Fire Technology, 52, 1035–1050, 2016

Manufactured in The United States
DOI: 10.1007/s10694-015-0536-4

The Effect of Wind on Burning Rate of Wood Cribs

Sara McAllister and Mark Finney, USDA Forest Service, RMRS Missoula Fire Sciences Lab, 5775 W US Highway 10, Missoula, MT 59808, USA*

Received: 30 April 2015/**Accepted:** 15 September 2015

Abstract. Wood cribs are often used as ignition sources for room fire tests. A wood crib may also apply to studies of burning rate in wildland fires, because wildland fuel beds are porous and three dimensional. A unique aspect of wildland fires is the ubiquitous presence of wind. However, very little is known about what effect the increased ventilation has on the burning rate of cribs in either the densely- or loosely-packed regime. Experiments were performed with seven cribs designs with a range of porosities and two fuel element sizes: 0.64 cm and 1.27 cm. These cribs were burned in a wind tunnel with wind speeds ranging from 0 m/s to 0.7 m/s. Changes in the observed flame structure and burning patterns with wind are noted and discussed. The effect of wind on the burning rate was seen to depend on the fuel thickness. At the highest wind speed tested, cribs built with the 1.27 cm sticks showed a 6.5% to 61.5% increase in burning rate depending on porosity. Cribs built with the 0.64 cm sticks showed a decrease of 36.7% to 60.6% that was relatively constant with wind speed. Possible mechanisms of these changes are discussed. Future work will include further testing to clarify the causes of these trends.

Keywords: Burning rate, Cribs, Forced ventilation, Wildland fire

1. Introduction

While wood cribs are often used as repeatable heat release sources in fire testing, a fundamental understanding of the mechanisms that govern the burning rate may be applicable to other fuel beds, such as wildland fuels. As the wildland fire community has been primarily concerned about the rate of spread, the burning rate of wildland fuel beds has largely been ignored. As with structural fires, the burning and heat release rate of wildland fuels is an important parameter governing fire behavior and thus a thorough understanding is warranted. As wildland fires typically occur with strong winds, one particularly important aspect is the effect of forced ventilation.

For cribs under natural ventilation, Gross demonstrated that the burning rate of unconfined cribs occurs in two regimes: open or loosely-packed and closed or densely-packed [1]. In the loosely-packed regime, the burning rate is more closely approximated by the free burning rate of the individual sticks and is governed by heat and mass transfer processes near the surfaces. In this regime, the burning

* Correspondence should be addressed to: Sara McAllister, E-mail: smcallister@fs.fed.us

rate is more of a function of the stick dimensions, and is independent of the "porosity" of the crib [1–3]. For cribs in the densely-packed regime, the burning rate is limited by availability of oxidizer within the fuel bed [1–3]. Here, the burning rate increases with the inter-stick spacing or the "porosity" of the crib. Perhaps one of the most well-known methods of defining the porosity of a crib was proposed by Heskestad [3]. Heskestad combined the experimental results from Gross [1] and Block [2] with the theoretical findings of Block [2] to relate the burning rate, scaled by the surface area A_s and stick thickness b, to the porosity ϕ as follows [3]:

$$\frac{R}{A_s b^{-1/2}} = fn(\phi) = fn\left[\left(\frac{A_v}{A_s}\right)s^{1/2}b^{1/2}\right] \quad (1)$$

where R is the burning rate (g/s), b is the stick thickness (cm), A_s is the exposed surface area of the sticks (cm^2), ϕ is the porosity, A_v is the area of the vertical shafts in the crib (cm^2), and s is the spacing between sticks (cm). Though not explicitly given in [3], the functional form of the dependency of this "reduced burning rate" on the crib porosity is approximately

$$\frac{10^3 R}{A_s b^{-0.5}} = 1 - \exp\left[-50\left(\frac{A_v}{A_s}s^{1/2}b^{1/2}\right)\right] = 1 - \exp[-50\phi]. \quad (2)$$

Though not immediately obvious or intuitive, the "reduced burning rate" given by the left hand side of Eqs. 1 and 2 is the result of a Spaulding's B number analysis for an individual burning stick [2]. Such an analysis predicts that the burning rate per unit surface area is proportional to the inverse square root of the stick thickness [2], so that the "reduced burning rate" is equal to a constant value. This condition should be approximately met in the loosely-packed regime. In the densely-packed regime, ventilation is limited and the burning rate is reduced below this value and a function of the crib porosity. The functional form described in Eq. 2 thus describes how the "reduced burning rate" increases with porosity until reaching the constant value predicted for individual sticks.

During their investigations into mass fires and fire storms, Grumer and Strasser [4] performed experiments with both unordered and ordered (but not cribs) beds. Of importance here, one series of tests involved blasting the unordered beds of burning wood cubes (2 cm to 9 cm on edge) with air. Although blasting the air into the fire column (plume) didn't change the burning rate, blasting the air into the fuel bed itself increased the burning rate up to six times greater than the burning rate in still air, confirming the results of McCarter and Broido [5] that the plume above the bed does not contribute much to the heat transfer governing the burning rate.

