Fire Safety Journal 104 (2019) 34–42

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Thermal characterization of firebrand piles

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ARTICLE INFO

Keywords:
Firebrands
Burning embers
Wildland-urban interface
Wildfire

ABSTRACT

The cause of the majority of structure losses in wildland-urban interface fires is ignition via firebrands, small pieces of burning material generated from burning vegetation and structures. To understand the mechanism of these losses, small-scale experiments designed to capture heating from firebrand piles and to describe the process of ignition were conducted using laboratory-fabricated cylindrical wooden firebrands. Two heat flux measurement methods were compared, and the influences of firebrand diameter, pile mass, and wind on heating from firebrand piles were explored. Diameter had little effect on heating, pile mass a moderate effect, and wind a large effect. Peak heat fluxes showed distinct differences between heat fluxes produced by firebrand piles as opposed to individual firebrands, which have been studied exclusively on the small-scale in the past. Above a critical mass, piles did not produce higher heat fluxes; however, they heated fuels for an increasingly longer duration and over a larger area. Water-cooled heat flux gauges provided reliable heat flux measurements for large firebrand piles and an array of thin-skin calorimeters indicated significant spatial variation in heat flux. A recipient fuel transitioned from smoldering to flaming under an adequate wind speed soon after a firebrand pile was deposited on its surface.

1. Introduction

Over the past several decades, the number of devastating wildland-urban interface (WUI) fires has increased drastically, driven by climate change, fuel management practices, and increased human development in WUI areas [1]. The WUI is the location where human development abuts or intermixes with wildland vegetation [2]. Fires in WUI areas pose a high hazard to homes, people, businesses, and infrastructure, destroying thousands of structures annually in the United States [3]. Global statistics reflect similar trends [4].

Structures ignite in a WUI fire when the structure is exposed to flames or heat from the fire via radiation, direct flame contact, or firebrand showers. Investigations of past fires [5–7] have found that firebrands are responsible for the majority of structure losses in WUI fires. Firebrands, or burning embers, are small pieces of burning material generated from vegetation or burning structures during a fire. Firebrands are lofted in the fire plume and can be transported up to 9 km ahead of the fire front [7]. They can land in either a glowing or a flaming state and cause ignition of a structure several hours after the main fire front has passed. Even though the evidence shows that firebrands cause the majority of structure ignitions, ignition by firebrands has received less research attention than radiant ignition.

There is little previous small-scale work on ignition of solid fuels by firebrand piles. Previous work on ignition by firebrands has focused primarily on ignition of vegetative fuels, ignition by individual firebrands, and large-scale ignition by firebrand showers. Ignition of vegetative recipient fuels is expected to differ from ignition of solid recipient fuels because vegetative fuels are relatively porous, allowing firebrands to embed themselves in the recipient fuel, thus increasing contact between the ignition source (i.e the firebrands) and the fuel. Firebrands accumulate in piles on top of solid fuels [8], such as decks, so the contact area between the fuel and the firebrands is much smaller. Full-scale tests have found that firebrands accumulate in the stagnation plane in front of structures, and that the accumulation of firebrand increases the ability of firebrands to ignite structures [8–10]. Firebrand pile heating is expected to differ from heating by a single firebrand because individual firebrands in a pile can interact through reheating. Reheating occurs when the firebrand pile shifts and the firebrands which have maintained a higher temperature provide heating to lower temperature firebrands, thus raising their temperature and continuing the smoldering reaction. Both the interaction between individual firebrands in the pile and the decreased contact area for solid fuels, as

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https://doi.org/10.1016/j.firesaf.2018.10.002
Received 29 June 2018; Received in revised form 16 October 2018; Accepted 17 October 2018
Available online 24 October 2018
0379-7112/

opposed to vegetative fuels, are expected to change the heat transfer mechanisms governing the ignition process of a solid fuel exposed to a firebrand pile.

The overarching goal of this work was to understand how heating from firebrand piles relates to ignition. To achieve this goal, this work was split into two phases - the first to determine how to best measure thermal characteristics of firebrand piles and the second to connect these characteristics to the onset of ignition. The objective of Phase I was to determine a reliable method of spatially and temporally resolving heat fluxes from firebrand piles to solid fuels, quantifying the effects of firebrand size and pile mass. Thermal measurements were isolated from ignition in Phase I to determine the heating directly from the firebrand pile without the influence of heating after the recipient fuel ignites. All tests for this phase were conducted on an inert material with no wind.

The objective of Phase II was to understand how thermal conditions, such as those measured in Phased I, at ignition are related to the occurrence of ignition. The process of ignition of a solid fuel exposed to a firebrand pile is not well understood, so a secondary objective was to describe, qualitatively, the ignition process. Three mechanisms of ignition were hypothesized: the firebrands could cause flaming ignition of the pyrolyzates of a recipient fuel; the firebrands could cause smoldering ignition of the recipient fuel which would itself later transition to flaming; or, the firebrands could directly ignite the solid fuel to glowing. Because ignition could not be achieved without wind, all tests in Phase II were conducted under a steady wind speed determined to cause ignition. Tests were conducted separately on both an inert material, to determine heat flux and temperature using the method from Phase I, and on a WUI fuel, to determine ignition time and mechanism. The inert tests under wind indicated the thermal conditions immediately preceding ignition. The goal of Phase II was not to understand the variability of wind, but to describe a single relevant wind condition.

2. Literature review

To the best of the authors' knowledge, no previous studies on firebrand ignition have measured the heat fluxes associated with ignition. Ignition thresholds are often given in terms of a critical sustained applied radiant heat flux, with lower values for smoldering, as opposed to flaming, ignition. For instance, polyurethane smoldering has been initiated with a 3.1 kW/m^2 [11] conductive heat flux and a 7 kW/m^2 incident radiant heat flux; analogous spontaneous flaming ignition has required 30 kW/m^2 [12]. Gratkowski et al. produced smoldering ignition of plywood in a cone calorimeter at an incident radiant flux of 7.5 kW/m^2, which agrees well with self-heating theory [13]. The smoldering ignition values are notably lower than those required for flaming ignition. Comparative values are available for a number of other materials in Ref. [14].

