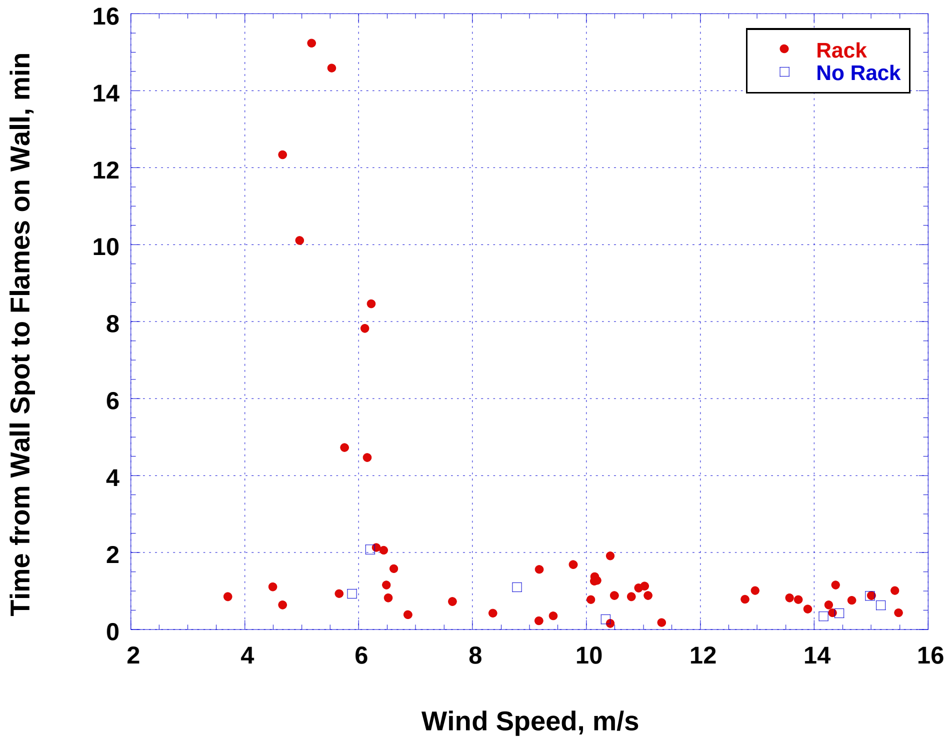

Fig. 56. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for all woodpile experiments with woodpile elevation differentiated.

All of the woodpile experiments with no rack were conducted at the same separation distance, 1.8 m (6 ft). This provides an opportunity to examine those results with only the rack and wind speed varied. Figures 57 through 60 are the set of ignition and flame times plotted versus wind speed at only 1.8 m separation distance with the woodpile elevation differentiated in the plots. In Fig. 57 for the time to the first spot fire versus wind speed, 44 % of the ignition times with a rack are greater than 1.3 min while 0 % of the ignition times with no rack are in that range. Another way to look at the distribution is that 56 % of the ignition times with a rack are less than 1.3 min while 100 % of the ignition times without a rack are less than 1.3 min. At low wind speed, the two experiments with no rack had spot fire ignition times of between 0.3 and 0.4 min while 67 % of the experiments with a rack had ignition times greater than 1.8 min.

For the time to the wall spot in Fig. 58, the difference between elevation results is even more pronounced. At low wind speed, 100 % of the wall spot ignition times for woodpiles on a rack are 3.4 min or greater while 100 % of the ignition time for woodpiles on the ground are less than 0.6 min. For medium wind speed, all four ignition times for woodpiles on a rack are greater than 1.3 min and the two ignition times for woodpiles on the ground are less than 1.2 min. At high wind speed, the average ignition time for the woodpiles on a rack is somewhat higher than that of the woodpiles on the ground, but the differences at that wind speed seem to be diminished and possibly insignificant.

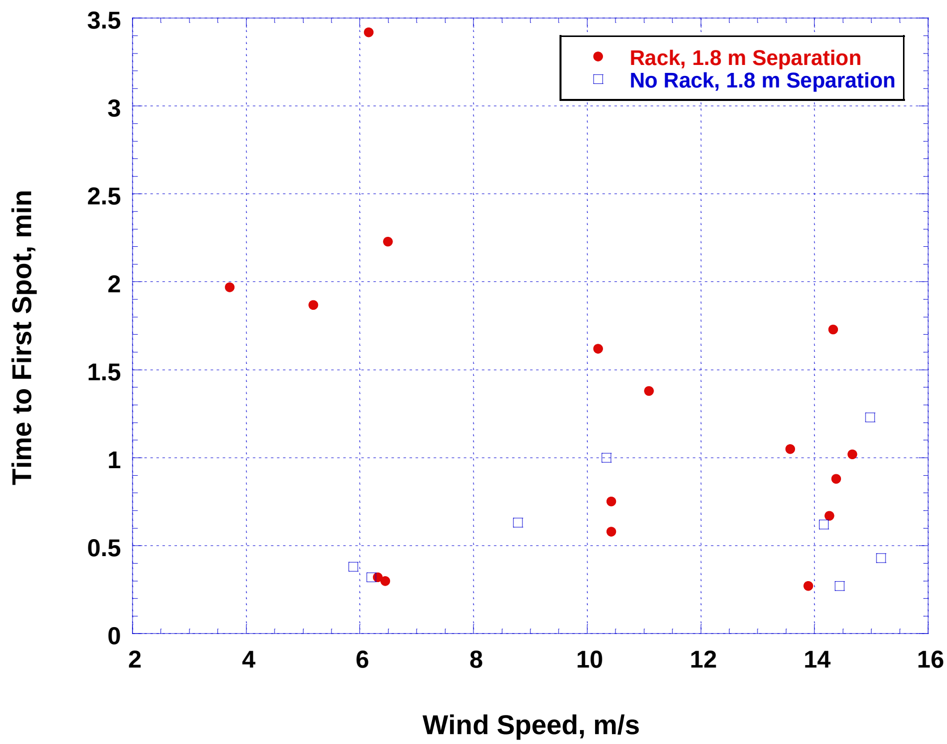

Fig. 57. Time to first spot fire plotted as a function of wind speed for 1.8 m separation woodpile experiments with woodpile elevation differentiated.

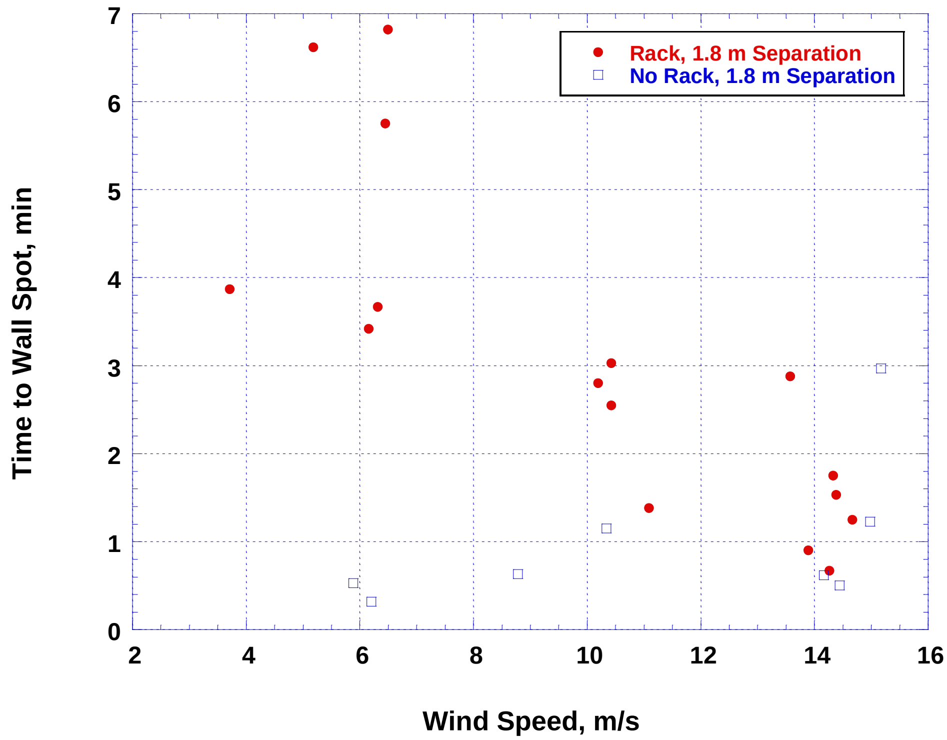

Fig. 58. Time to spot fire that first reaches the wall plotted as a function of wind speed for 1.8 m separation woodpile experiments with woodpile elevation differentiated.