In his work with compartment fires, Harmathy investigated the ventilation effect on both charring and non-charring materials [6]. He tested cribs made of a variety of materials including wood, PMMA, and other polymers. The thickness of the fuel elements ranged from 1.8 cm to 3.2 cm and the porosity, as defined by

Heskestad [3] and Eq. 1, of the cribs ranged from densely to loosely-packed (ϕ = 0.016 cm to 0.158 cm). In his tests, it was clear that forced ventilation only increased the burning rate of the charring materials. This increase in burning rate for the charring materials was seen regardless of the crib porosity—even the cribs that were normally not ventilation limited showed increased burning rate. Interestingly, the height of the crib was a factor and taller cribs showed more of an increase. As the forced ventilation increased beyond a certain point, however, the burning rates began to decrease, presumably due to either heat loss or Damköhler number effects.

Recently, the effect of ventilation on burning and heat release rates in tunnel fires has been investigated. Because experimental data is relatively limited and piece-meal, Carvel et al. [7] performed a Bayesian analysis that included both experimental data and expert option on the effect of forced ventilation on the burning rate of heavy goods vehicles in tunnels. Based on this analysis, they predicted that the maximum heat release rate with a 10 m/s flow could be up to ten times the value under natural ventilation conditions. Ingason and others have since performed scale model tests with cribs in tunnels with varying ventilation velocities [8–10]. By comparing the data of Harmathy [6] and Croce and Xin [11] to the correlation of Heskestad [3], Ingason and Lönnermark [9] emphasize that the effect of ventilation will be dependent on the porosity of the fuel bed. Densely-packed beds will be more sensitive to increases in ventilation than loosely-packed beds. In their tunnel tests in [8–10], they burned two crib designs—one with sticks 1.5 cm thick and crib porosity 0.21 cm (loosely packed regime), the other with sticks 1 cm thick and crib porosity 0.062 cm (transition regime). They saw the burning rate increase 1.3–1.5 times the burning rate in the naturally ventilated case depending on the crib porosity. This increase occurred quickly as the ventilation was added, and then leveled off for higher velocities. Because of the heat feedback from the tunnel, the burning rate of the naturally-ventilated case was 1.3–1.4 times the burning rate of the free-burning case. This produces a heat release rate increase of up to 1.5 to 2.2 times the free-burning heat release rate for the velocities tested.

In contrast to the work described above, the effect of wind on the burning rate of spreading fires appears less clear. Steward and Tennankore built fuel beds of vertical cylinders of birch wood and allowed the fire to spread with wind speeds from 0 m/s to nearly 2.8 m/s [12]. They devised an apparatus that allowed them to weigh a single fuel element during the course of the tests. Though they found that the burning time was strongly related to the fuel element diameter, no effect of wind was seen. In spreading fire tests in ponderosa pine needle beds, Beaufait [13] saw that the effect of wind depended on which direction the fire was spreading relative to the wind. For backing or opposed-flow spread, the flame residence time and burning rate was unaffected by the wind. For heading or concurrent flame spread, the residence time increased and the energy release *rate per area* (calculated with mass loss rate, flame zone depth, and heat of combustion) decreased as the wind speed was increased. For concurrent flame spread in cribs built with 0.64 cm sticks, however, Bryam et al. [14] found that the energy release *rate* (calculated using an unknown method) increased linearly with wind. An important distinction between the results of Beaufait [13] and Byram [14] that may explain the discrepancy is the difference in units—Beaufait normalized his energy release rate by the burning area, whereas Byram did not. In his model for the unit area burning rate of spreading fires, Nelson [15] only includes the "weak" effect of wind indirectly via the effective particle heat transfer coefficient and average reacting mixture temperature. However, there was considerable discrepancy between his model predictions and the experimental results using excelsior and pine needle beds.

Experimental exploration of the effect of forced ventilation on the burning rate of porous fuel beds is still relatively limited and not all parameters have been fully explored. The few studies that do exist have been conducted with relatively limited crib designs with thick fuel elements, and several in tunnels which changes the heat feedback mechanisms to the fuel bed. An experimental campaign is thus underway to fully elucidate the effect of forced ventilation on porous fuel beds for a variety of fuel bed designs and fuel element thickness.

2. Experiment Description

The wind tunnel used was large (3 m × 3 m) compared to the size of the cribs (see Table 1) so that the flames did not interact with the walls. Three load cells spaced equally apart were used to weigh the cribs during each test. As shown in Figure 1, a thin aluminum sheet was used as the support platform. To minimize heat transfer to the load cells, the sheet was fitted with three aluminum feet with hemispherical divots so that contact with the load cells was made with 1.3 cm ball bearings. Multiple sheets of ceramic paper insulation were placed on top of the support platform to further minimize heat transfer to the load cells. Previous work has shown that the burning rate can be very sensitive to available oxidizer from below, so the cribs were placed on 7.62 cm (3 in) metal spacers to provide ample air movement below the crib. All cribs were conditioned in an environmental chamber at 35°C and 3% relative humidity for at least 3 days, resulting in an equilibrium moisture content of approximately 1%.