Most ignition theories pertain to radiant ignition, although Gol'shleger et al. [15] proposed a theory of hot spot ignition, which assumes a hot object creates pockets of heating in a recipient fuel and ignition occurs in these pockets. Qualitative agreement was found for experiments investigating the ignition of porous fuel beds using a hot metal sphere, varying particle size and temperature [16]; however, hot spot theory assumes no ongoing reactions in the particle. Further work with hot metal spheres has highlighted the importance of heat losses from the particle in controlling whether a recipient fuel ignites [17,18]. This work has also found that ignition is not purely a function of particle temperature or energy [19].

Babrauskas outlines four mechanisms of solid fuel ignition [14], three of which could be applicable to the ignition of solid wood-based WUI fuels. The first mechanism of ignition is flaming ignition of flammable fuel vapors in the gas phase. The second is smoldering ignition of the fuel. The third is direct surface ignition of the fuel (e.g. glowing ignition for wood) [14]. Glowing combustion is the burning of a solid material which produces light, but no flame, while smoldering is the "heterogenous oxidation of a solid fuel", which produces neither a flame nor light [14]. One of these mechanisms could potentially describe ignition of recipient fuels by either firebrands or a hot object. Manzello et al. [20] propose an energy balance in which the firebrands heat the surface of the fuel, causing production of pyrolyzates, which are ignited in the gas-phase by heat from the firebrands. Fernandez-Pello [21] proposes that the firebrand could either act as a pilot or that the flammable gas mixture could spontaneously ignite. Fernandez-Pello also indicates that a different process could occur in which the hot particle causes smoldering of the fuel which itself transitions to flaming [21].

Much experimental work specifically on firebrand ignition has focused on vegetative fuels or ignition by individual firebrands. In tests using pine needles, shredded paper, and cedar wood crevices as recipient fuels [22], a single glowing firebrand initiated smoldering in dry shredded paper under a 0.5–1.0 m/s wind. Four large firebrands ignited pine needles, which transitioned from smoldering to flaming under a 1.0 m/s wind. No glowing firebrands were able to ignite the cedar crevice. In similar tests on shredded hardwood mulch, pine straw mulch, and cut grass, a single glowing firebrand never produced ignition. Four glowing firebrands initiated smoldering ignition for some fuel beds under wind [23]. In tests using a hot metal sphere [24], the density of a recipient fuel was found to affect the likelihood of ignition.

In experiments using firebrands on solid fuels [25], ignition probability increased with increasing wind speed. Dowling [26] conducted firebrand tests in bridge timbers and found that 7 g of firebrands produced ignition. Manzello et al. deposited four glowing firebrands into crevices made of either plywood or oriented strand board (OSB) and varied wind speed and recipient fuel moisture content (MC) [27]. Ignition was sensitive to angle; only tests on fuel with 0% MC at 60°or 90°under a 2.4 m/s wind ignited. The authors expected that the fuels with higher (11%) MC did not ignite due to the higher thermal inertia of these samples [27]. MC has been highlighted [21,23,28,29] as one of the most important parameters governing ignition for porous fuel beds exposed to hot objects.

Large scale experiments exploring structural vulnerabilities to firebrand showers are summarized in Ref. [9]. In particular, ignition tests exposing decking assemblies to constant wind firebrand showers determined pile sizes to cause ignition. Under an 8 m/s wind, 7–25 g of firebrands were sufficient to cause flaming ignition of the deck surface. A lower wind speed of 6 m/s required a larger mass of firebrands [30]. The only previous small-scale ignition tests with firebrand piles used charcoal to simulate firebrands on a solid wood recipient fuel [31].

3. Materials and methods

3.1. Experimental setup

An experimental apparatus, shown in Fig. 1, was constructed to enable heat flux measurements of firebrand piles using either a 1.27 cm

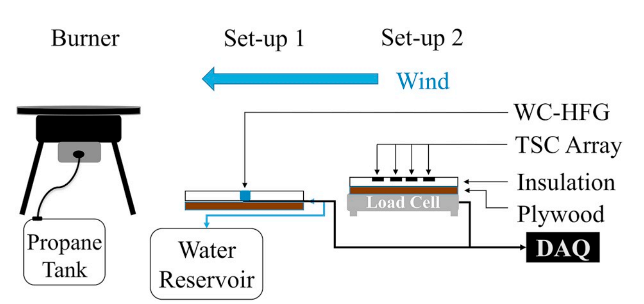

Fig. 1. Schematic side view of both heat flux experimental set-ups for Phase I ambient tests with a propane burner for fabricating firebrands. Figure of burner from Caton [32]. Not drawn to scale.

diameter water-cooled heat flux gauge (WC-HFG) or an array of thin-skin calorimeters (TSCs). This apparatus was used for heat flux measurements for both Phase I and Phase II of this work. The 18 cm × 18 cm test surface consisted of a 1.5 cm thick sheet of Superwool 607 High Temperature ceramic insulation board clamped to a sheet of plywood, which was used as a stabilizing mass. The inert material allowed heat fluxes produced by the firebrand pile to be isolated from ignition. The setup was placed inside a laminar flow hood for ambient experiments. Air fluctuations within the hood were on the order of 0.1 m/s. For one setup, the measuring surface of a WC-HFG was set flush with the insulation on the test surface. For the other setup, TSCs were arranged in a 4 × 4 array, the centers of the sensors separated by 1.5 cm, the gauge surfaces flush with the insulation surface. A K-type thermocouple, fabricated in-house, with a 0.25 mm diameter wire and 0.3 mm diameter bead was placed on top of the insulation, beneath the firebrand pile, and provided an estimated temperature beneath the pile. The thermocouple did not provide the temperature of the firebrands. It was not in constant contact with a firebrand throughout the test due to the random deposition of the firebrand pile, as described in Sections 3.3 and 4.1. A camera recorded video from an elevated side view.

Table 1 provides the range of individual firebrand diameters and pile sizes (measured as mass) tested, where the initial mass is the mass of wood before burning. All ambient tests indicated in the matrix were replicated five times, all wind tests were replicated seven times, and all ignition tests three times. The test using 12.7 mm initial diameter firebrands for a 100 g initial pile mass was replicated nineteen times to determine whether a higher number of tests produced higher uncertainties. Table 2 shows the number of firebrands used for each mass and the equivalent mass of smoldering firebrands deposited on the test surface. Deposited mass was measured in separate tests in a quiescent environment. Initial mass was kept constant and firebrands were produced following the procedure described in Section 3.3. The first few seconds of mass were averaged for each test and the masses presented in Table 2 are an average of three test repetitions.