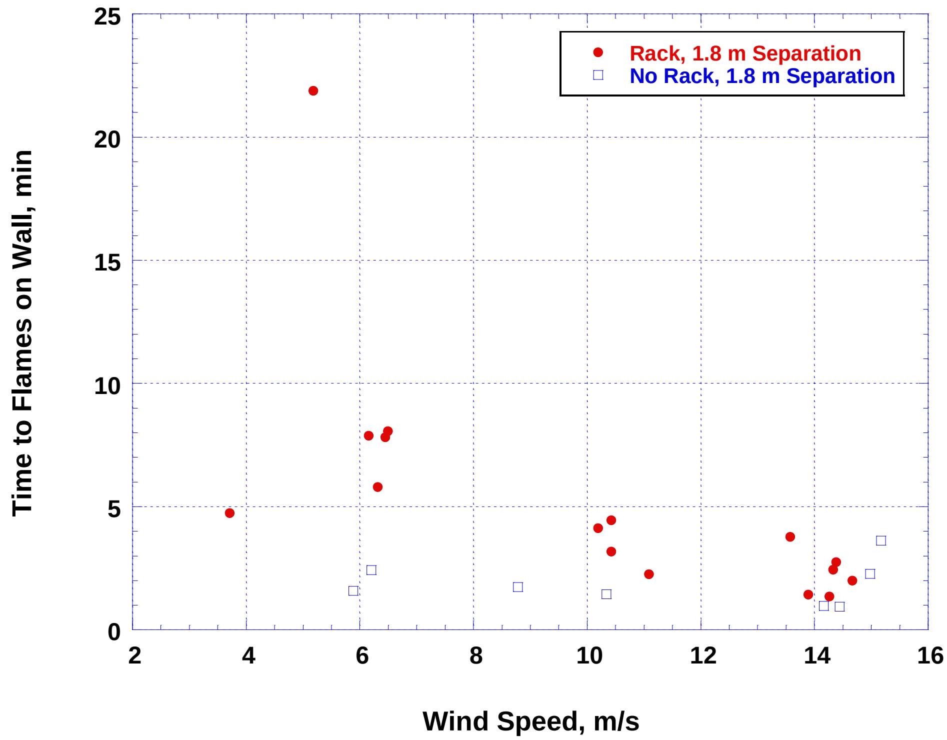

Fig. 59. Time to flames on wall plotted as a function of wind speed for 1.8 m separation woodpile experiments with woodpile elevation differentiated.

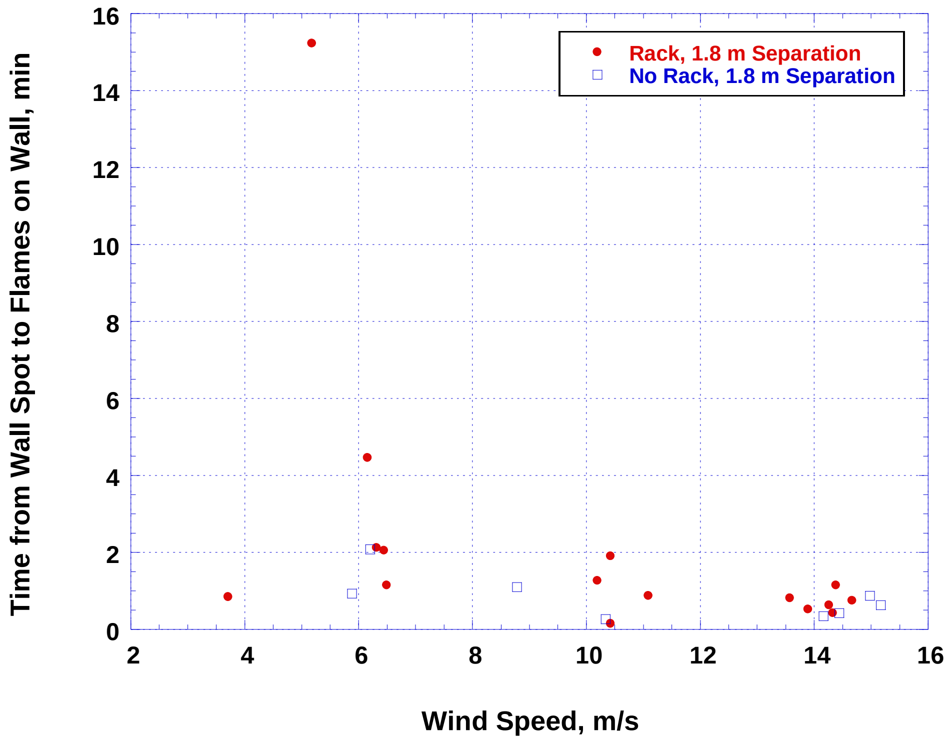

Fig. 60. Time between ignition of wall spot fire and flames on wall plotted as a function of wind speed for 1.8 m separation woodpile experiments with woodpile elevation differentiated.

For the time to flames on the wall in Fig. 59, all six of the times with a rack are in the 4 min to 22 min range while the two experiments without a rack experienced less than 3 min for flame times. For medium wind speed, all four of the times with a rack were greater than 2 min while the two without a rack were less than 2 min. There was no perceivable difference between rack and no rack for the high wind speed at 1.8 m (6 ft) separation distance.

For the time between wall spot ignition and flames on the wall in Fig. 60, there are no obvious differences between the rack and no rack times. This again makes sense in that once spot fires that are going to reach the wall have ignited, they should not spread differently because of the source configuration.

3.8. Flames

As part of hardening homes against wildland fires, it is already recommended that firewood piles be kept at least 9.1 m (30 ft) away from homes [11] so flames from a burning firewood pile impinging on a structure would not be an issue. Nevertheless, plume flame lengths were observed and recorded during these experiments. The lengths were not thoroughly analyzed, but generally at all wind speeds, steady flame lengths sometimes extended 1 m (3.3 ft) or more forward horizontally and 1 m (3.3 ft) upward vertically from where they were attached to the woodpile. In some cases, intermittent, brief flames extend about 2 m (6.6 ft) forward.

Due to the fast nature of spot fire ignition and spread to the shed, many woodpiles were never fully engulfed, and the fire did not always have time to spread to the shed end of the woodpile. Some woodpiles, especially under slower, low wind experiments, did become more fully involved with fire. When a woodpile is fully involved in fire, it may collapse due to partial destruction of logs and deterioration of the stacked woodpile structure. A photograph of one such collapsed woodpile is provided in Fig. 61. The photo shows that the fire grew wider and the flames extended further due to the collapse. Firebrand production appeared enhanced by the physical disruption of the woodpile fire and may have been maintained due to the spread of the burning firewood and increased surface area of exposed fuel.

Fig. 61. A photo of a collapsed tall, sides, no rack dry oak woodpile under 6 m/s (13 mi/h) winds.

3.9. 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, including one woodpile experiment.

3.9.1. Experimental Design

Three long-range firebrand experiments were performed at the Frederick facility described in Section 2.1. The woodpile experiment is described here; the others are discussed in the fence/mulch report [1]. The experiment was oriented along the pond to allow for maximum firebrand travel distance downwind. The applied wind field was directed from the SSE at an angle of 148° ± 1°. The shed structure was not included in this test setup. A stacked woodpile of maple firewood 1.2 m (4 ft) long was arranged with the target mulch bed located 26.8 m (88 ft) from the upwind end of the woodpile, and the wind machine propeller was located 3.4 m (11 ft) farther upwind. The surface between the woodpile 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 woodpile 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 the 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.

3.9.2. Firebrand Spotting

The images in Fig. 62 (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. It should be emphasized that the wind speeds generated by the wind machine diminished significantly with distance which explains why only high winds maintained sufficient speed to carry the firebrands over the long distance.

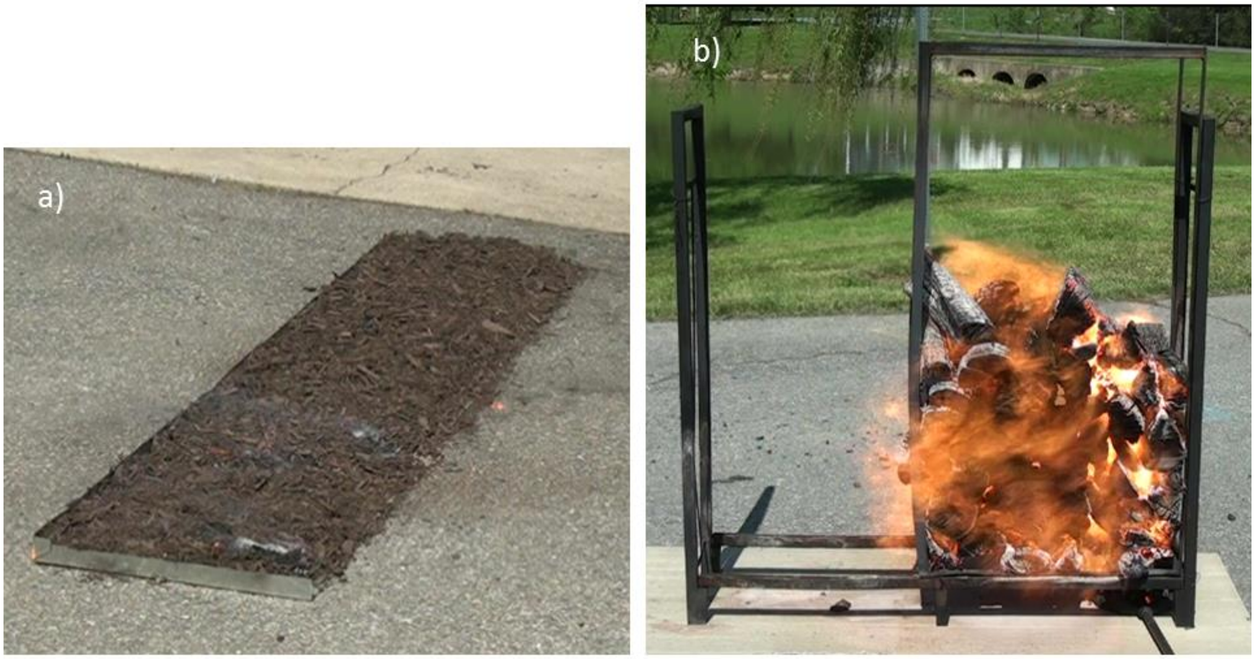

Fig. 62. Woodpile experiment without a structure and with a) a target mulch bed situated 25.6 m (84 ft) from the downwind end of b) the woodpile.