Table 1
Crib Dimensions

Crib design #	Stick thickness (b) [cm]	Stick length (l) [cm]	l/b [ ]	Number of sticks per layer (n) [ ]	Number of layers (N) [ ]	Stick spacing (s) [cm]	Surface area (A_s) [cm^2]	Heskestad Porosity (φ) [cm]
1	1.27	12.7	10	2	25	10.16	3077.41	0.1205
2	1.27	12.7	10	7	10	0.64	3319.35	0.00393
3	1.27	20.32	16	6	14	2.54	7432.24	0.0390
4	1.27	25.4	20	4	21	6.77	10077.40	0.1202
5	0.64	25.4	40	10	10	2.12	5606.44	0.0725
6	0.64	25.4	40	14	15	1.27	11502.82	0.0213
7	0.64	60.96	96	20	9	2.54	25435.43	0.1163

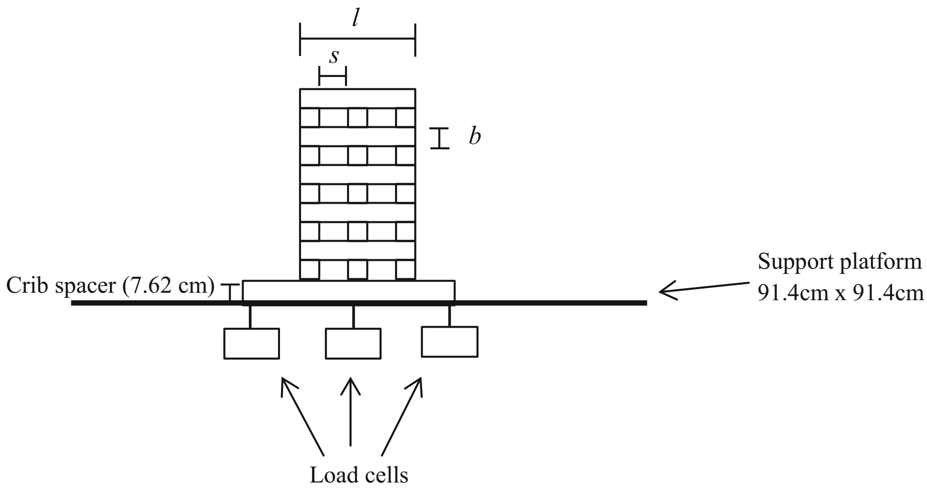

Figure 1. Sketch of apparatus for a crib with 3 sticks per layer (*n* = 3) and 10 layers (*N* = 10).

Simultaneous ignition of the cribs was achieved by quickly dunking the crib in isopropyl alcohol and allowing it to drain. The total mass of fuel used was 10% or less of the crib weight. The liquid fuel was observed to easily burn off before the steady state burning of the crib was achieved. Mass of the cribs was recorded at 10 Hz. A sample of the raw data is shown in Figure 2. Figure 3 shows the derivative of the mass data with time using a spline fit with ten degrees of freedom. Figures 2 and 3 both show three distinct phases of burning—burning off of the liquid fuel and stick ignition, steady burning, and burnout. The noise at the beginning of the test (Figure 2) is due to walking around the weighing platform to ignite the crib, while the noise at the end of the test is due to crib collapse. Only data from the steady burning portion of the curve was used to calculate the burning rate. The burning rate was found from the slope of the best-fit line through the data.

Wood cribs were built using square ponderosa pine sticks with thicknesses of 0.64 cm (1/4 in) and 1.27 cm (1/2 in). As detailed in Table 1, four crib designs with 1.27 cm sticks and three crib designs with 0.64 cm sticks were tested. The crib designs were chosen to span a range of porosities from the densely-packed regime to the loosely-packed regime. Additional consideration was given to the final weight of the crib. Heavier cribs were found to give cleaner data as they tended to not move in the wind as much as lighter cribs. Too large of cribs, however, would exceed the capacity of the load cells and generate large flames relative to the wind tunnel dimensions. As indicated in Table 1, the stick surface area (A_s) and ratio of stick length to thickness (or aspect ratio $-l/b$) were varied by about an order of magnitude. Four wind speeds were tested: 0 m/s, 0.24 m/s, 0.37 m/s, and 0.7 m/s. Each crib design and wind speed combination was tested three times and the results averaged.

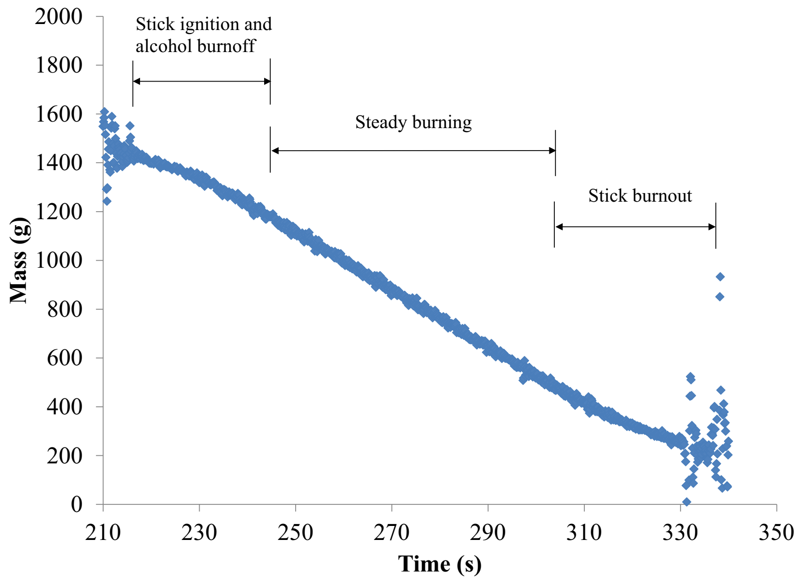

Figure 2. Sample raw data for crib design #4 with 0.24 m/s wind velocity.