For ignition tests in Phase II, a 6.35 mm thick, 300 mm long aluminum plate with a super elliptical leading edge (for more details see Ref. [33]) was placed several centimeters in front of the outlet of a laminar blower (see Ref. [34] for description of flow characteristics) to allow for the formation of a laminar boundary layer before the firebrand test section. An 18 cm × 18 cm sheet of OSB was placed behind the aluminum edge, flush with its surface. OSB was chosen because of its common usage as a building material, as sheathing for walls and roofing, and for its use as a recipient fuel for ignition tests in other studies [27]. OSB was dried at 103 ± 2 °C, per ASTM D4442 [35], until it reached 0% MC, then cooled and stored in desiccant before testing.

Initial tests were unable to produce flaming ignition without wind. As a result, increasing airflow was applied to a set pile size to determine a repeatable wind speed and pile size for ignition of OSB. Ignition tests in Phase II were conducted for 5.2 g and 9.6 g deposited mass piles of 12.7 mm firebrands (see Fig. 3e) under a 1.84 m/s wind, a speed consistent with average local wind speeds found in fires (e.g. 1.8 m/s in the New Jersey Pine Barrens prescribed burns [36]). The pile masses are consistent with pile sizes necessary for ignition of decking assemblies exposed to firebrand showers in Ref. [30]. A camera recorded video from an elevated side view.

3.2. Measurement techniques

WC-HFGs and TSCs, used for Phase I and Phase II thermal measurements, are typically used for radiative or convective heat flux measurements. The gauges are also exposed to conductive heat fluxes from firebrand piles; however, this work found that the heat transfer in firebrand piles is dominated by re-radiation. Tests were conducted on the TSC array in which a single firebrand was placed on a central TSC. Adjacent, uncovered calorimeters whose nearest edges were 0.5 cm away received an average of one third of the maximum heat flux received by the covered TSC. This result suggests that at least a third of the heat transfer is radiation; however, this estimate may be on the low end. Uncovered TSCs are subjected to large convective losses and the reduced view factor for an adjacent TSC could both appear to reduce the radiation contribution. Additionally, the firebrand pile, unlike the individual firebrand, is a noncontinguous heat source, which is likely to be dominated by radiation [14]. The importance of re-radiation in controlling the heat transfer suggests that the WC-HFG is appropriate for this application.

Experiments with a single-point 1.27 cm diameter WC-HFG provided time-resolved heat flux measurements and were used to validate the TSC calibration. A larger WC-HFG (2.54 cm) was found to cool the firebrand pile resulting in decreased heat fluxes. Tests with the 1.27 cm WC-HFG minimized cooling effects, showing higher heat fluxes, more variation in heat flux, and better time resolution than analogous tests with the 2.54 cm WC-HFG. Although the smaller gauge reduced the cooling effects, it may not have removed them entirely, particularly for tests using small piles or individual firebrands whose size was on the order of the size of the gauge.

TSCs were fabricated by welding a 0.25 mm diameter K-type thermocouple wire to the backside of a 1 cm^2, 0.508 mm thick Inconel alloy 625 plate. Total heat flux was determined by calculating the heat transfer components from a measured temperature history, using the assumptions of one-dimensional heat transfer and lumped capacitance [37]. Due to the challenge of describing the energy balance (see Ref. [38]), a correction factor from a calibration technique based on Hildalgo et al. [39] was applied to account for the unknown emissivity of the TSCs, conduction into thermocouple wires and insulation, and the unknown contact resistance between the firebrand pile and the sensors. This correction factor is assumed to be a fraction of the incident radiant heat flux, and both radiative heat flux and conduction losses are assumed to be temperature dependent. Sensors were calibrated against a reference WC-HFG using a radiant propane heater at 5–15 radiative heat fluxes ranging from 5 to 55 kW/m^2 for each sensor. TSCs underestimated heat flux by around 10–35% for low heat flux values (below 10 kW/m^2) to an average of 50% for high heat flux values (45–55 kW/m^2) when compared to steady values of a reference WC-HFG. Additionally, the TSCs had a time lag of approximately 150 s to reach a steady value, making them inappropriate for time-resolved data.

Comparison with WC-HFG results show that TSC measurements can be used as a qualitative indication of heat flux trends. The TSCs provide a reasonable overall (rather than time-resolved) heat flux estimate without wind; however, increased convective cooling from applied

Table 1
The test matrix. For each type of test, experiments were conducted using the individual firebrand diameter and pile masses of firebrands indicated. Note that the masses listed are initial mass before burning.

Pile sizes tested				
Diameter	Ambient WC-HFG	Ambient TSC	Wind WC-HFG	Ignition
6.35 mm	1 brand (0.5 g), 20 g, 50 g, 100 g	100 g	None	None
9.52 mm	1 brand (1.2 g), 20 g, 50 g, 100 g	100 g	None	None
12.7 mm	1 brand (2.0 g), 20 g, 50 g, 100 g	1 brand (2.0 g), 20 g, 50 g, 100 g	50 g, 100 g	50 g, 100 g

Table 2
The equivalent deposited mass of glowing firebrands and number of firebrands for the initial mass of wood.

Initial Mass	1 Firebrand	20 g		50 g		100 g	
Initial Diameter	Deposited mass (g)	Number of firebrands	Deposited mass (g)	Number of firebrands	Deposited mass (g)	Number of firebrands	Deposited mass (g)
6.35 mm	0.1 ± 0.05	40	1.0 ± 0.31	101	2.9 ± 0.85	202	6.3 ± 1.35
9.52 mm	0.2 ± 0.06	16	1.2 ± 0.17	46	5.0 ± 0.65	92	8.2 ± 1.25
12.7 mm	0.6 ± 0.15	10	2.7 ± 0.76	26	5.2 ± 0.61	52	9.6 ± 1.77

wind causes particularly high errors in heat flux calculations. Under wind conditions, the TSCs predict heat flux values an average of twice as large as are measured by the WC-HFG. In wind conditions, the TSC is an adequate measure of temperature, but a poor measure of heat flux. Whether in ambient or wind conditions, the array of TSCs is necessary to determine the spatial distribution of temperature or heat flux, as well as the area heated by the firebrand pile for different pile conditions. WC-HFGs cannot provide spatially resolved heat flux because an array of WC-HFGs would provide significant cooling to the firebrand pile. The combination of the WC-HFG and the TSC array are therefore complimentary when used together.

