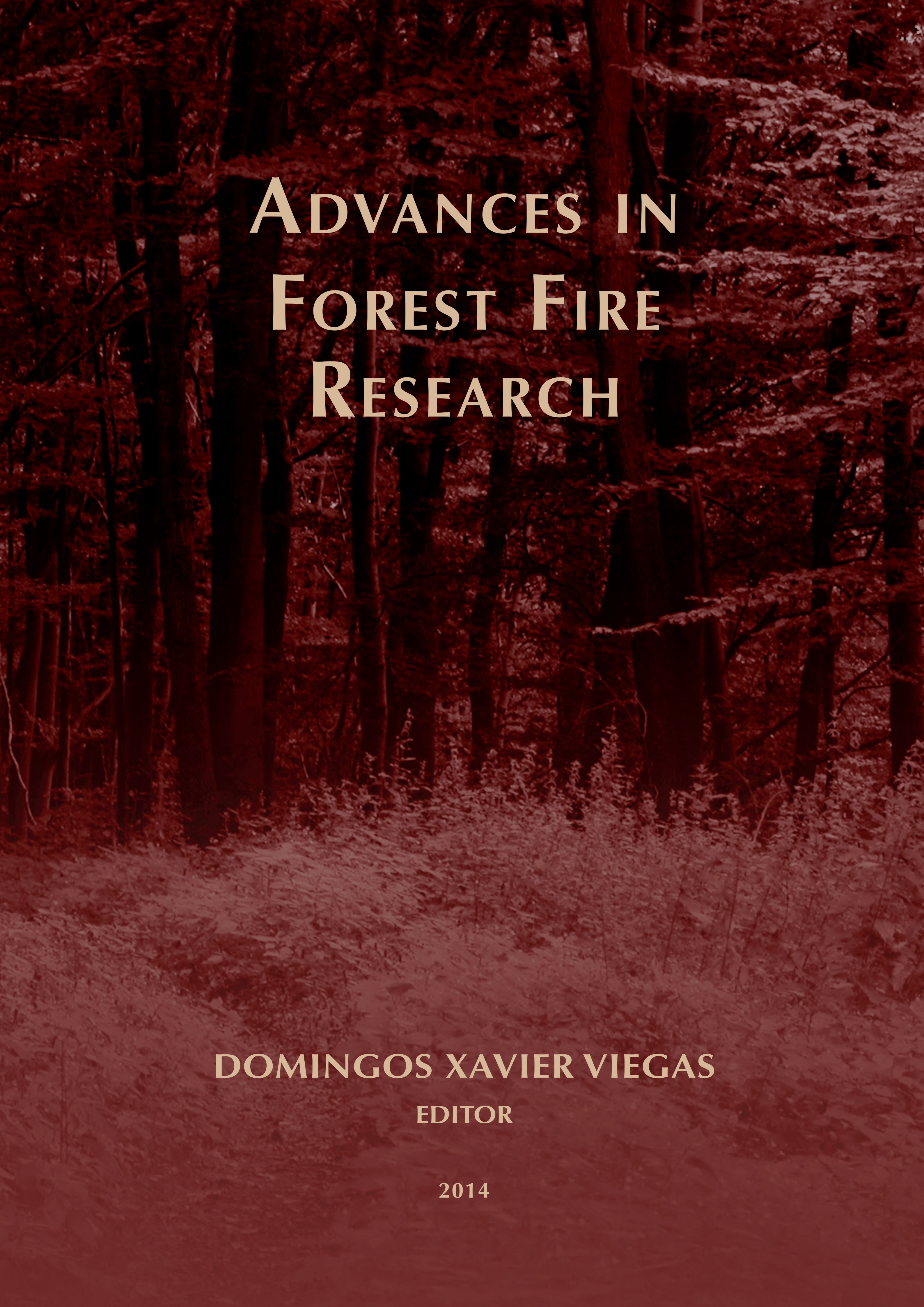

Advances in Forest Fire Research

DOMINGOS XAVIER VIEGAS

EDITOR

2014

Effect of layout and below-bed ventilation on burning rate of porous fuel beds

Sara McAllister[a], Mark Finney[b]