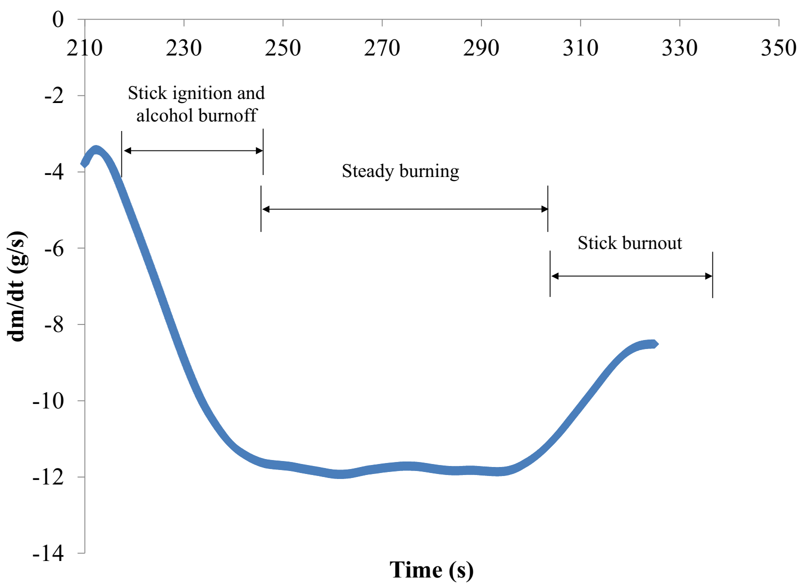

Figure 3. Sample plot of dm/dt for crib design #4 with 0.24 m/s wind velocity.

3. Results and Discussion

Before delving into a quantitative discussion of the results, it is worth noting some of the observations made during the experiments. For cribs burning in still air, sufficiently ventilated cribs typically burn uniformly with the entire crib engulfed in flames simultaneously. Densely-packed cribs and cribs with insufficient spacing underneath will usually burn symmetrically from the outside edges inward. Forced ventilation was seen to result in asymmetric burning. Either the windward or lee side of the crib would burn faster, depending on the crib design and wind speed. Table 2 includes a note regarding the side of faster burning for each crib layout and wind speed. In all cribs with wind, flames were seen to extend out of the bottom of the crib, hug the bottom surface, turn the corner, and continue to hug the lee side of the crib. All cribs were seen to generate a pair of horizontal roll vortices off the top lee corners as well. These flame patterns can be seen in Figures 4, 5, 6, 7, 8 and 9.

For cribs built with the thicker, 1.27 cm sticks, the flames remained largely upright and the cribs continued to burnout symmetrically at the lowest wind speed tested (0.24 m/s). As the wind speed increased, two of the four crib designs burned out faster on the side facing the wind. The tallest crib (crib design #1, Figure 4) was the only crib that burned out faster on the lee side, while crib design #4 never seemed to develop a side of preferential burning (Figure 6).

For cribs built with the 0.64 cm sticks, the flames noticeably tilted over at all wind speeds and all cribs burned out faster on the windward side. The cribs in the transition and loosely-packed regimes (crib designs #5 and #6) were seen to burn evenly and uniformly without wind. However, with wind they burned from the outside edges inward with the windward side being faster (Figures. 7, 8).

Table 2 lists the average burning rates, along with the standard deviations, for all crib designs and flow velocities tested. Figures 10 and 11 plot the reduced burning rate (Eq. 1) as a function of flow velocity with the error bars indicating one standard deviation of the data. As seen in Table 2, one standard deviation was typically less than 10% of the mean. Also shown in Figures 10 and 11 are the lines for the ideal burning rate for Douglas-fir wood as defined by Tewarson and Pion [16]. The ideal burning rate is defined as the burning rate where the additional heat flux (such as from nearby burning surfaces) is just balanced by the heat losses. Alternatively, the ideal burning rate is also related to the ratio of the absorbed flame heat flux to the heat of pyrolysis. For the 1.27 cm thick sticks, this ideal (reduced) burning rate is 1.47 g/scm$^{1.5}$, and is 1.04 g/scm$^{1.5}$ for the 0.64 cm thick sticks. As seen in Figure 10, crib design #4 actually approaches and slightly exceeds this ideal rate at the highest wind speed tested. For the cribs in the transition and loosely-packed regimes with 0.64 cm thick sticks, Figure 11 shows that the burning rate with no wind is actually quite close to this ideal condition, but dramatically decreases with wind. This suggests that either the additional heat flux is decreasing or the heat losses are increasing for the thin sticks, reducing the burning "efficiency."