For the Phase II ignition tests with wind, a FLIR ThermCAM SC3000 infrared (IR) camera with a spectral response of 8–9 μm recorded IR video from directly above the set-up, recording in the temperature range of 350–1500 °C. This range was chosen to cover the initial high temperatures of the firebrands. The emissivity of the firebrands was unknown, though previous researchers have used values between 0.6 and 1.0 [1]. A value of 0.92 was chosen arbitrarily because IR results were meant to give a qualitative rather than quantitative view of heating from the top of the pile. An elevated side-view camera recorded visual video for comparison.

3.3. Experimental procedures

While firebrands come in different shapes and sizes, collection studies by Manzello et al. [40,41] found that cylindrical sticks are one of the most common brand shapes for vegetative firebrands. Although Santamaria et al. [31] also found bark to be a common firebrand, sticks are more reproducibly simulated. Firebrand diameters and length (see Table 1) were chosen in this study to be near the average sizes based on collection studies. Although 12.7 mm initial diameter firebrands are larger than average, the initial diameter is given of the wood dowel and the diameters of the burned firebrands decrease. The percentage decrease from initial to burned diameter was not measured. Birch was chosen as it was readily available in the average sizes of firebrands; however, its density is higher than that of softwoods more commonly found in WUI fires [42].

A repeatable method to produce firebrand piles was necessary to test the effect of glowing firebrands on recipient fuels. Firebrands were fabricated from 25.4 mm long cylindrical birch dowels by exposing the wood in a wire mesh basket to a propane flame. Once the majority of the wood pieces ignited, the propane flame was extinguished and the firebrands were left to flame for 150–200 s, a method based on [22]. After the cessation of flaming, glowing firebrands were deposited on the test set-up by pouring the firebrands from the edge of the wire mesh basket, guided by tongs, resulting in a variable pile organization (see Fig. 2 for a comparison of pile organization for different pile sizes). Individual firebrands were placed directly on the sensor using tongs. Individual placement was not possible for full piles before firebrands broke apart or transitioned to ash and is not representative of behavior observed in the field. Data acquisition continued until the temperature of both the thermocouple and the TSCs decreased below 27 °C. This firebrand production method was repeatable to conduct; however, larger quantities of firebrands (e.g. 100 g vs 20 g of wood) sustained flaming for longer periods of time after the burner was shut off. As a result, the larger firebrand piles appeared to be in a more degraded state upon deposition than smaller piles or individual firebrands. The differences in the degradation state may introduce a small error which cannot be quantified here, as differences in the degraded firebrand diameters were not explicitly tested.

4. Phase I results

4.1. Spatial heat flux distribution

Within each firebrand pile, there were differences between individual firebrands: some firebrands were primarily charred, while other glowed throughout their length (see Fig. 3e). This variability is an indication of the natural variability in the smoldering combustion of wood. Although firebrands were deposited in a glowing state, they quickly transitioned to ash. This transition was accompanied by a decrease in heat flux, followed by a rise in heat flux when the ash was blown off (e.g. by ambient air fluctuations), revealing glowing firebrands beneath the ash. As a result, the ash was thought to insulate hot glowing cores of firebrands.

The TSC array provides a way to observe how heating changes based on pile location. Heating changes within the pile due to the natural variability of smoldering wood, increased cooling from the edges of the pile, and the way the pile deposits on the TSC array. The method of pile deposition results in a random pile organization, meaning that firebrands may either fully or partially cover an individual sensor. A sensor that is only partially covered will experience greater convective cooling, influencing the heat flux measured.

Fig. 3a–c shows how heat flux evolves spatially during a test. The areas of highest heat flux change throughout the test, from two areas at the first time step to a single concentrated area at the third time step. Fig. 3d and f compare the maximum heat flux obtained for an individual firebrand and the largest pile tested, 9.6 g deposited mass, respectively. The single firebrand heats a large area, indicating the importance of re-radiation from the firebrand. The large pile produces higher heat fluxes that are not centered in the center of the pile. The spatial distribution of the heat flux within a pile indicates the importance of the area heated by the firebrands, which increases with increasing pile size. It is expected that a critical heat flux over a larger area may influence likelihood of ignition, as area heated is an important characteristic of ignition sources [14].

4.2. Heating comparison

Two main quantities of interest were varied to determine their effect on measured heat flux: initial firebrand diameter and pile size, measured as deposited mass. The initial mass of the wood pile was controlled, because it was difficult to control the deposited mass of the glowing firebrand pile; however, results are shown using the averaged deposited mass of the glowing firebrands. Firebrand diameter was varied because firebrand size was found to be important in previous studies using individual firebrands, where a single larger firebrand could ignite a porous fuel bed when a smaller firebrand could not [22,23]. For individual firebrands, the largest diameter produced the highest heat flux over time and continued heating for longer than the smaller diameters did, potentially because the contact area to the sensor was larger. Piles made of different firebrand diameters, though, showed