3.10. Mitigation Experiments

The hazard of firebrands from burning firewood piles igniting spot fires in downwind combustibles has been evaluated under a variety of wind and separation distance conditions. Since the wind cannot be controlled in real-life WUI fire situations, and distance does not seem to diminish the generation of spot fires under medium and high winds, effective mitigation strategies are needed so that homeowners can keep firewood near their homes without putting their homes, their neighbors' homes, or other parcel-level features (such as sheds) at additional unnecessary risk during WUI fires.

To begin exploring potential mitigation strategies, three experiments were conducted. All three utilized dry oak firewood, tall woodpile height, log sides orientation, and elevation on a rack. The conditions for the mitigation experiments were medium wind and 3.66 m (12 ft) separation distance.

The first mitigation experiment simply placed a noncombustible wall downwind of the firewood pile. The wall was a 1.83 m (6 ft) tall by 1.22 m (4 ft) wide panels of JamesHardie™ fiber cement board. On the downwind side, it was attached to a wood frame and angle braces made from two-by-fours. Photographs of the arrangement are provided in Fig. 63. It was observed during the experiment that the firebrands were blown around the shield wall, were re-entrained in the main wind flow, and caused spot fires in the target mulch bed. The spot fire timings were within the range for medium wind experiments

Fig. 63. Photographs showing the first woodpile mitigation experiment, which used a noncombustible wall as a shield in an attempt to decrease downwind spot fires.

The second mitigation experiment wrapped a fire-retardant treated tarpaulin around the woodpile. The tarp met the flame resistance requirements of CPAI-84 and was compliant with California Fire Code (CFC) 3101. The tarp was secured around the woodpile with bungee cords. Photographs of the woodpile wrapped in the tarp are provided in Fig. 64. It was discovered during ignition of the burner that the fire-retarded tarp would not burn but was easily damaged by flames. Due to the tendency of this tarp to develop holes and shrink from flame impingement, the tarp had little positive effect on preventing escape of firebrands and ignition of spot fires and the spot timings were similar to those without a tarp.

Fig. 64. Photographs showing the woodpile mitigation experiment using a fire-retarded tarp in an attempt to decrease downwind firebrand spot fires.

The third mitigation experiment involved construction and placement of an aluminum screen enclosure surrounding the firewood pile. For the first attempt at a screen enclosure, aluminum screen with 1.6 mm (1/16 in) holes in the mesh was used. The screen was supplied in a roll. Sections for the 4 sides and top were overlapped with the overlapping parts folded over on themselves and stapled to stay folded. The overall dimensions were roughly 1.22 m (4 ft) long by 1.52 m (5 ft) tall by 0.91 m (3 ft) wide. The screen enclosure bottom was held to the ground with narrow steel bars to keep it from blowing and also to seal gaps at the ground. Photographs of the screen enclosure experiment are provided in Fig. 65.

Fig. 65. Photographs showing the woodpile mitigation experiment using a screen enclosure in an attempt to decrease downwind firebrand spot fires.

It was known that aluminum screen might melt away locally if contacted by flames for long, and such a mishap occurred when attempting to ignite the burner at the beginning of the experiment. The experiment was halted, the burned hole was patched, and the experiment was restarted with the enclosure placed on the woodpile after it was ignited to prevent creation of any more holes by the burner or propane torch ignitor. The results of this experiment were 20 min to the wall spot and 23 min to flames on the wall. The delay of about 20 min for spot fires and subsequent flames on the shed wall was seen as a significant, although limited, mitigation, especially considering that the aluminum screen was not the best material to select for this application. The delayed impact of firebrand spotting in the mulch bed suggests that there is a need to further explore this mitigation strategy. Additional experiments have been planned which utilize either a galvanized steel or stainless steel screen material, both of which should be much more resilient than aluminum against flames.

4. Discussion

Burning woodpiles present a hazard to the residences in a community during a WUI fire, with exposures resulting from both firebrands and fire. In this study, a series of experiments on burning firewood piles was conducted, with an emphasis on firebrand exposures. The results have been described in Section 3. All of the woodpile experiments, under all conditions tested, resulted in spot fires in the target mulch bed that spread to the shed wall. The parameters of the woodpile and test conditions were varied in order to evaluate whether any of them had a significant impact on the generation of firebrands and the timing of ignition of spot fires in the target mulch bed and flame spread to the shed. Wind speed had the greatest impact, with the lowest winds delaying spot fire ignition and flame spread by up to a half hour in some cases. Medium and high winds typically caused spot fires in less than 3 min and flames spread to the wall in less than 5 min. Unfortunately, even if wind speed were controllable, the delay in ignition is not long or reliable enough to confidently mitigate the hazard from burning woodpiles.

While there were some minor possible effects from the firewood species and moisture content and the woodpile orientation, height, and elevation, none of these factors indicated that they would be determinative in a potential mitigation strategy. Wind speeds over 7 m/s (16 mi/h) overwhelmed any differences that were observed.

As an alternative to eliminating the woodpile, increasing its separation distance from a residence or other structure has become a popular mitigation strategy. This strategy is currently recommended by programs such as Firewise [11], which advises a minimum distance of 9.1 m (30 ft) for woodpiles. While increasing the separation distance is a useful approach for preventing the radiative and convective heat from flames from reaching the structure, it is not effective for protection against firebrands. This study shows that for all but the lowest wind speeds, the separation distance of the woodpile had little impact on spot fire ignition timing and flame spread to the shed wall. The long-range firebrand experiment showed that ignition may be achieved at a distance of at least 27 m (88 ft) for high winds near the woodpile. Other long-range experiments with burning fences and mulch found that spot fire ignitions occurred within a few minutes 47 m (155 ft) downwind for high wind speeds [1], which demonstrates that separation distance is an inadequate solution.

Other mitigation strategies that were evaluated included a shield wall and a fire-retarded tarpaulin. Both of these methods were easily defeated by the wind and woodpile firebrands. It is possible that other design and material variations on these methods could be more effective, but it is unlikely that they would be sufficiently effective to allow for close proximity of a firewood pile to a structure without substantial risk.

The screen enclosure tested in this study showed promise in decreasing the firebrand exposure from woodpiles. It was, however, made using a material that could be damaged by flames and was eventually defeated by the burning woodpile. Other screen enclosures with more resilient materials would likely be more effective.

During a fire, an effective protective firewood enclosure would reduce the number of firebrands that could land on the woodpile. If the woodpile were to ignite anyway, the enclosure would inhibit firebrands generated by the woodpile from igniting spot fires downwind. Even before the fire occurs, more-effectively designed tarps, screens, or other enclosures could minimize the accumulation of combustible debris, such as leaves or pine needles, close to or contacting the woodpile. This in turn would reduce the vulnerability of the woodpile to ignition by firebrands because of the reduced presence of adjacent fine fuels. Fine fuels are more easily ignited by firebrands than larger pieces of wood; once an accumulation is ignited, it would be a more effective ignition source for the woodpile than individual firebrands themselves. Maintaining a noncombustible zone around the enclosed woodpile would do even more to ensure that ground fires and debris accumulation do not contribute to fire spread to the woodpile.

One mitigation approach that is under consideration as a regulation by the California state Board of Forestry and Fire Protection is an ember-resistant zone around a home that would be required to have no combustible material. To be fully effective, the area would need to be maintained to remove any accumulated debris, and the effectiveness would be reduced if during a WUI fire event with high winds, combustible materials accumulate at the base of the house after homeowners have evacuated. Protective guidance (such as [11]) provided to homeowners in WUI-fire-prone areas already recommends this approach to greatly diminish the likelihood of the ignition of spot fires near homes by firebrands from any source, including woodpiles.

While this study provides insights into the firebrand hazard from woodpiles, other NIST studies have focused on the fire hazard from similar flaming sources. Structure separation experiments (SSE) with and without wind [12, 13] have been performed to (a) study and compare the fire hazards for wood and steel storage sheds containing wood cribs to simulate high and low fuel loadings and (b) to determine the minimum safe separation distance of the sheds from a nearby structure. Although the wood cribs differ from woodpiles in geometry and the absence of bark, the results from these experiments demonstrate two important points that relate directly to the fire hazard from woodpiles. First, flame length and thermal exposures are functions of the size of the fuel loading. Second, the steel enclosures were effective in confining flames (and firebrands) except in the direction of the shed door, which was kept open in these experiments.