[a]*USDA Forest Service, RMRS Missoula Fire Science Laboratory, 5775 W US Highway 10, Missoula, MT 59808, USA, smcallister@fs.fed.us*
[b]*USDA Forest Service, RMRS Missoula Fire Science Laboratory, 5775 W US Highway 10, Missoula, MT 59808, USA, mfinney@fs.fed.us*

Abstract
Wood cribs are often used as ignition sources for room fire tests. A fundamental understanding of the mechanisms that govern the burning rate of a wood crib may also have applications to wildland fires. The burning rate of unconfined cribs has long been identified to occur in two regimes: the densely-packed regime where the burning rate is proportional to the crib porosity and the loosely-packed regime where the burning rate is independent of porosity. Though the cribs used to define these burning regimes were primarily cubic in dimension, there are seemingly endless possible ways to build a crib with a given porosity. This work explores the burning rate of cribs with a wide variety of geometries in the loosely-packed regime to determine whether the porosity-burning rate relation in the literature holds. The porosity was kept approximately constant while the number of sticks per layer, number of layers and the length to thickness ratios (l/b) were varied. For l/b less than 36, the burning rate of all cribs matched the porosity-burning rate relation from the literature. For larger l/b, the burning rate was considerably reduced, implying that the crib porosity is a function of l/b above some critical threshold. A second set of experiments was performed to examine the effect of the spacing distance between the crib and the support platform. The critical spacing distance was shown to be larger than previously thought and a function of the length to thickness ratio. It was quite apparent that as the l/b ratio increases, a significant portion of the required oxidizer comes from the bottom of the crib, even for supposedly loosely-packed cribs. For the cribs with l/b = 48, a larger crib-platform spacing the increased the burning rate of these cribs so that the burning rate was closer to the cribs with smaller l/b. For cribs with l/b = 96, the burning rate was still well below the predicted value, even for large crib-platform spacing. Future work will focus on exploring the burning rate and the effect of the crib-platform spacing for cribs with large l/b.

Keywords*: burning rate, cribs, porosity, residence time*

1. Introduction

Wood cribs are often used as ignition sources in room fire tests (for example in UL 1715 and ISO 9705 test standards) and for various other tests requiring repeatable heat release rates, such as fire extinguisher performance (ANSI/UL 711). To vary the burning rate of the source fire, cribs can be built with different stick thicknesses and arrangements. Thus predicting the burning behavior of a crib a priori can be particularly useful when designing a new testing procedure. The prediction of the burning rate of a crib may also have applications outside of fire testing. The burning rate of wildland fuels, both in the litter layer on the forest floor and the trees and shrubs themselves is not well understood. Even though wildland fuels do not have the same predictable arrangement as wood cribs, it is possible that a fundamental understanding of what governs the burning rate of a crib will apply to the wildland fire context (Fons *et al*. 1963, Byram *et al*. 1964, and Anderson 1990). All wildland fuels are essentially individual fuel particles with some spacing distance between them. For the needle litter layer, this spacing is small and relatively homogeneous. For trees and shrubs, this spacing will be greater with more variability due to the needles and leaves occurring only along branches. Once the burning rate of wildland fuels is better understood, other aspects of wildland fire behaviour will become more clear. For example, if the fuel loading and the burning rate of the fuel structure are known, the fireline intensity and flame zone depth can be estimated. These two parameters characterize the fluid dynamics and radiative and convective heat transfer that spread the fire. Thus the fire spread rate can be better predicted with a better understanding of the burning rate. One important complexity of wildland fires that is often overlooked is that most wildland fuels are not homogeneously distributed. Wildland fuels often occur in clumps, such as clumps of native grasses, shrubs, or trees. The residence time of the fire at a particular fuel clump can be determined from the burning rate of that fuel structure. This residence time is itself an important consideration for fire spread – if the residence time for a fuel structure is less than the ignition time for the next structure, the fire won't spread. This is of particular concern when discussing the thresholds for crown fire spread, a currently poorly understood aspect of wildland fire. And finally, this residence time is also important for fire ecologists when evaluating fire effects. An important key to predicting tree mortality is knowing the duration of heating. It is for these reasons that a closer look into the driving mechanisms of crib burning rates is currently being undertaken.