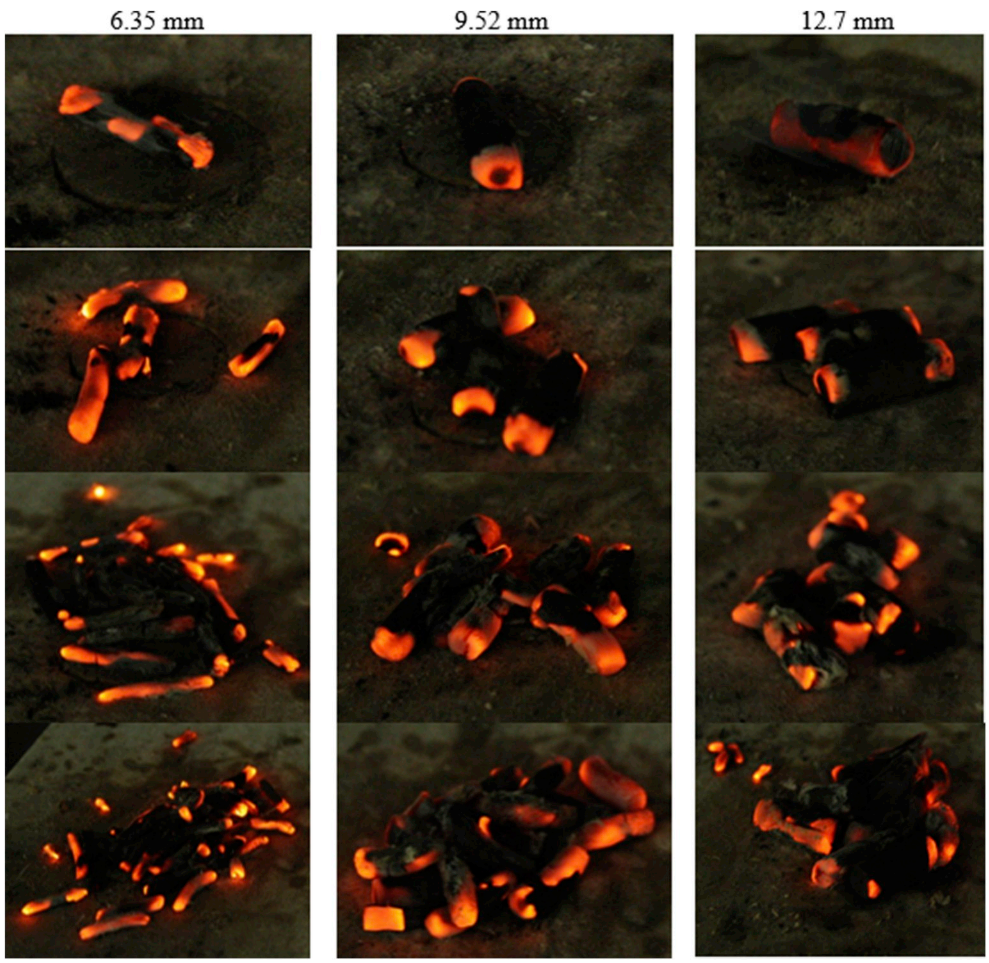

Fig. 2. Photos showing varying firebrand pile sizes and variable pile organization, increasing in diameter from left to right and increasing in pile mass from top to bottom: 1 brand, 3 brands, 10 g, and 20 g (initial mass). Note that these images are from preliminary tests with the 2.54 cm WC-HFG, not the 1.27 cm gauge.

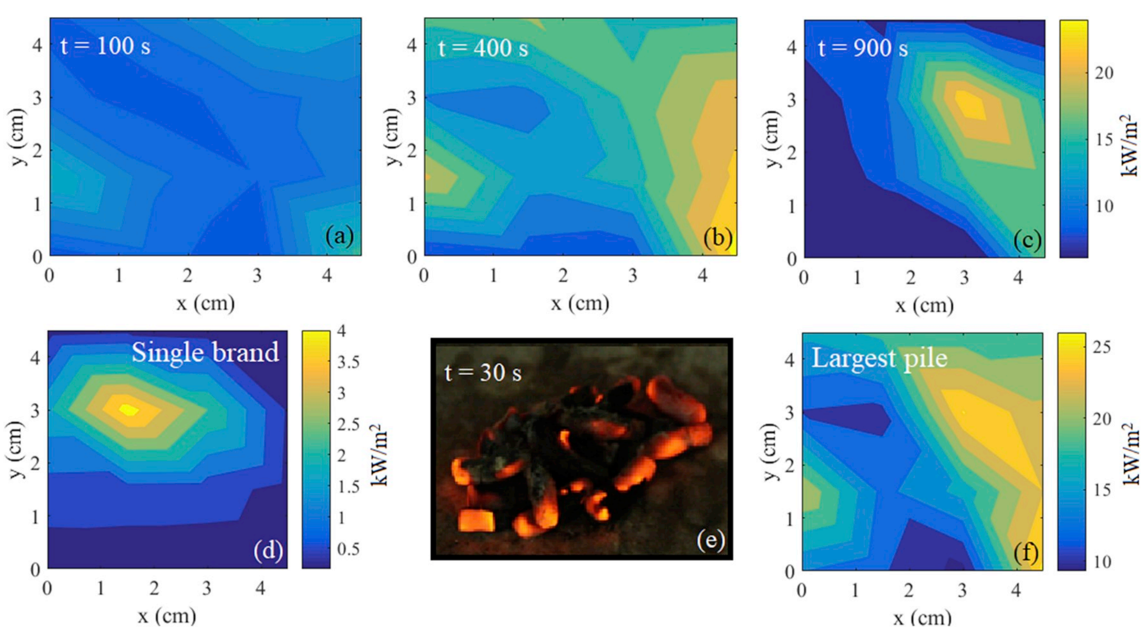

Fig. 3. Ambient tests. Top: Evolution of spatial distribution of heat flux, measured by the TSC array, for a single 9.6 g deposited mass pile of 12.7 mm diameter firebrands at 100 s, 400 s, and 900 s after firebrands are deposited. Bottom: Comparison of maximum heat flux maps for (left) a single firebrand, and (right) the largest pile size, 9.6 g deposited mass, both 12.7 mm diameter firebrands. Bottom middle image shows high variability in smoldering behavior within a pile.