Generally, whatever enclosure is used to store a woodpile must both keep the woodpile protected from ignition by firebrands from other sources and prevent the potential spread of firebrands if the woodpile should somehow be ignited, such as by a fire moving along the ground. Such an enclosure must not be combustible itself or distort and lose function due to the heat of nearby flames. It must meet the needs of a firewood enclosure that keeps wood dry, lets fresh air in, and allows access to remove logs without having gaps large enough for flames or firebrands to enter and ignite the wood. A successful woodpile fire enclosure could make it possible to store firewood on a property without increasing the risk to a home from firebrands. Facing the door of the steel shed away from the structure kept the flames from impinging on its walls and eaves.

For a more comprehensive discussion of mitigation approaches for WUI fires, including the effectiveness of removing, reducing, and relocating the fuels and hardening the structures, see the *WUI Parcel/Structure/Community Fire Hazard Mitigation Methodology* (HMM) [6].

4.1. Hazardous Scenarios

The wind-blown firebrands from the burning woodpiles in this study presented a hazard to the combustible target mulch bed in front of the target structure through spot fire ignitions and subsequent fire spread to the structure wall. This was observed in all cases in this study, for all parameters and conditions that were explored. The fact that spot fires ignited and spread under all wind speed conditions puts woodpile fires in a high hazard category. Under medium and high winds, the quickness of the spot fire ignitions made the hazard even more severe, although not to the level of very high hazard as described in [1]. The effects of wind speed dominated the effects of other parameters including separation distance.

Firewood pile fires were found to generate more spot fires than fences and mulch under the same wind conditions, but it is not known whether more firebrands were generated or that their size and characteristics were more favorable for igniting the mulch. The fire behavior found for firewood piles in this study should be taken into account for fire codes/standards and best practices for communities, since one firewood pile fire could impact several downwind parcels and homes, creating one or more chain reactions.

In large WUI incidents, first responders may not be available to suppress in a timely manner a woodpile fire that can quickly impact downwind combustibles. Also, if fire reached the interior of a large woodpile where water suppression had difficulty penetrating, it could take an extended time to extinguish the fire effectively. During WUI events, even one small woodpile fire could bring the fire to many structures and other combustibles via firebrands before defensive actions by first responders could stop possible structure ignitions. Firewood piles can act as a ladder fuel to carry flames from the ground to combustible items at higher levels such as tree branches.

A more detailed discussion on implementing guidance based on the relationships among fuel layout, fire hazard, and structure hardening can be found in the NIST report entitled *WUI Parcel/Structure/Community Fire Hazard Mitigation Methodology* (HMM) [6].

4.2. Limitations

This study was a survey of the fire behavior in wind of various configurations of woodpiles near a structure. It revealed the dominant and negligible factors related to the hazards posed by burning woodpiles. An understanding of the limitations of this work will help to direct its applications. Some limitations of this research include:

The experimental design focused primarily on the firebrand hazard from woodpiles: A detailed study of the hazard from fire, including thermal radiation, convection, and flame contact, would have required woodpiles of a range of sizes arranged at closer separation distances from the structure than in all but a couple of cases in this study. For a study of the flame hazard from burning wood cribs, see the NIST reports on structure separation experiments [12, 13].

The range of wind behavior was limited: These experiments were conducted with steady wind at three levels in one direction relative to the woodpile and shed wall. Flows around a structure from different angles will change the deposition pattern of firebrands. The wind field generated for these experiments was only consistent across the center of the test area and dropped off at the edges. Real winds will gust over a range of speeds and directions, which could change the deposition of firebrands and potentially make the situation more hazardous. The winds in real events may be higher than those tested. In these experiments, the wind was not blocked by vegetation or landscape objects, which can induce swirl and areas of low pressure that might be favorable for firebrand deposition.

The woodpiles tested were not realistically large: Some homeowners may keep a woodpile of similar size to the ones tested, especially as a convenient close-to-the-house replenishment subset of their total winter supply; however, the woodpiles tested were relatively small compared to many typical firewood storage arrangements. Larger woodpiles would change the flow near the woodpile and cause low pressure and lower winds on the lee side, which could cause different patterns of firebrand deposition downwind. While burning, the larger quantity of agglomerated combustible materials is expected to produce larger fire plumes [12, 13, 1], and the greater surface area will produce more firebrands for the wind to pick up and deposit, making larger woodpiles even more hazardous.

The structure used was restricted in size: The target shed used in this study is smaller than a house and many other real structures. The height as well as the width of a structure change the flow in front of and around it. Different relative angles of the wind will cause significant changes in the flow pattern as well.

The mulch represented a worst-case combustible target: The target mulch bed was a surrogate for any ground cover of fine combustibles such as grass, leaves, etc. It was used as a worse-case scenario. If there are no combustibles at all surrounding a house, then spot fires cannot ignite. CAL FIRE’s proposed regulation for a new ember-resistant zone (Zone 0) within 0 to 5 feet of a home would attempt to address spot-fire prevention. Nevertheless, any vulnerabilities in the combustible surface of the structure itself could be sites for firebrand ignition. Hardening the home against firebrands would be necessary to address the hazard from firebrands generated from firewood and other sources. Most houses will lie between the extreme cases of combustible-free and hardened versus surrounded by combustibles and structurally vulnerable. Burning firewood piles would pose a threat to any downwind combustible object that was close enough to ignite via flames or could ignite via firebrands.

Distance downwind was limited for long-range spotting study: The longest distance tested at the test site with a burning woodpile was only 27 m (88 ft) and likely underrepresents the spotting potential.

Woodpiles were ignited at a single location on or near the ground: The test protocol provided repeatable conditions to characterize woodpile fire performance and identify both dangerous and potentially mitigating attributes of woodpiles. In WUI fires, however, firebrands can also ignite a woodpile at the top or at multiple locations. Multiple ignition locations could result in faster fire spread and firebrand generation while ignition at the top of the woodpile could result in slower fire spread but possibly different firebrand generation and transport because of the initially elevated fire.

Ignition was by gas burner rather than a natural source: In these experiments, the woodpiles 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. Natural ignition sources would include single firebrands with sufficient mass and energy to ignite small protuberances of firewood or bark that in turn have low enough mass to be ignited (direct firebrand ignition) and accumulation of debris such as leaves or twigs or a combustible ground cover that are ignited by a firebrand and produce flames sufficiently close to ignite the firewood (indirect firebrand ignition). The burner produced heat orders of magnitude greater than direct firebrand ignition and possibly similar to some but probably several times greater than most indirect firebrand ignitions.

5. Conclusions

This section lists the key findings, practical recommendations based on the findings, and recommendations for future work. The fence/mulch report [1], which was the first in this series of reports, listed Key Findings (14), Primary Recommendations (7) and Recommendations for Future Work (5). This report on woodpiles adds to those lists to generate a unified set of conclusions related to NIST's series of studies of the hazards associated with various categories of landscape combustibles.

5.1. Key Findings

Firewood piles exhibited fire behavior in the high hazard range, supporting fire spread and generating firebrands and producing moderate flames when fully involved. There are four new findings for woodpiles.

F15. Woodpiles generate copious amounts of firebrands that are capable of igniting spot fires in downwind combustibles. Every experiment with woodpiles generated firebrands that ignited spot fires.

F16. Firebrands from woodpiles can ignite spot fires in 3 min or less in fine combustible materials over significant distances and bring flames to a structure adjacent to the combustibles in less than 5 min. The ignition and fire spread phenomena become even faster at higher wind speeds. Spot fire ignitions occurred even at the maximum distance studied for woodpiles of 27 m (88 ft). At wind speeds of 7 m/s (16 mi/h) or more, any slight differences in spotting behavior seen at lower wind speeds due to aspects of firewood piles disappear.

F17. Wind-blown burning woodpiles can generate fire plumes with steady flames that extend over 1 m (3.3 ft) which could ignite nearby combustibles through flame impingement or thermal radiation. Intermittent plume flames briefly reach over 2 m (6.6 ft). Flames become longer as fire spreads through the whole woodpile. Flame lengths will most likely be longer for woodpiles larger than the 1/12 cord pile size used in this study.

F18. Burning woodpiles may collapse which changes the hazard. When a wind-blown burning woodpile collapses, it appears to increase the fire plume size and length likely due to the spreading of the burning fuel over a larger area and increase in the surface area of exposed burning wood. Firebrand flux may also increase which may be due to the increase in burning surface area and the physical disturbance caused by the collapse.

5.2. Primary Recommendations

The results of this study add to a comprehensive effort to reduce the vulnerability of structure and parcels to fire and firebrands. A hazard mitigation methodology [6] has been developed with the goal of allowing structures in the WUI to survive fire and firebrand exposures without intervention by first responders. The recommended strategy is to balance a reduction of the exposure with increased hardening of the structure. The exposure may be reduced by removing or reducing the fuels or by relocating the source.

Unlike other landscape features, woodpiles can’t be replaced with a noncombustible option that performs the same function. There are measures short of removal that may reduce the fire hazard of woodpiles, including the following recommendations resulting from this study.

R8. In WUI-fire prone areas, protect firewood piles from potential ignition by flames or firebrands to reduce fire spread. Storing firewood in an enclosure made of noncombustible material, such as steel, is expected to substantially reduce the likelihood of ignition. If the firewood does ignite, the enclosure will also act to protect exterior items from the fire, as shown in structure separation experiments [12, 13]. The enclosure should be well-sealed (apart from firebrand-resistant vents). The door and any other openings should face away from nearby structures and be kept closed to eliminate openings for flames or firebrands to penetrate.