The burning rate of unconfined cribs has long been identified to occur in two regimes: open or loosely-packed and closed or densely-packed. 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 rate is more of a function of the stick dimensions, and is independent of the "porosity" of the crib. For cribs in the densely-packed regime, the burning rate is limited by availability of oxidizer within the fuel bed. In this regime, the burning rate increases with the inter-stick spacing or the "porosity" of the crib. There are many ways to evaluate the porosity of a crib (see for example Gross (1962), Block (1971), Heskestad (1973), and Anderson (1990)), but perhaps the most commonly used is that of Heskestad (1973). By recorrelating the data of both Gross (1962) and Block (1971), Heskestad suggested that the burning rate is a function of the crib porosity given by

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

where R is the burning rate (g/s), A_s is the exposed surface area of the sticks (cm^2), b is the stick thickness (cm), A_v is the area of the vertical shafts in the crib (cm^2), and s is the spacing between sticks (cm). This relation predicts the burning rates of the cribs burned in both Gross (1962) and Block (1971) well (±20%).

There are two important aspects that required close consideration when applying knowledge gained from crib theory to the wildland fire context. One is the effect of the crib size and layout. By necessity, wildland fuels will be represented by cribs with a wide range of external dimensions and stick spacing distances. The effect of the ratio of the stick length to the stick thickness will be important when considering different fuel types like needle litter versus slash fuels because this will change the fuel thickness (b) and flame zone depth (l). Another important aspect to consider is the effect of the spacing between the crib and the support platform. Ground fuels, like the needle litter layer, have no way of supplying oxidizer through the bottom surface. These fuels would thus be more like cribs placed directly on the support platform. On the other hand, crown fuels, like trees and shrubs, have ample oxidizer supply from the bottom. These fuels would be more like cribs with a large spacing distance between the crib and the support platform.

Unfortunately, the crib geometries tested by both Gross and Block that were used to generate the relation in Eq. 1 were fairly limited. Gross primarily tested cubic cribs, with ten layers with stick lengths equal to ten times the thickness. Block extended the length to thickness ratio of his cribs to 20. In the wildland context, the fuels clearly are not arranged in such cubic or nearly cubic designs. As one can imagine by looking at Eq. 1, there are seemingly endless possible ways to build a crib with a given porosity. Only a few others have considered a wider range of crib geometries and layouts. Byram

et al. (1964) tested the effect of crib footprint area by keeping the stick spacing (*s*) and crib height constant and increasing the length of the sticks. However, this was an early publication and no attempt was made to correlate the data. O'Dogherty and Young (1964) tested a wide range of crib designs, but were unsuccessful in using applying the Heskestad correlation to their data. Smith and Thomas (1970) and Thomas (1973) had more success in correlating the O'Dogherty and Young data with different relations that included the height of the crib. However, Thomas (1973) excluded cribs with "a large ratio of horizontal to vertical dimensions." In Smith and Thomas (1970), they included the results of Byram *et al*. (1964), but these data were poorly correlated. Clearly, the effect of crib geometry and layout is not well understood.
The only work in the literature found that considered the effect of the distance between the crib and the support platform is that of Block (1970). In this work, Block tested five crib designs with crib-platform spacing distance ranging from 0.159 cm (1/16") to 2.54 cm (1"). The burning rate of all cribs was seen to increase by about 15% as the spacing distance increased from 0.159 cm (1/16") to 1.27 cm (½"). For spacing distances larger than 1.27 cm (½"), no further change in the burning rate was seen. However, only five crib designs were tested and all cribs had a fixed stick length to thickness ratio (*l/b*) of 10, so it is difficult to say that these results are universal to all crib designs.
This work explores the burning rate of cribs with a wide variety of layouts and geometries to determine whether the correlation of Heskestad holds. The effect of the spacing distance between the crib and the support platform is also considered for a selection of crib designs.