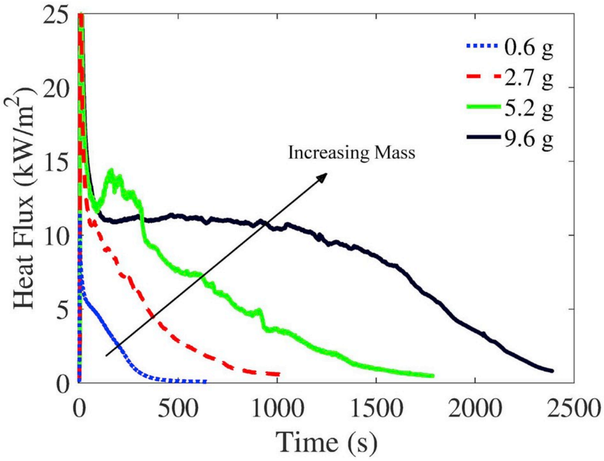

Fig. 4. Average heat flux of five replicates, measured by the WC-HFG, as a function of time for 12.7 mm diameter firebrands under ambient conditions shows increased long-time heat flux values and longer test duration as deposited pile mass increases. Standard deviations vary from 5 to 15 kW/m^2. The smallest mass shown, 0.6 g, is a single firebrand. The averages do not always end at 0 kW/m^2 as some tests lasted longer than others, even at the same diameter.

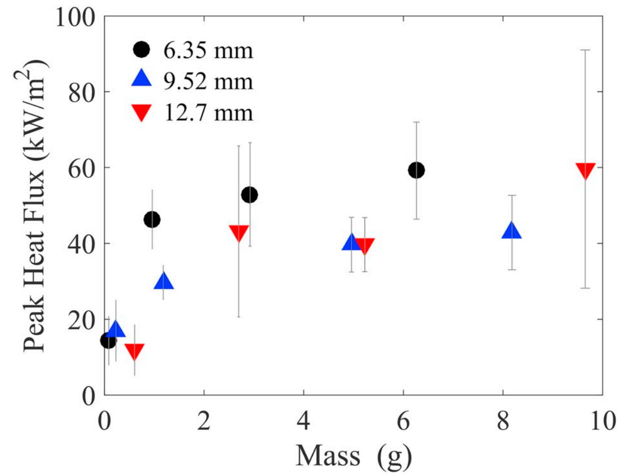

Fig. 5. Peak heat flux as a function of deposited pile mass under ambient conditions, measured by the WC-HFG. A single firebrand (lowest mass) peaks below 20 kW/m^2. As pile mass increases, the peak heat flux stays approximately steady, with only a slight increase, which is within the standard deviation of the tests. Each marker is an average of all five repetitions conducted for a specific test condition. Error bars are the standard deviation of the repetitions.

no differences in heating greater than the standard deviation of the test. It is expected that dependence on contact is important for individual firebrands, but re-radiation dominates the pile behavior, decreasing the dependence on contact area.

Deposited mass shows a better trend with heating than initial firebrand diameter. Larger masses of firebrands produced elevated heat fluxes for a longer period of time, as shown in Fig. 4. All firebrand diameters showed the same trend; the steady heat flux value after an initial peak increased with increasing pile size. The largest pile size, 9.6 g, had the longest semi-steady period of heat flux. The slight peak in heat flux in the 5.2 g pile is expected to be due to reheating or pile shifting behavior that occurred at the same time in multiple tests. Similar small spikes occurred in all tests, but often at different times, so that averaging smoothed out the overall heat flux curve.

Five test repetitions per mass were averaged to produce Fig. 4. The average standard deviations vary from 5 to 15 kW/m^2. These large uncertainties are anticipated to be due to variability in smoldering and reheating behavior and differences in when ash is blown away from piles, exposing glowing firebrand cores which will increase heat flux to the sensor. Although five repetitions are averaged here, uncertainties were similar when averaged over nineteen repetitions. The maximum standard deviation for nineteen repetitions was about 5.75 kW/m^2. The standard deviations for several arbitrary five tests out of the nineteen were within 2 kW/m^2 of the values for nineteen repetitions, indicating that the variability in the behavior is not due to errors in the experiment, but to uncertainties resulting from variations in wood and smoldering behavior.

Due to the high variability in heat flux curve shapes over time, a parameter to quantify and compare the overall heating between different tests would be useful. Initially, the peak heat flux was used to compare tests. Fig. 5 shows that the peak heat flux is higher for piles than for an individual firebrand; however, the peak heat flux steadies off with pile mass, only increasing slightly. The variation of the peak heat flux between different pile sizes is small and within the standard deviation for a given firebrand diameter. As the peak heat flux provides little comparison between different pile sizes, a net heating parameter was introduced. It was calculated as the area under the heat flux versus time curve and represents the total heat released by the firebrand pile to the heat flux gauge throughout the test. Fig. 6 shows that the net heat released does not appear to be dependent on initial firebrand diameter, but is related linearly to the deposited pile mass. The net heat released by the firebrand pile increases as the pile size increases, which is expected as a larger mass of firebrands has a larger potential chemical energy to release over time.

The number of firebrands in a pile has been suggested as a potential measure of pile size; however, plotting the net heat released as a function of the number of firebrands produces a different linear trend for each firebrand diameter, likely because vastly different numbers of firebrands are needed to produce piles of the same mass for different firebrand diameters, as shown in Table 2. Plotting peak heat flux as a function of number of firebrands shows that peak heat flux generally increases with number of firebrands; however, the trend is again different for different diameters, though the divergence is not as sharp as for the net heating parameter results. Deposited mass is recommended as a better metric, as it allows the diameters to collapse towards a single linear trend.

Although the net heating parameter provides some useful information, it is calculated over an entire test, which neglects that a critical condition (e.g. heat flux) is needed to ignite a material. Previous flaming and smoldering ignition experiments [11,13,43] have found that it is necessary to maintain a critical steady heat flux (or temperature) for a given time in order to produce ignition. The time to ignition is dependent on the heat flux, and time to ignition decreases as heat flux increases; however, below a critical heat flux, ignition will not occur. This time dependence is important but is not captured by either the peak heat flux or the net heating parameter. Additionally, Fig. 4 shows that heat fluxes are not steady throughout the test. Current ignition thresholds assume a steady heat flux to determine time to ignition.