To more clearly illustrate the effect of wind, Figures 12 and 13 show the percent change in the burning rate with wind compared to the no wind case. These fig-

Table 2
Crib Burning Results

Crib design #	Stick thickness (b) [cm]	l/b [ ]	Heskestad Porosity (φ) [cm]	Wind speed [m/s]	Side of fastest burning	Average burning rate (R) [g/s]	Ave $10^3R/(A_s b^{-0.5})$ [$g/scm^{1.5}$]	Standard deviation of R [% of mean]
1	1.27	10	0.1205	0	Even	2.9812	1.0917	6.01
				0.24	Fairly even	3.0725	1.1252	3.30
				0.37	Lee	3.2671	1.1964	2.24
				0.7	Lee	3.3780	1.2370	0.99
2	1.27	10	0.00393	0	Outside in	0.7077	0.2403	2.00
				0.24	Windward	0.8677	0.2946	1.67
				0.37	Windward	0.9879	0.3354	7.06
				0.7	Windward	1.1430	0.3880	5.51
3	1.27	16	0.0390	0	Outside in	6.1589	0.9339	4.57
				0.24	Fairly even	6.5971	1.0003	3.23
				0.37	Windward	6.2521	0.9480	1.96
				0.7	Windward	6.5564	0.9941	3.07
4	1.27	20	0.1202	0	Even	10.6917	1.1956	1.76
				0.24	Even	11.5653	1.2933	1.05
				0.37	Fairly even	12.4083	1.3876	0.68
				0.7	2 Lee, 1 Windward	13.2097	1.4772	5.57
5	0.64	40	0.0725	0	Even	6.9982	0.9604	8.73
				0.24	Windward[a]	4.4318	0.6082	8.76
				0.37	Windward[a]	4.1606	0.5710	2.80
				0.7	Windward[a]	4.2328	0.5809	4.15
6	0.64	40	0.0213	0	Outside in	7.3806	0.5113	13.40
				0.24	Windward	3.7529	0.2600	1.72
				0.37	Windward	3.8957	0.2699	9.19
				0.7	Windward	4.0930	0.2835	3.86
7	0.64	96	0.1163	0	Even	34.5367	1.0820	21.14
				0.7	Windward[a]	17.4363	0.5463	3.36

[a] Cribs were the center was very slow to burn with wind that would normally burn evenly without wind

Figure 4. Flame structure from crib design #1 with 0.7 m/s wind speed.

Figure 5. Flame structure from crib design #3 with 0.37 m/s (*left*) and 0.7 m/s (*right*) wind speed.

ures suggest that the effect of wind is dependent on the thickness of the fuel elements. In Figure 12, the cribs built with the thicker 1.27 cm sticks show an increase in the burning rate with wind, while in Figure 13, the cribs built with the thinner 0.64 cm sticks show a decrease. The burning rate increase for the thicker sticks is proportional to the wind speed, with values ranging from 6.5% to 61.5%

Figure 6. Flame structure from crib design #4 with 0.7 m/s wind speed.

Figure 7. Flame structure from crib design #5 with wind speed of 0.7 m/s.

Figure 8. Flame structure from crib design #6 with wind speed of 0.7 m/s.

Figure 9. Flame structure from crib design #7 with 0.7 m/s wind speed.

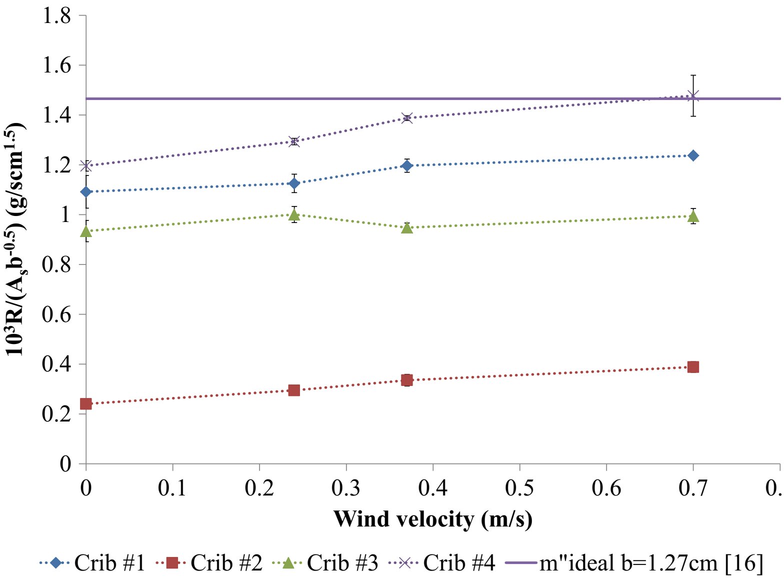

Figure 10. Reduced burning rate as a function of wind for stick thickness b = 1.27 cm. Error bars indicate one standard deviation.

at the highest wind speed tested. The burning rate decrease was relatively constant with wind speed, and ranged from 36.7% to 60.6%.