2. Experiment description

The experimental chamber used was very large (12.4m x 12.4m x 19.6m) so that the airflow to the cribs was not restricted. Three load cells spaced equally apart were used to weigh the cribs during each test. As shown in Figure 1, two thin aluminum discs, separated by pins to reduce heat transfer to the load cells, were used as a support platform for the cribs. Multiple sheets of ceramic paper insulation were placed on top of the support platform to further minimize heat transfer to the load cells. A thermocouple was located near the load cells to assure that the temperature remained fairly constant. All cribs were conditioned in an environmental chamber at 35°C and 3% relative humidity for at least three days, resulting in an equilibrium moisture content of approximately 1%.
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. Both mass and temperature were logged at 2 Hz. A sample of the raw data is shown in Figure 2, where four distinct phases of burning can be seen – burning off of the liquid fuel, stick ignition, steady burning, and burnout. 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.

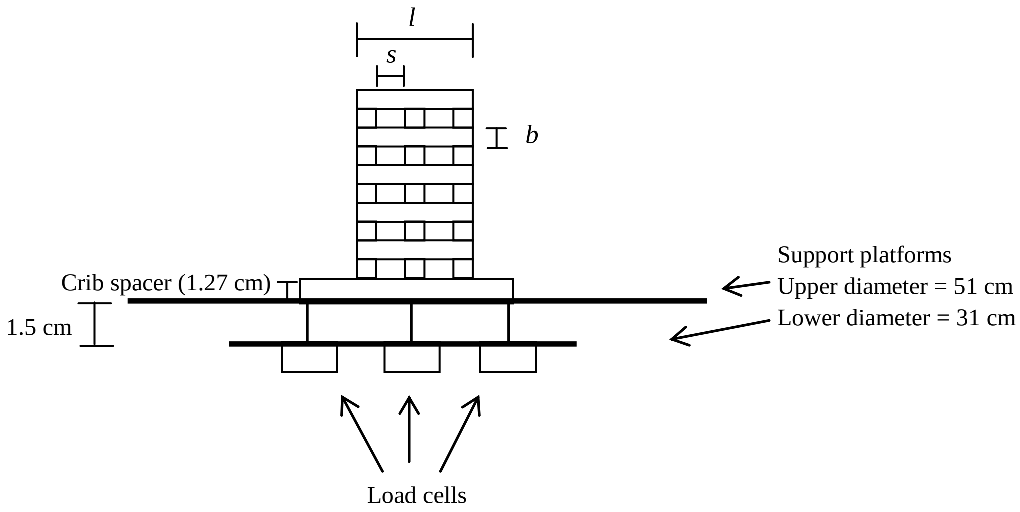

Figure 1. Sketch of apparatus for a crib with 3 sticks per layer (n = 3) and 10 layers (N = 10).