5. Phase II results

A single relevant ignition condition is presented here to understand the parameters that affect ignition. Two experiments were conducted for Phase II; inert tests allowed for measurement of heat flux in wind, and tests on OSB allowed for a qualitative description of the ignition process. The ignition condition was chosen as one that repeatedly produced ignition of OSB, a common and well-studied material. Ignition tests were conducted under wind, because tests without external wind were unable to produce ignition of OSB. The goal of this work is not to fully characterize the effect of wind on firebrand ignition. By combining inert and ignition tests under the same conditions, we can

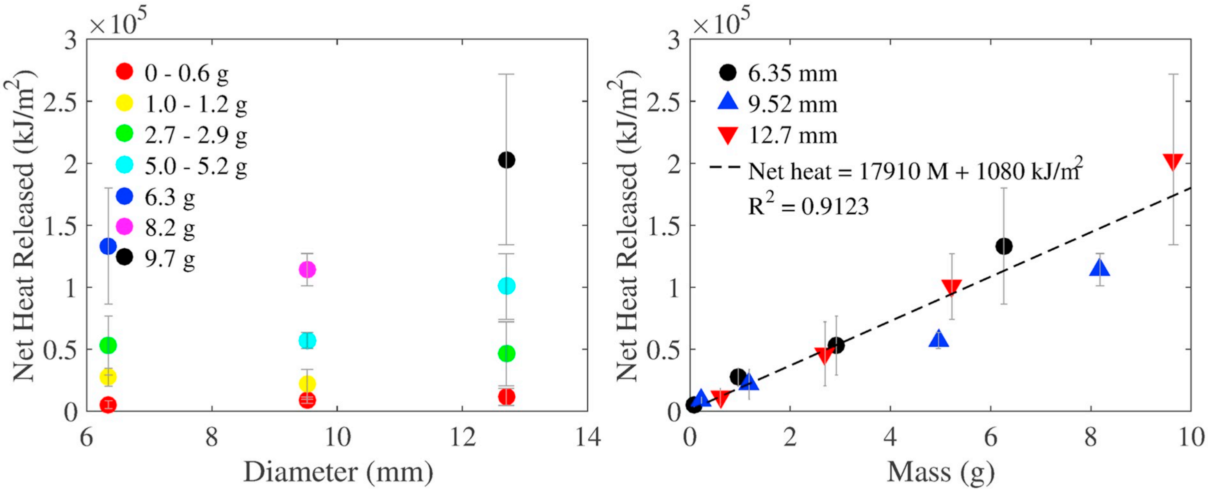

Fig. 6. Net heat imparted to the WC-HFG under ambient conditions as a function of (left) initial diameter, and (right) deposited pile mass. Net heat released is not a function of the firebrand diameter, but has an approximately linear relationship with deposited pile mass, as shown. Each marker is an average of all five repetitions conducted for a specific test condition. Error bars are the standard deviation of the repetitions.

create a picture of the process of ignition and the thermal conditions present at ignition.

5.1. Heat flux under wind

Tests using two pile masses, 5.2 g and 9.6 g of 12.7 mm initial diameter firebrands, and a wind speed of 1.84 m/s, a repeatable ignition condition determined from preliminary experiments, were conducted on an inert surface to measure related heat fluxes. Wind had a dramatic effect on heating. Fig. 7 shows the heat flux for two pile sizes under both wind and ambient conditions. Heat fluxes peaked higher and were sustained at higher values throughout the wind-driven tests, in comparison with the no-wind tests. Heat flux also dropped off more sharply with time under wind conditions, compared to ambient conditions.

5.2. Ignition description

Firebrands exposed to the wind flamed briefly when deposited on the OSB, but flaming quickly ceased and firebrands continued glowing. A visual sign of potential smoldering of the recipient fuel was a char

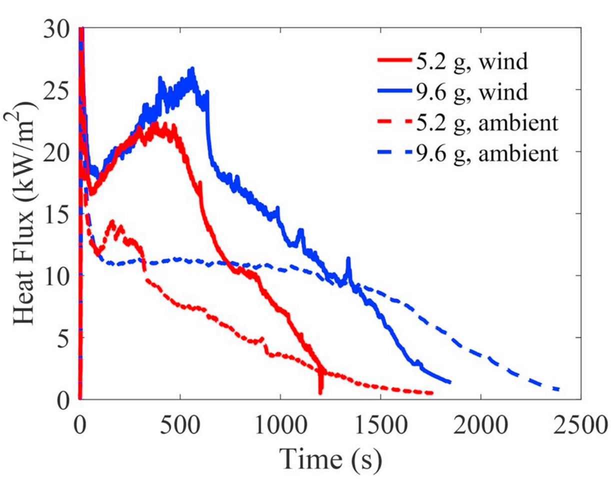

Fig. 7. Averaged heat flux, measured by the WC-HFG, as a function of time for 5.2 g and 9.6 g deposited mass of 12.7 mm diameter firebrands under wind, 1.84 m/s, and ambient conditions. Tests with wind produce higher heat fluxes than those without. Standard deviation on the 5.2 g wind is 6 kW/m^2 and on the 9.6 g wind tests is approximately 8 kW/m^2, peaking at 14 kW/m^2, with seven replicates per test.

front in areas not directly in contact with firebrands. Approximately 1.5 min into the test, a visible flame was anchored to the recipient fuel in front of the glowing core of the firebrand pile (see Fig. 8). Fig. 8 also shows an IR image of the same pile at the time immediately before the flame anchors to the fuel. This image shows the increased temperature away from the firebrand pile which indicates probable heating or smoldering of the recipient fuel. The IR camera results are used only qualitatively, as the emissivity of the firebrands is unknown and changes as the firebrands glow, smolder, and degrade.

As the test progressed, flaming continued from several locations on the surface of the fuel, on the wind side of the firebrand pile, for approximately 10 min. After about 15 min, the fuel ceased flaming and the firebrand pile was primarily ash. The fuel continued to smolder for nearly an hour with intermittent reheating. The times and behavior described above for a single representative test were the same in other test repetitions of the same condition.

6. Discussion

Point measurements using the WC-HFG provided what we expect is a good representation of the heat flux for large piles, while the TSC array showed the variation in heat flux spatially. There are limitations to both heat flux measurement methods. Although the WC-HFG is fairly accurate for large piles, it is expected to cool small piles and individual firebrands because the size of the gauge is on the order of the size of the firebrand. The TSC array primarily provided an understanding of qualitative trends, rather than quantitative heat flux values because of difficulties with the calibration resulting from the unknown and changing emissivity of the calorimeter surface. Overall, the TSC provides reasonable heat flux trends for ambient conditions, but has high errors for heat flux values when exposed to wind. Ultimately, an array combining a WC-HFG and TSCs may provide the best heating information to determine which parameters influence heating, by indicating quantitative heat flux values and spatial trends.