R9. Avoid proximity of exposed woodpiles to the residence and other parcel structures, as well as neighboring structures, to prevent direct ignition by flames or flame radiation. The relationship between spacing and structure to prevent structure ignition from woodpiles is a function of woodpile size and structure design, including construction materials and assembly. Structures need to be hardened against the fire hazard from both flames and firebrands (See R7).

In addition to the above recommendations that are specific to woodpiles, other recommendations from the fence/mulch report [1] are reinforced by the findings in this report. They are repeated and emphasized here:

R3. Avoid proximity to other combustible fuels, to reduce fire intensity and limit fire spread. Burning woodpiles are a source of flames and firebrands that readily spread fire to nearby combustible materials. Fuel agglomeration increases fire exposures and reduces defensible space.

R7. Harden structures against firebrands, to prevent structure ignition from firebrands produced by fences and other combustible sources. Burning woodpiles produce firebrands that are capable of spreading fire over long distances downwind.

For more detailed recommendations on spacings of combustible elements including woodpiles and hardening of structures and parcels, refer to the WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology report [6].

5.3. Recommendations for Future Work

This study on woodpile fires suggested additional research to improve mitigation and reinforced recommendations listed in the fence/mulch report.

S6. Additional research is needed to identify other effective methods to mitigate the firewood pile hazard in WUI-fire prone areas. While some design criteria for enclosing the woodpile were discussed earlier, the practical aspects of making a firewood storage unit that meets all of the requirements for proper wood storage but is not vulnerable to firebrands in either direction (in or out) are not simple and should be explored. NIST already has plans to further explore screen effectiveness as part of a mitigation strategy.

There are many combustible landscape features that may contribute to fire hazards in a parcel or community. Recommendation S2 from the fence/mulch report describes additional fire spread behavior work ongoing at NIST to understand the interactions of fires on landscape timbers, creosote-treated timbers, retaining walls, and sheds. The work will include strategies for mitigation. Together, these studies will inform existing and new codes, standards, and best practices with quantitative fire spread mitigation and structure protection strategies based on experimental data.

Recommendation S3 in the fence/mulch report describes improved data collection methods for better understanding and characterizing the hazards generated by woodpiles and other combustible landscape features. For woodpile fires that generate moderate flames, the radiative and convective heat flux received at vulnerable locations could be evaluated by heat flux sensors and/or infrared imaging. For woodpile fires that generate copious firebrands, 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 [14]. This tool will be especially helpful to determine the effectiveness of any mitigation strategies. It could also be helpful to determine the change in firebrand flux after a woodpile collapse. Prototypes of this “emberometer” have already been tested with woodpiles during this series of experiments.

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Appendix A. List of Abbreviations and Acronyms

AHJ
Authority Having Jurisdiction

CFC
California Fire Code

FDS
Fire Dynamics Simulator

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

RH
Relative humidity

rpm
revolutions per minute

SSE
South-Southeast

SSW
South-Southwest

WUI
Wildland-urban interface

Appendix B. Characterization

Measurements from the bidirectional probe array described in Section 2.6.1 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 determine 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 woodpile was of particular interest.

This discussion builds on Appendix C of the fence/mulch report [1]. Because the woodpile experiments were carried out over a longer range of distance within the test area, this report extends our understanding of the development of the wind field from the fan.

B.1. Measurement Distance from Wind Machine

The first step in 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 was a fixed distance from the upwind end of the burning woodpile and the windward length of the woodpile varied with orientation, this distance varied as a function of both the separation distance and the length of the woodpile.

The geometry of the experimental setup is shown in Fig. B.1. This diagram focuses on the location of the probe array relative to the wind machine, woodpile, and target shed. The horizontal distance d_{wp} from the wind machine to the bidirectional probe array was 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 between the probe array and the target shed was equal to the distance d_{pf} from the probe array to the fuel (woodpile) plus the length d_{wood} of the woodpile plus the separation distance d_{sep} of the woodpile from the target shed, or $d_{ps} = d_{pf} + d_{wood} + d_{sep}$. Combining these equations results in $d_{wp} = d_{ws} - \left(d_{pf} + d_{wood} + d_{sep}\right)$.

As was the case for the fence and mulch experiments, the distance between the wind machine and the shed was fixed at d_{ws} = 10.67 m (35 ft), and the probe array was always located at the same distance upwind of the fuel, with d_{pf} = 1.22 m (4 ft). Thus, the final equation for the distance from the wind machine to the probe array as a function of separation distance and woodpile length was

$$d_{wp} = 9.45\ m - \left(d_{wood} + d_{sep}\right) \tag{B-1}$$

with all measurements in meters.

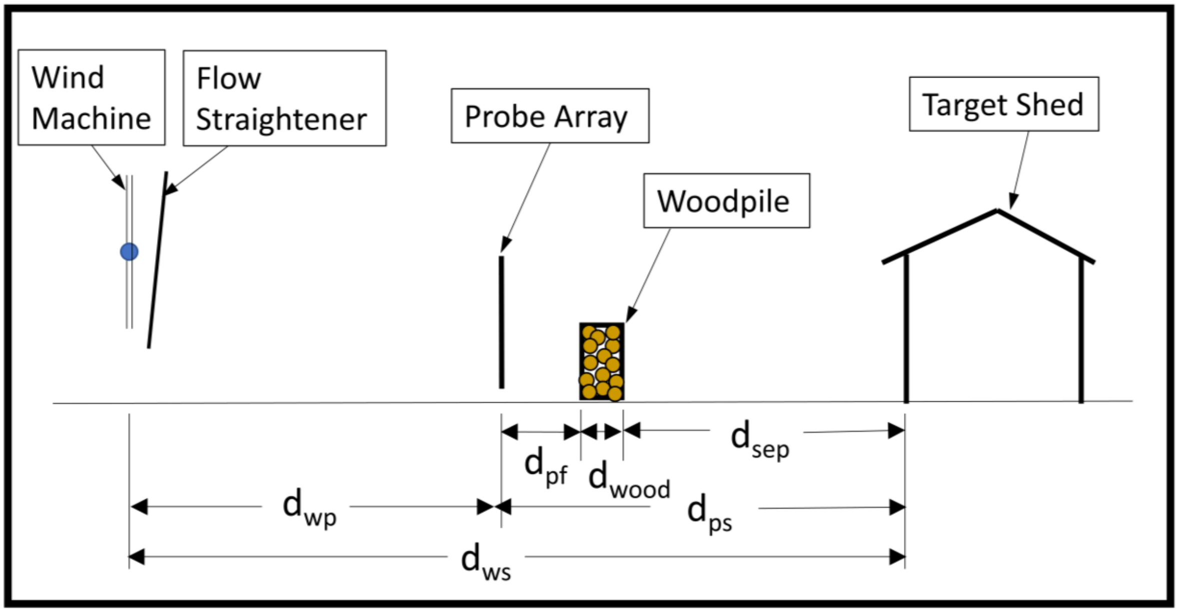


Fig. B.1. Distances between experimental elements. Distances approximately to scale.

The windward length of the woodpile depended on its height and orientation in each experiment. As described in Sections 2.9.5 and 2.9.7, the woodpiles consisted of logs 0.41 m (16 in) wide. The logs could be stacked in a tall configuration 1.22 m (4 ft) high by 0.61 m (2 ft) long or in a short configuration 0.61 m (2 ft) high by 1.22 m (4 ft) long. The logs could be oriented with sides or ends facing the wind. The effects of the arrangement of the woodpile on the woodpile length d_{wood} are shown in Fig. B.2, with the wind from the left. Note that the height does not matter for calculating the length of the woodpile oriented with ends facing the wind.

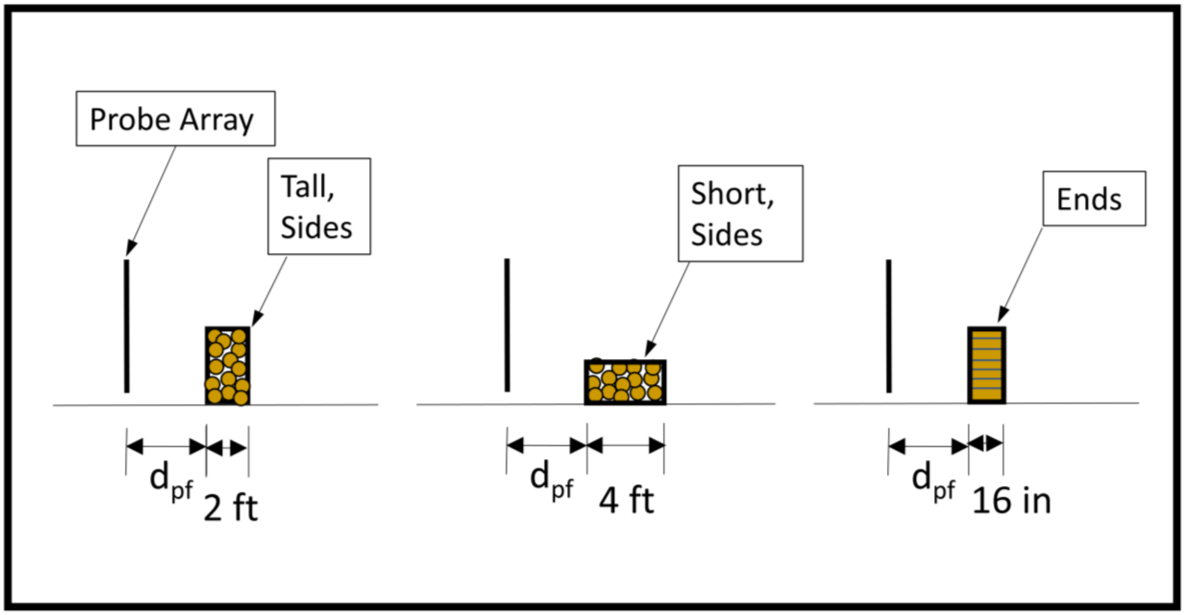


Fig. B.2. Effects of woodpile height and orientation on woodpile length, d_{wood}.