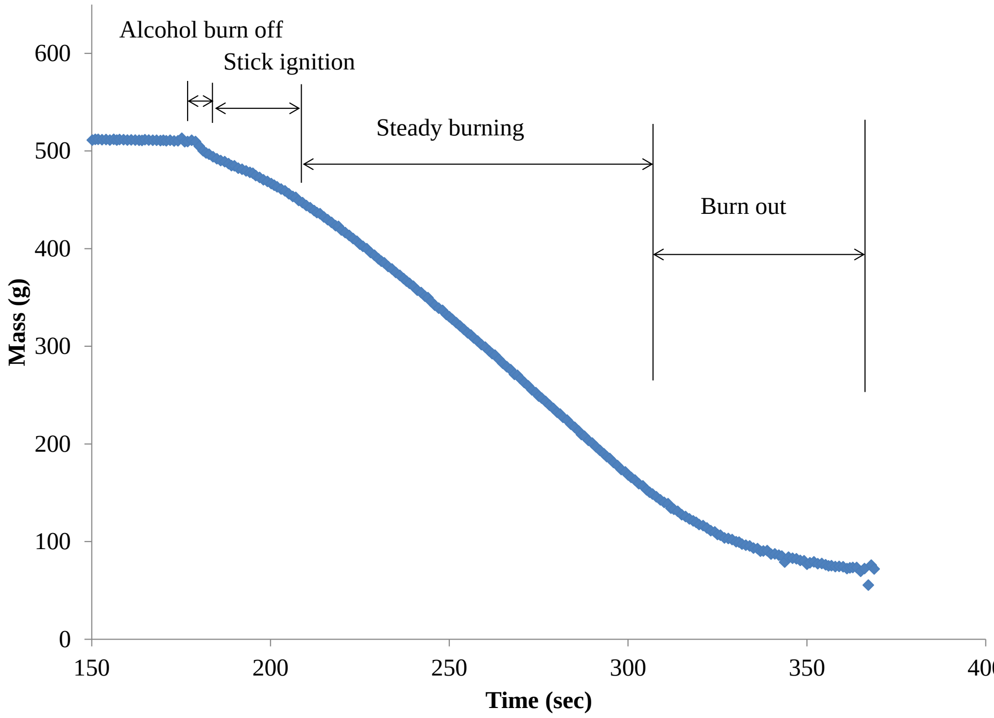

Figure 2. Sample raw data for 1.27-12-3-14 crib.

Wood cribs were built using square ponderosa pine sticks with thicknesses ranging from 0.159 cm (1/16 in) to 1.27 cm (0.5 in). In the first series of tests, a wide variety of crib designs were explored. Table 1 shows the details of all cribs burned. Each crib layout was tested three times and the results averaged. The first phase of experiments was performed to validate the testing apparatus against the known data of Gross (1962). In the second phase of experiments, the effect of crib layout in the loosely-packed regime was explored. The loosely-packed regime was chosen because it was indicated by Fons *et al*. (1963) that all wildland fuels would burn in this regime. For these experiments, the porosity factor of Heskestad (1973) (Eq. 1) was kept approximately constant while the number of sticks per layer, number of layers and the length to thickness ratios (*l*/*b*) were varied. The stick surface area was varied over an order or magnitude and (*l*/*b*) nearly an order of magnitude to really test the range of validity of the Heskestad correlation. As indicated in Table 1, the number of layers must decrease to keep the porosity constant as more sticks per layer are added. For this set of experiments, the cribs were placed on two steel spacers of 1.27 cm (0.5 in) as this was the critical spacing distance indicated by Block (1970).

A second series of experiments was performed with a subset of the cribs to explore the effect of the spacing distance between the crib and the support platform. Spacing distances of 0 cm, 0.64 cm, 1.27 cm, 2.54 cm, and 7.62 cm were tested. The list of crib designs tested is listed in Table 2. Again, the cribs used here had an approximately constant porosity in the loosely-packed regime while a range of length to thickness ratios (*l/b*) was tested. Each crib layout was tested three times and the results averaged.

Table 1. Crib dimensions for tests with variable crib geometry and layout.