Harmathy argued that the burning rate of cellulosic and other charring materials is governed by the heat released from char oxidation [6]. This was demon-

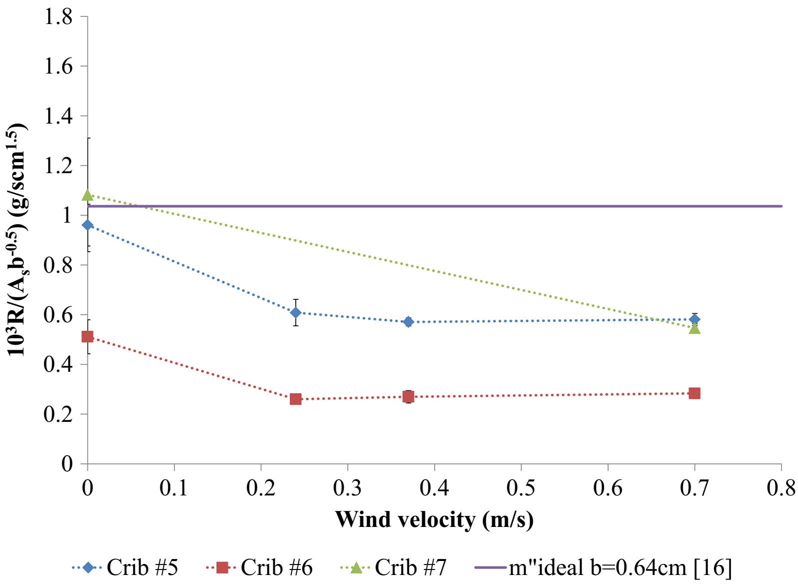

Figure 11. Reduced burning rate as a function of wind for stick thickness b = 0.64 cm. Error bars indicate one standard deviation.

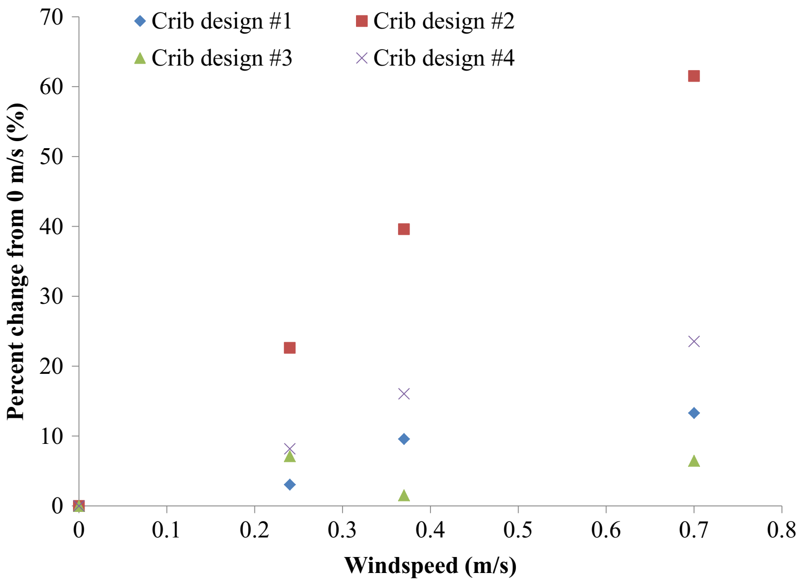

Figure 12. Change in burning rate with wind compare to no wind case for stick thickness b = 1.27 cm.

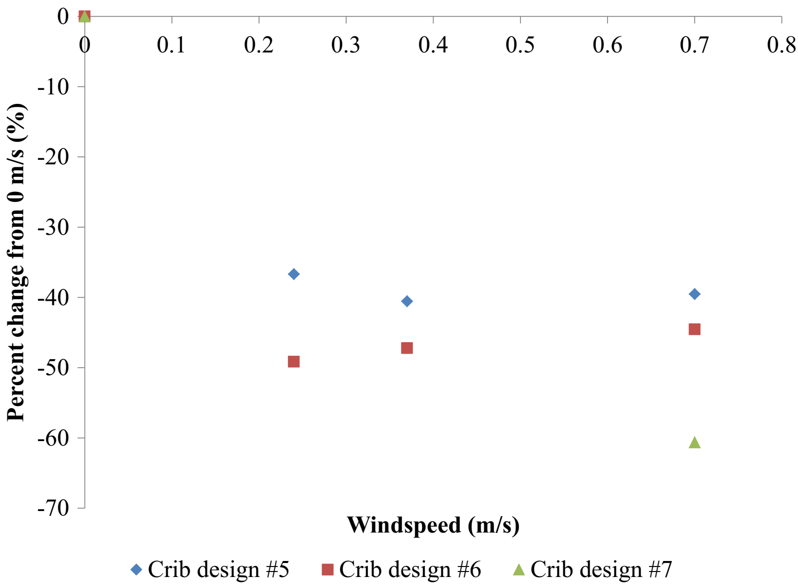

Figure 13. Change in burning rate with wind compare to no wind case for stick thickness b = 0.64 cm.