Knowing what variables influence heating is important when determining parameters to measure in order to estimate a firebrand “flux” representative of exposure in WUI fire conditions [44]. Previous studies have found that ignition by individual firebrands is dependent on firebrand size; however, these tests found that firebrand diameter has a limited effect on pile heating, as re-radiation rather than contact area dominates pile behavior. The deposited pile mass is a more important parameter that affects heat flux and net heat released. The peak heat flux results highlight the major differences between individual

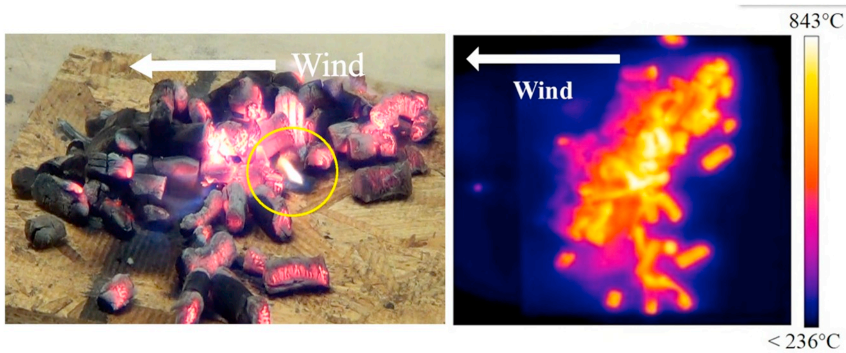

Fig. 8. Left: Recipient fuel ignition 1 min into wind test at 1.84 m/s for a 9.6 g deposited mass pile of 12.77 mm diameter firebrands. Right: Corresponding IR image of left hand pile at same instance. The temperatures shown for the IR image are qualitative, as the emissivity factor of the firebrands is assumed rather than measured.

firebrands and large piles. Piles provide a drastically different heat flux value, but the peak heat flux changes little as a function of pile size. As firebrands reliably deposit in piles during WUI fires, it is essential to conduct testing on piles in order to understand heating and ignition.

Three possible processes for ignition were initially hypothesized, based on [14,21,30]. First, glowing firebrands could transition to flaming and the heat of the flaming could cause pyrolysis of the recipient fuel. Then the flaming of the firebrands could cause piloted ignition of the gaseous fuel. Second, glowing firebrands could heat the recipient fuel and cause the fuel to begin smoldering and itself transition to flaming, possibly in front of the firebrand pile where more oxygen is available. Third, the firebrands could heat the recipient fuel and cause a transition to glowing ignition on the surface of the fuel. Based on visual and IR observations of the wind tests, it appears that a form of the second process is most likely. The first process does not fit the observed behavior, as sustained flaming of firebrands did not occur for tests without a recipient fuel, including those tests conducted under the same wind and pile configurations. Additionally, because the flaming of the firebrands was of short duration, these flames would be insufficient to raise the temperature of the fuel to a critical ignition temperature or to pyrolyze enough of the fuel to produce a critical mass flux of fuel vapors for ignition. The recipient fuel transitioned to flaming early in the test and the transition was preceded by a char layer spreading away from the firebrand pile. The early flaming and char layer indicate that direct surface ignition via glowing may not accurately represent the ignition process in this experimental scenario. It is important to note that the immediate deposition of the entire firebrand pile is unlikely to be found in a WUI fire. It is more likely that individual firebrands gradually deposit on a pile over time.

The heat flux results and ignition process described highlight that re-radiation and reheating within the firebrand pile play key roles, processes which are not present for a single firebrand. Understanding heating of solid fuels and the relationship between the occurrence of ignition and heating conditions preceding ignition could allow for the development of a model of the ignition process. Reheating may be important to consider in future ignition models, as it resulted in re-initiation of flaming during some ignition tests. The applied airflow is clearly important as it was required for ignition and produced higher heat fluxes, likely due to increased airflow which induces more oxidation.

7. Conclusions

In this study, a methodology for producing firebrand piles without wind and measuring resultant heat fluxes using both a WC-HFG and an array of TSCs has been developed. The WC-HFG provides reliable measurements in both ambient and wind conditions. The TSC provides reasonable heat flux measurements under ambient conditions, but can be better used for temperature under wind conditions. Heat flux results show high variation in spatial heating. The thermal characteristics of an ignition condition were described to connect heat fluxes with ignition.

Several trends were identified which can motivate decisions on variables to study in future work, both in the laboratory and in the field. Deposited pile mass was found to be the most important variable affecting heat flux and net heat imparted. The results from piled firebrands are also distinctly different than those from an individual firebrand, as the re-radiation within the pile appears to play an important role in heating. Under ambient conditions, firebrand diameter had a limited influence on the heat fluxes and net heat imparted to the sensor, even though firebrand size can be a critical ignition factor for a single firebrand. Ultimately, the firebrand diameter used for ignition experiments with firebrand piles becomes less important than the deposited pile mass.

Finally, this study confirmed the importance of wind for ignition, showing how wind dramatically affects the heat flux that a firebrand pile produces. Firebrands ignited the recipient fuel by causing smoldering ignition which transitioned to flaming. The ignition of a recipient fuel took place very early after firebrand piles were deposited. The early ignition results differ from investigative reports that find that firebrand piles may ignite WUI fuels long after the fire front has passed. Two differences in real WUI events may account for the seemingly long-time ignition reported during investigations. First, winds during WUI events are variable, rather than steady, changing the airflow provided to the firebrand pile. Second, a full firebrand pile is deposited at once during these experiments, while single firebrands may be added to growing piles during an actual WUI fire.

Acknowledgments

The authors would like to thank Evan Sluder, Alicea Fitzpatrick, Erin Griffith, and Seth Lattner for their assistance with laboratory experiments, and Jiann Yang, Nelson Bryner, and the NIST WUI group for advice and support. This research was funded by the United States Department of Commerce, National Institute of Standards and Technology Fire Research Grant Program under financial assistance awards 60NANB15D358, 70NANB16H284 and 70NANB17H288.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.firesaf.2018.10.002.

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