The woodpile experiments were performed at five separation distances d_{sep} between the downwind end of the woodpile and the shed, as described in Section 2.9.2. The variations in woodpile length shown in Fig. B.2 mean that for every separation distance there was a range of probe array locations. However, only a few experiments were performed in the short, sides configuration that caused the largest displacement of the probe array. In combining the wind fields from multiple experiments, these experiments were excluded. The positions of the probe array for each separation distance could therefore be defined as midway between the tall, sides and ends configurations with an uncertainty of ±0.10 m (4 in).

Exceptions to this assumption for the probe array position were made for a separation distance of 0.91 m (3 ft). Since only one experiment each was performed at medium and high wind speeds at this separation distance, the actual probe array locations were used, labeled as EE and EE* as shown in Fig. B.3.

In Fig. B.3, the locations of the probe array are highlighted for the five separation distances between woodpile and target shed used in this study. To demonstrate the coverage of the test space by the wind fields derived from the woodpile experiments, the position of the woodpile that corresponds to the separation distance $d_{sep,CC}$ = 3.66 m (12 ft), is shown in gray. For cases at this separation distance, the woodpile sees a wind field between those at probe array locations CC and DD. 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.

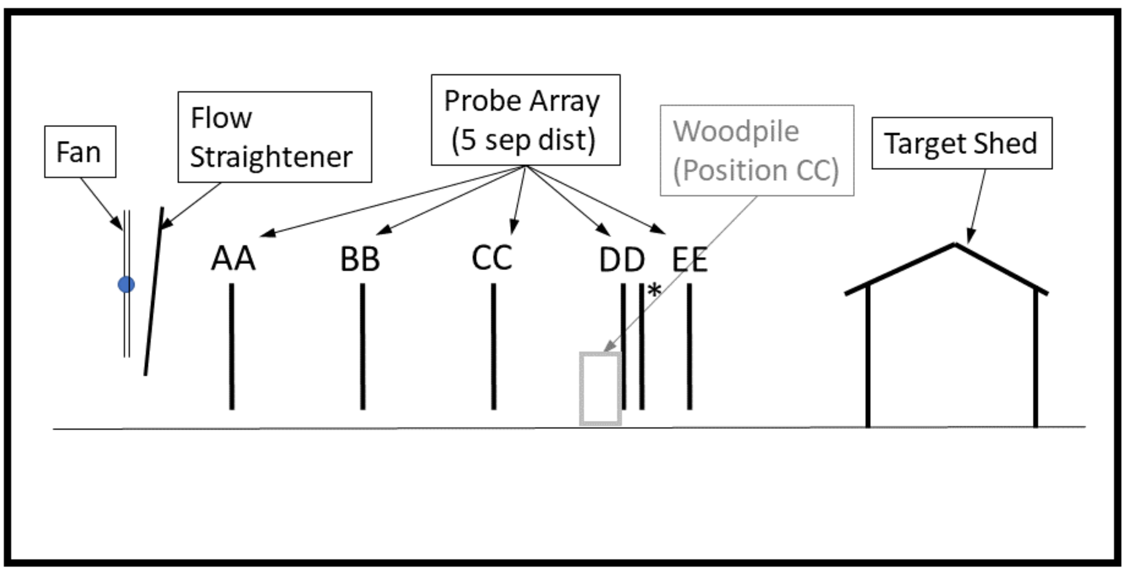


Fig. B.3. Locations of bidirectional probe array for woodpile separation distances of (AA) 7.32 m (24 ft), (BB) 5.49 m (18 ft), (CC) 3.66 m (12 ft), (DD) 1.83 m (6 ft), and (EE) 0.91 m (3 ft). Distances approximately to scale.

Table B.1 lists the assumed distance from the fan to the probe array 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.

As discussed in the fence/mulch report, an expectation can be established for the uniformity of the velocity profiles by referring to the literature on ducted axial fans [1]. 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 B.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 was exceeded for every probe array location except for AA and BB.

Table B.1. Distances from fan for bidirectional probe array at various separation distances.

Array location	Separation distance to woodpile d_{sep} (m (ft))	Distance from probe array to shed d_{ps} (m (ft))	Distance from fan to probe array d_{wp} (m (ft))	Distance from fan to probe array / Fan diameter d_{wp}/D
AA	7.32 (24)	9.04 (29 ⅔)	1.63 (5 ⅓)	0.8
BB	5.49 (18)	7.21 (23 ⅔)	3.45 (11 ⅓)	1.6
CC	3.66 (12)	5.38 (17 ⅔)	5.28 (17 ⅓)	2.5
DD	1.83 (6)	3.56 (11 ⅔)	7.11 (23 ⅓)	3.4
EE*	0.91 (3)	3.35 (11)	7.32 (24)	3.5
EE	0.91 (3)	2.74 (9)	7.92 (26)	3.8

The positions for the bidirectional probe array for the woodpile experiments are compared in Fig. B.4 to the positions in the fence and mulch study. The wind fields determined for positions A, B, C, and D can be found in Appendix C.2 of the fence/mulch study. This figure shows how much more of the wind field over the test area can be viewed using the data from the woodpile experiments compared to the wind field from the limited distance of the fence/mulch testing.

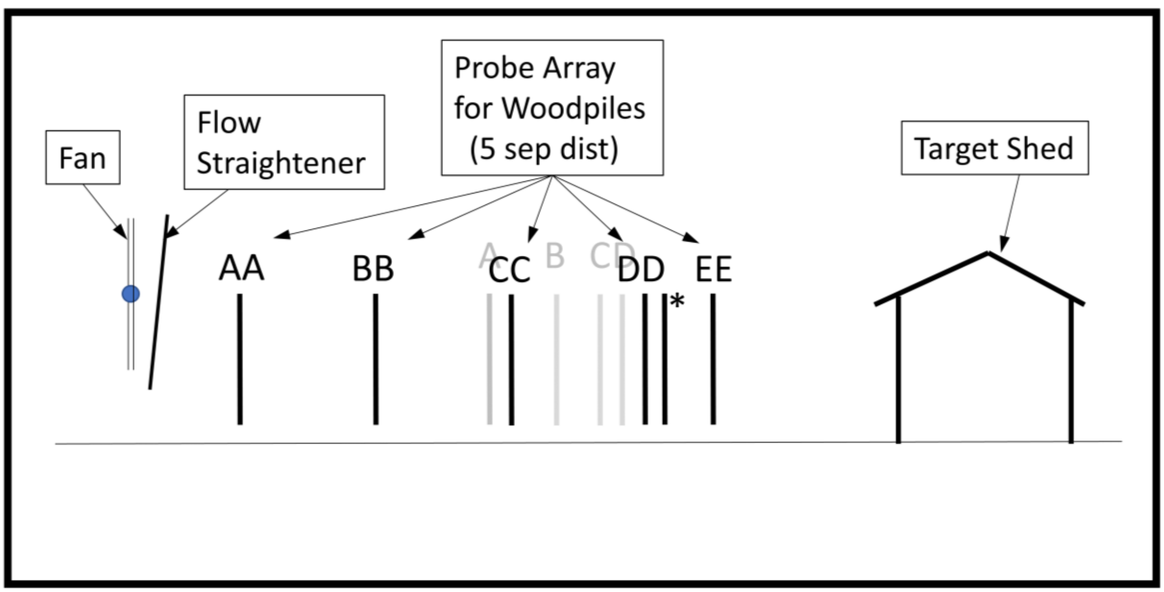


Fig. B.4. Comparison of locations of bidirectional probe array for woodpiles to those of fences (See Appendix C of fences/mulch report [1]).

B.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 AA, BB, CC, DD) used in the study. In addition, mean wind fields were available for array locations EE and EE* by means of the two experiments performed at a separation distance of 0.91 (3 ft). For array locations AA through DD, experiments with woodpiles in the short, sides configuration were not included.

The number of experiments used for each of these categories is shown in Table B.2.

Table B.2. Number of experiments in each category of wind speed and array location.