strated in his experiments with cribs built of charring and non-charring materials. Because forced ventilation provides more available oxygen to oxidize the char, the cribs in his experiments that were built with charring materials showed an increase in the burning rate with wind whereas the cribs built of non-charring materials didn't. This explanation matches the observation that the majority of cribs tend to burn out fastest on the windward side. As in the tests here with the thicker 1.27 cm sticks, the increase in Harmathy's experiments was also proportional to the flow rate. However, as Harmathy continued to increase the flow rate, the effect began to plateau. This was not seen in the current experiments, perhaps because not a high enough wind velocity was tested. Harmathy also noted a larger change in burning rate for taller cribs. This effect of height was not noted here but a different burnout pattern (lee side versus windward side) was noticed (Table 2). Instead, for the three cribs tested in the transition to loosely-packed regime (crib designs #1, #3, and #4), the increase in burning rate was more related to the surface area and stick spacing (blue diamonds in Figure 14). Larger stick spacing presumably allowed for more air penetration into the crib and more surface area meant more area for char oxidation. Interestingly, of these three crib designs, the largest change in burning rate was crib design #4 that was observed to never develop a preferential side of burning (Table 1).

As pointed out by Ingason and Lönnermark [9], cribs that are ventilation limited under normal conditions will logically benefit significantly from the increased available oxidizer that forced ventilation provides. For this reason, the densely-packed crib with 1.27 cm sticks had a significantly larger increase in burning rate

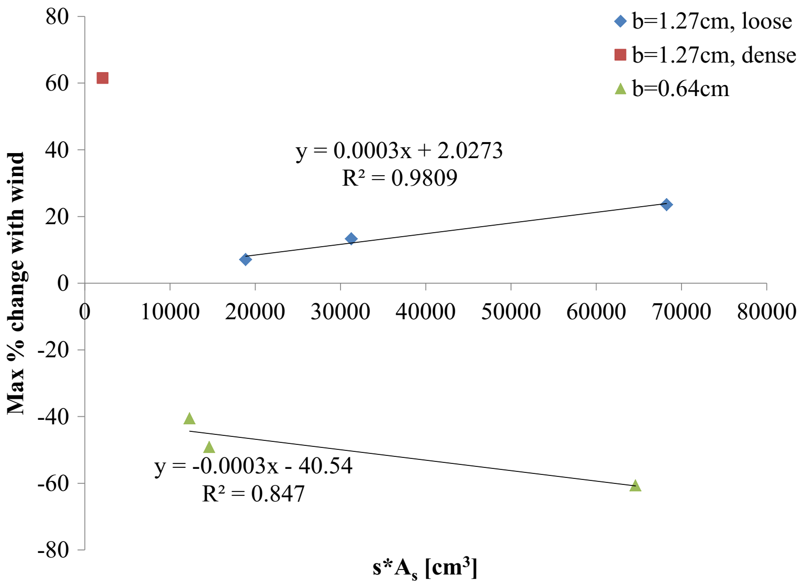

Figure 14. Maximum percent change with wind related to the stick spacing (*s*) and surface area (A_s).

(61.5%) compared to the cribs in the transition and loosely-packed regime (6.5–23.6%). In Figure 14, however, the maximum change in the burning rate for the densely-packed crib (red square, crib design #2), doesn't follow the same trend with stick spacing (s) and surface area (A_s) as the cribs in the loosely-packed regime (blue diamonds in Figure 14). The increase in the burning rate of these cribs with thicker sticks occurred despite the fact that the flame plume that would normally be directly above the crib was completely tilted over. By shielding their cribs from flame heat transfer with no subsequent change in the burning behavior, McCarter and Broido demonstrated that by far the majority of the heat transfer controlling the burning of cribs occurs within the fuel bed itself [5].

However, the burning rate of solid fuels is also controlled by heat losses [16]. As the sticks get thinner, convective cooling becomes more effective. For example, the convective heat transfer coefficient for a round cylinder of diameter 1.27 cm is 24.5 W/m^2K with a flow velocity of 0.7 m/s [17]. In that same wind, a round cylinder of diameter 0.64 cm will have a convective heat transfer coefficient of 34.8 W/m^2K. There is the small possibility as well that the smaller surfaces of the thin sticks aren't as efficient at emitting and absorbing radiant heat and that the heat transfer from the flame plume itself may play a more significant role in governing the burning rate. It is worth noting that the cribs tested by McCarter and Broido were built with the thicker 1.27 cm sticks [5]. This is merely speculation and further measuring the heat fluxes in a method similar to McCarter and Broido is required. However, there are several indicators that this may in fact be the case. If the reduction in burning rate were driven primarily by convective heat losses, one would expect the burning rate to continue to decrease as the wind speed increases. Here the decrease in burning rate seems relatively constant with wind speed. For the three cribs considered, the decrease is instead proportional to the stick spacing and surface area of the cribs (Figure 14), even for the densely-packed crib. Additionally, these cribs burned out faster on the windward side, where the cooling effect of the wind should be the greatest. The decrease in the burning rate may also be related to the some of the observations discussed earlier. With no wind, crib designs #5 and #7 would burn simultaneously. However, with wind, the center of these cribs didn't burn. This generally wasn't associated with white clouds of unburned fuel that would normally be seen if the crib was ventilation limited. The centers seemed to merely not receive enough heat to even char. The cribs tested with the thinner sticks tended to have the largest aspect ratios (l/b) which could be changing the flow regime of the air around and through the crib as well. Despite the uncertainty in the actual mechanism, it is clear that the balance between heat lost and heat gained is somehow reducing burning rate with the thin sticks.

4. Conclusions and Future Work

The burning rate of wood cribs is important not only for fire testing, but an understanding of the governing mechanisms may have applications to wildland fires. Because wildland fires typically do not occur without wind, the effect of wind on the burning rate is of concern. A variety of cribs were built and tested under a range of wind conditions. Adding forced ventilation not only produced some interesting flame structures, but changed the burning rate in rather unexpected ways. For cribs built with 1.27 cm thick sticks, the burning rate increased with wind, particularly for the densely-packed crib. However, for the cribs built with 0.64 cm sticks, the burning actually decreased with wind. This decrease was seen even for the densely-packed crib. Possible mechanisms for this decrease in burning rate include increased convective heat losses, a greater relative importance of heat transfer from the flames compared to within-bed radiation, and airflow changes around and through the cribs as the sticks get smaller and aspect ratio (l/b) larger.

Further testing of cribs with a wider range of designs and stick thicknesses is required to fully understand the trends seen here. In particular, cribs with 1.27 cm thick sticks but with aspect ratios (l/b) similar to those of the cribs with thin sticks should be tested ($l/b \geq 40$). Alternatively, cribs with 0.64 cm thick sticks should be considered with smaller aspect ratios ($l/b \leq 20$). This will help evaluate whether the airflow around and through the cribs is changing the burning behavior. Wildland fuels typically have a characteristic dimension of around 1 mm, so testing cribs with even thinner sticks will not only help clarify the trends but also help link these results back to wildland fuel beds. Measuring the heat fluxes from flame and within the bed to determine their relative importance as the stick thickness decreases is imperative. Placing thermocouples on and around selected fuel elements may also help give a clearer picture of the heat balance driving the burning behavior. Numerical modeling may also provide some insight into the mechanisms of both the increase and decrease of burning rate with wind.

Acknowledgments

The authors wish to thank Sophia Vernholm for her tireless and careful construction of the cribs and Cyle Wold for setting up the data acquisition system. Funding for this work was provided by the National Fire Decision Support Center.

References

1. Gross D (1962) Experiments on the burning of cross piles of wood. J Res Natl Bur Stand—C Eng Instrum. 66c(2):99–105
2. Block JA (1971) A theoretical and experimental study of nonpropagating free-burning fires. Symp Combust 13:971–978
3. Heskestad G (1973) Modeling of enclosure fires. Symp Combust 14:1021–1030
4. Grumer J, Strasser A (1965) Uncontrolled fire—specific burning rates and induced air velocities. Fire Technol 1(4):256–268. doi:10.1007/BF02588468
5. McCarter RJ, Broido A (1965) Radiative and convective energy from wood crib fires. Pyrodynamics 2:65–85
6. Harmathy TZ (1978) Experimental study on the effect of ventilation on the burning of piles of solid fuels. Combustion Flame 31(1):259–264
7. Carvel RO, Beard AN, Jowitt PW, Drysdale DD (2001) Variation in the heat release rate with forced longitudinal ventilation for vehicle fires in tunnels. Fire Saf J 36(6):569–596
8. Lönnermark A, Ingason H (2008) The effect of air velocity on heat release rate and fire development during fires in tunnels. Fire Safety Science 9:701–712
9. Ingason H, Lönnermark A (2010) Effects of longitudinal ventilation on fire growth and maximum heat release rate. In: Fourth international symposium on tunnel safety and security, Frankfurt, 17–19 March 2010
10. Ingason H, Li YZ (2010) Model scale tunnel fire tests with longitudinal ventilation. Fire Saf J 45:371–384
11. Croce PA, Xin Y (2005) Scale modeling of quasi-steady wood crib fires in enclosures. Fire Saf J 40:245–266
12. Steward FR, Tennankore KN (1981) The measurement of the burning rate of an individual dowel in a uniform fuel matrix. Symp (Int) Combust 18:641–646
13. Beaufait WR (1965) Characteristics of backfires and headfires in a pine needle fuel bed. U.S. Forest Service Research Note INT-39, Intermountain Forest and Range Experiment Station, Ogden, Utah
14. Byram GM, Clements HB, Elliott ER, George PM (1964) An experimental study of model fires. Technical Report No. 3 Forest Service, USDA Southeastern Forest Experiment Station
15. Nelson RM (2003) Reaction times and burning rates for wind tunnel headfires. Int J Wildland Fire 12:195–211
16. Tewarson A, Pion RF (1976) Flammability of plastics—I. Burning intensity. Combust Flame 26:85–103
17. Churchill SW, Bernstein M (1977) A correlating equation for forced convection from gases and liquids to a circular cylinder in crossflow. J Heat Transfer 99:300–306