Array Location	Low Wind Speed	Medium Wind Speed	High Wind Speed
AA	4	3	5
BB	4	5	2
CC	3	6	3
DD	7	5	9
EE*	0	0	1
EE	0	1	0

The statistical analysis described in the fence/mulch report [1] was performed on the dataset collected from the bidirectional probes in the woodpile study. The measurements from experiments that fell into each of the categories listed in Table B.2 were combined to estimate the means and uncertainties of data from each of the 13 bidirectional probes, weighting the data by the number of measurements from each experiment. The calculation required the assumption that measurements from all experiments in the same category were taken from the same data distribution. This assumption was 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.

In Fig. B.5 the weighted mean values of the probe velocities are shown for the three nominal wind speeds and five 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. 12. Velocity scales are identical within each family of nominal wind speeds and are the same as those used in the fence/mulch report. This allows the wind patterns to be observed and compared but limits the ability to distinguish the highest velocities. For each wind speed category, the highest velocities were found closest to the fan at position AA and were as much as 34 % higher than the maximum scale value.

The plots in Fig. B.5 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 1.2 m to 1.5 m (4 ft to 5 ft). The vertical center of the region affected by the fan varied with distance from the fan from roughly 1.5 m (5 ft) close to the fan to about 1.0 m (3 ft) at the farthest measured distance. This results from the angled flow straightener that tilted the flow field toward the ground. The wind field close to the fan showed 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 the central region at positions DD, EE*, and EE. The burning woodpile was exposed to more uniform wind fields at separation distances less than 3.7 m (12 ft) than it saw at 5.5 m (18 ft) and above.

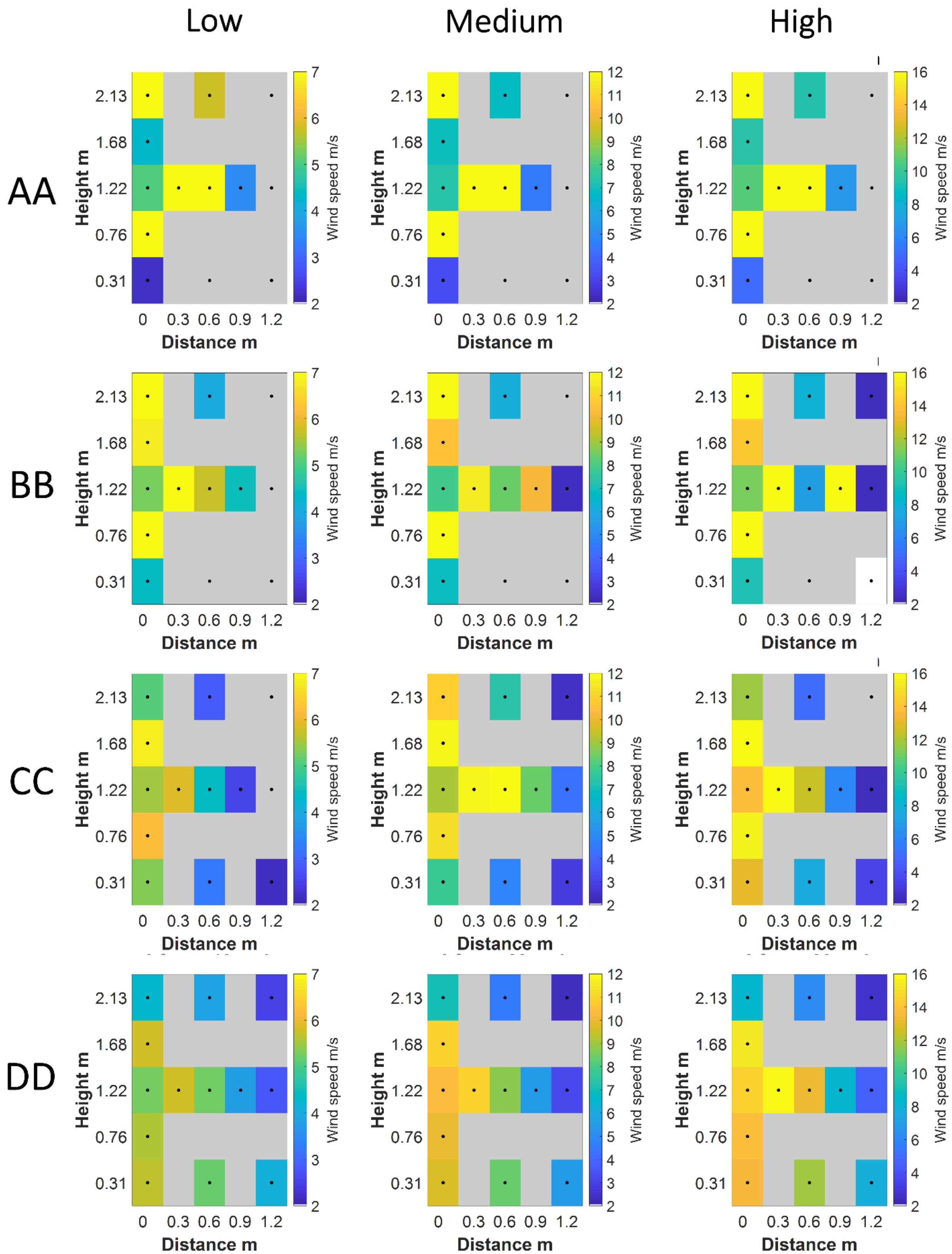


Fig. B.5. Mean wind speed pseudocolor plots by wind speed and probe array location, over all woodpile experiments. Dimensions to scale.

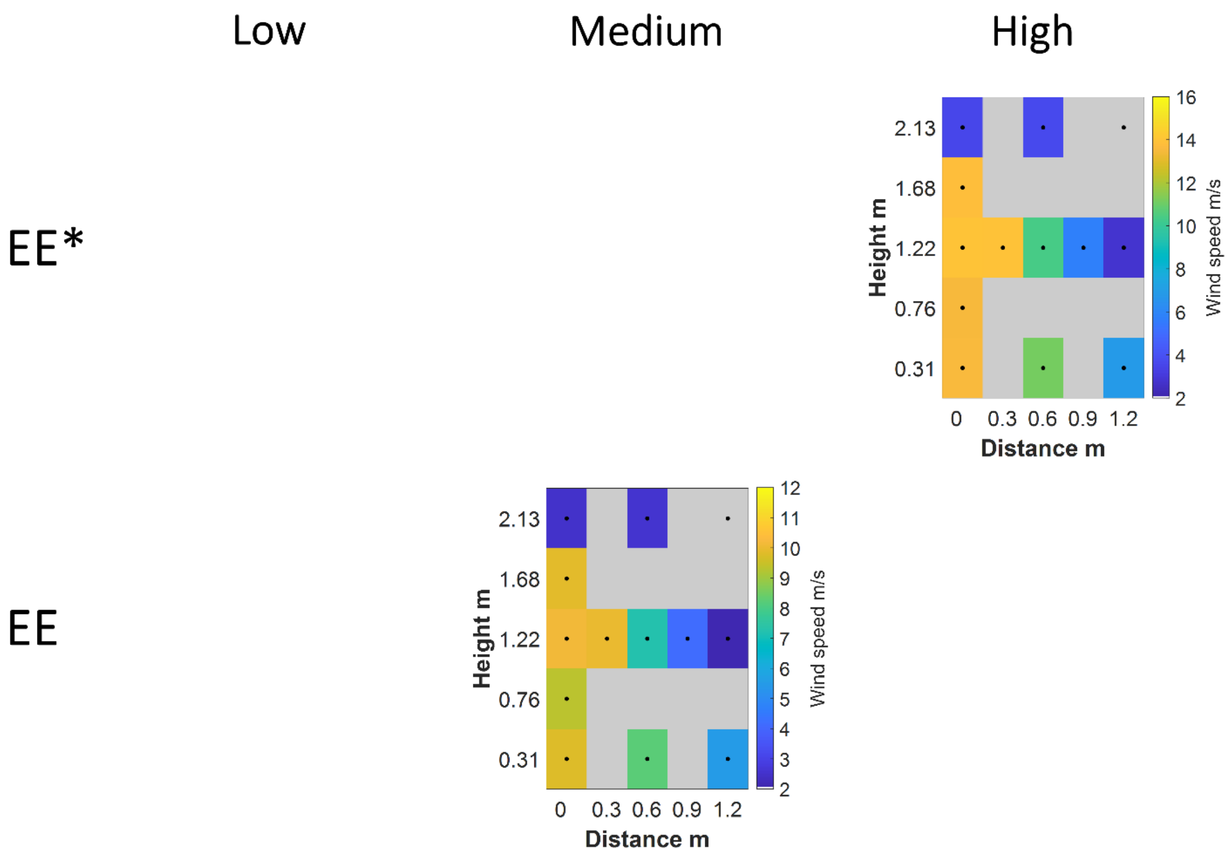


Fig B.5 (cont.). Mean wind speed pseudocolor plots by wind speed and probe array location, over all woodpile experiments. Dimensions to scale.

A comparison of the pseudocolor plots for probe array locations CC and DD in Fig. B.5 with those for probe array locations A through D from Fig. C.4 in the fence/mulch report [1] showed reasonable agreement. This was as expected from the overlapping locations shown in Fig. B.4. The increasing wind field uniformity from locations CC through EE agrees with the 2 ½ diameter threshold for uniform flow discussed for Table B.1.

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 under 0.05 for all but three combined probe measurements, with the highest value at 0.068. This was higher than that found for the fence and mulch experiments, which makes sense due to both the low number of experiments combined for each set of nominal wind speed and probe array locations and the variation in probe array location for each separation distance. However, this is smaller than the relative standard uncertainty for the bidirectional probe measurement of $u_{r,BP} = 0.0703$ as discussed in Appendix A.2 of the fence/mulch report. 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. B.6 and Fig. B.7 provide a more quantitative look at the wind speed data across the center of the profile both horizontally and vertically.

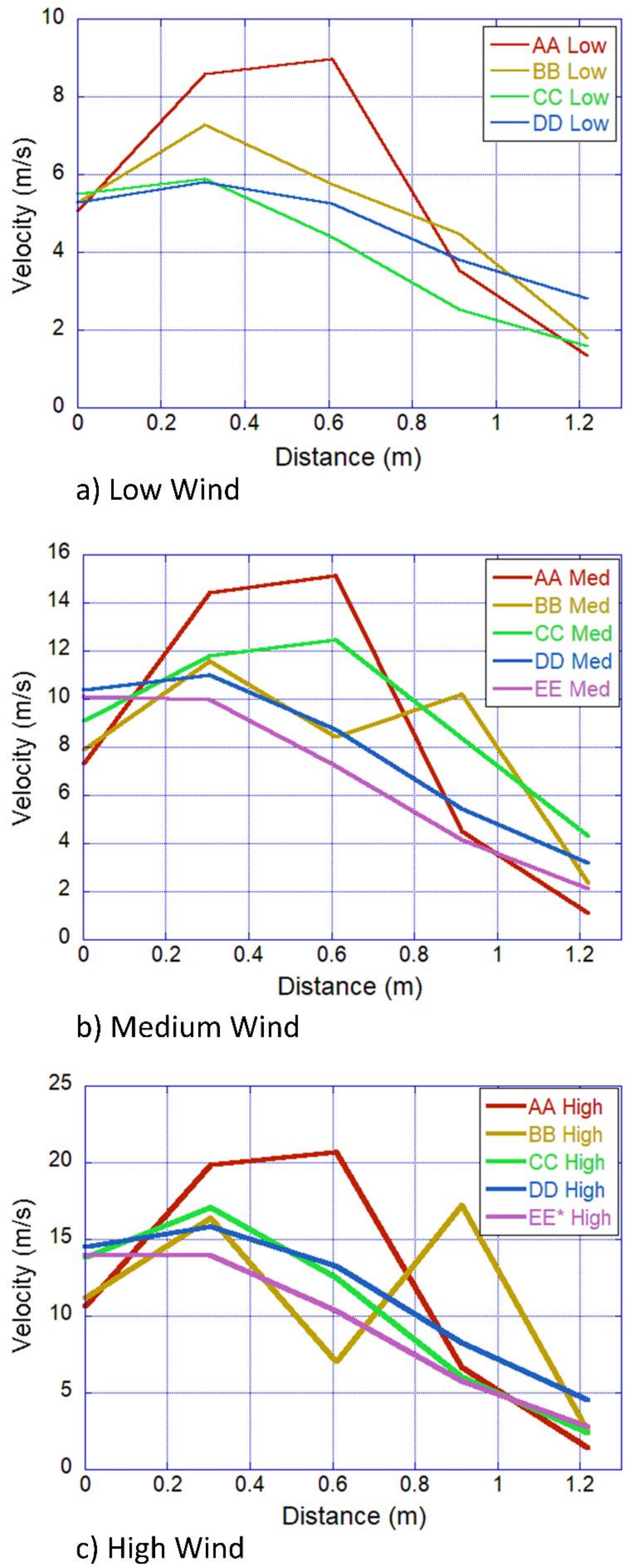
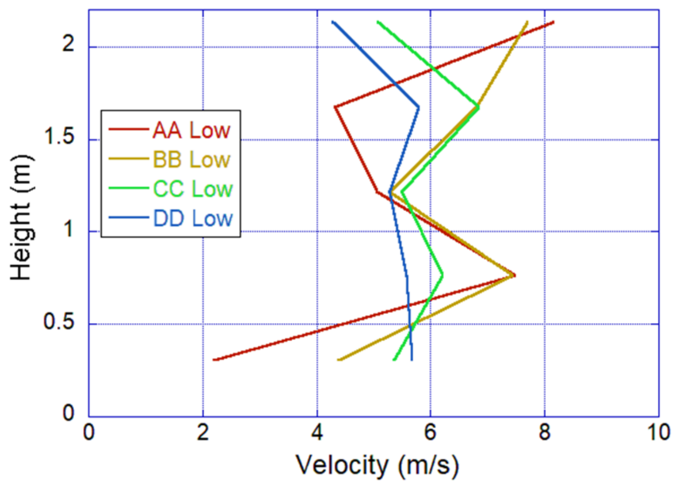
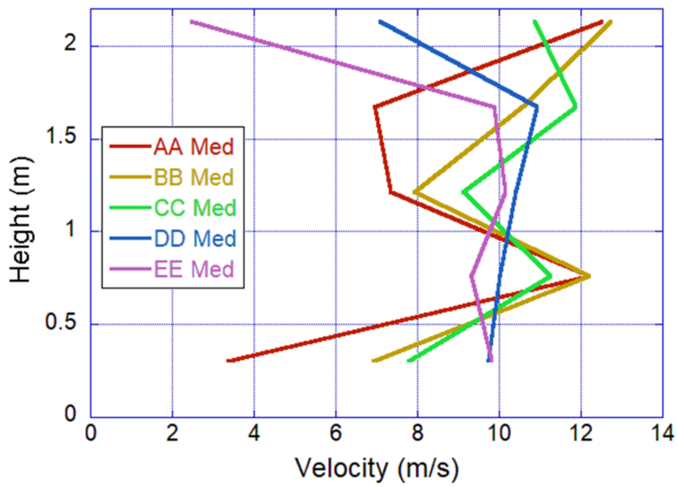


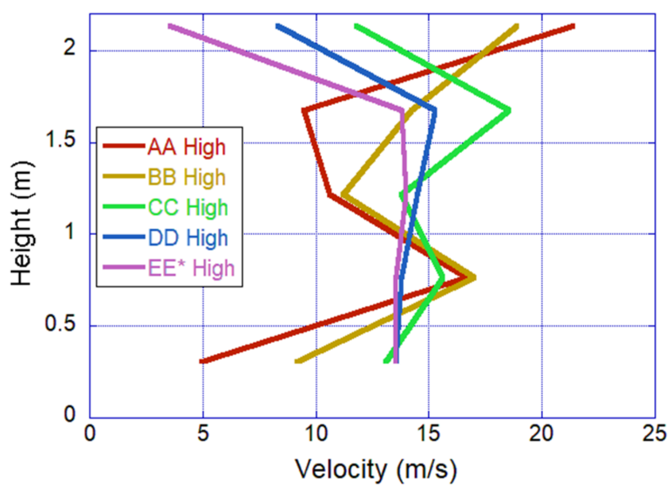
Fig. B.6. Horizontal weighted mean wind speed profiles 1.22 m (4 ft) above the ground for a) low wind, b) medium wind, and c) high wind fan conditions.



a) Low Wind



b) Medium Wind



c) High Wind

Fig. B.7. Vertical weighted mean wind speed profiles along the centerline for a) low wind, b) medium wind, and c) high wind fan conditions.

In Fig. B.6, the velocity is plotted as a function of distance from the centerline at a height 1.22 m (4 ft) above the ground. For each of the three wind speed categories, low, medium, and high, the plots demonstrate the trend toward a more uniform flow field as the distance downwind from the fan increases from position AA (red) to position EE (purple). The minimum in wind speed at the center due to the hub of the fan flattens out with distance; wind speeds for probe #9 on the centerline and probe #8 next to it were within ±5 % for positions DD and EE. Wind speeds for the adjacent probe #7 were significantly lower (15 % to 25 %) at those positions for medium and high winds, which may reflect the gradual lowering of the center of the wind field with distance downwind due to the flow straightener.

The vertical profiles in Fig. B.7 give velocity as a function of height along the centerline for low, medium, and high wind conditions. The plots again show a trend toward a more uniform flow field with increasing distance from the fan, with wind speeds for the bottom four probes within ±7 % for probe array positions DD and EE. The double maximum of the wind speed along the vertical profile for positions AA through CC displays the characteristic ring pattern of flow from an axial fan. The effects of the tilted flow straightener are seen in the downward shift of the upper maximum wind speed from top probe #13 at position AA to probe #10 at positions BB and CC.

Combining these results with the wind analysis for positions A though D from the fence/mulch report indicates that the woodpiles in this study with a separation distance equal to or less than 3.66 m (12 ft) (corresponding to probe array position CC as shown in Fig. B.3) experienced a reasonably uniform wind field. At the largest separation distances of 5.49 m (18 ft) or 7.32 m (24 ft), woodpiles were exposed to a more variable wind field. In these experiments, the highest wind levels were roughly ¾ m (2 ½ ft) above the ground, which was at the top of woodpiles 0.61 m (2 ft) high and in the middle of woodpiles 1.22 m (4 ft) high.