Shorthand (b-l/b-n-N)	Stick thickness (b) [cm]	Stick length (l) [cm]	l/b [ ]	Number of sticks per layer (n) [ ]	Number of layers (N) [ ]	Surface area (A_s) [cm^2]	Porosity (φ) [cm]
0.64-10-3-10	0.64	6.35	10	3	10	442.74	0.0530
0.64-10-5-10	0.64	6.35	10	5	10	665.32	0.0108
0.64-10-7-10	0.64	6.35	10	7	10	829.84	0.00196
1.27-10-3-10	1.27	12.7	10	3	10	1770.96	0.1060
1.27-10-5-10	1.27	12.7	10	5	10	2661.29	0.0215
1.27-10-7-10	1.27	12.7	10	7	10	3319.35	0.00393
0.64-10-2-12	0.64	6.35	10	2	12	370.97	0.1249
1.27-12-3-14	1.27	15.24	12	3	14	3009.67	0.117
0.64-16-2-30	0.64	10.16	16	2	30	1503.22	0.1249
0.64-16-3-12	0.64	10.16	16	3	12	878.22	0.126
0.64-16-4-6	0.64	10.16	16	4	6	574.19	0.1284
0.64-16-5-4	0.64	10.16	16	5	4	471.77	0.1089
0.64-16-6-2	0.64	10.16	16	6	2	290.32	0.1247
0.64-24-3-27	0.64	15.24	24	3	27	3012.09	0.1215
0.64-24-4-14	0.64	15.24	24	4	14	2045.16	0.129
0.64-24-5-9	0.64	15.24	24	5	9	1616.93	0.1246
0.64-24-6-6	0.64	15.24	24	6	6	1277.42	0.123
0.64-36-8-8	0.64	22.86	36	8	8	3406.45	0.118
0.64-48-12-6	0.64	30.48	48	12	6	5051.60	0.119
0.32-48-6-12	0.32	15.24	48	6	12	1328.22	0.123
0.16-96-9-10	0.16	15.24	96	9	10	838.76	0.119

Table 2. Crib dimensions for crib-platform spacing tests.

Shorthand (b-l/b-n-N)	Stick thickness (b) [cm]	Stick length (l) [cm]	l/b [ ]	Number of sticks per layer (n) [ ]	Number of layers (N) [ ]	Porosity (φ) [cm]
1.27-12-3-14	1.27	15.24	12	3	14	0.117
0.64-24-4-14	0.64	15.24	24	4	14	0.129
0.64-48-12-6	0.64	30.48	48	12	6	0.119
0.32-48-6-12	0.32	15.24	48	6	12	0.123
0.16-96-9-10	0.16	15.24	96	9	10	0.119

3. Results and discussion

3.1. Effect of crib geometry and layout

The burning rates of all cribs are listed in Table 3. As mentioned above, three replicates of each crib fire were performed. The average and standard deviation from these replicates are also shown in Table 3. The standard deviation ranged from less than 1% to about 10% of the mean value. The average burning rate for each crib layout is plotted in Figure 3 using the form of Eq. 1. The black line in Figure 3 is the correlation from Heskestad (1973).

Table 3. Burning rate results for cribs with variable geometry and layout.

Shorthand (b-l/b-n-N)	Porosity (φ) [cm]	Burning rate Test 1 [g/s]	Burning rate Test 2 [g/s]	Burning rate Test 3 [g/s]	Mean burning rate [g/s]	Standard deviation [% of mean]
0.64-10-3-10	0.0530	0.4942	0.5510	0.5295	0.5249	5.46
0.64-10-5-10	0.0108	0.3419	0.3517	0.3772	0.3569	5.11
0.64-10-7-10	0.00196	0.1529	0.1516	0.1547	0.1531	1.02
1.27-10-3-10	0.1060	1.7031	1.7632	1.7559	1.7407	1.88
1.27-10-5-10	0.0215	1.9573	1.9474	1.8551	1.9199	2.94
1.27-10-7-10	0.00393	0.7157	0.6913	0.7160	0.7077	2.00
0.64-10-2-12	0.1249	0.5134	0.4991	0.5329	0.4984	8.80
1.27-12-3-14	0.117	3.2160	3.2113	2.8836	3.1036	6.14
0.64-16-2-30	0.1249	2.1110	2.0994	2.2587	2.1564	4.12
0.64-16-3-12	0.126	1.2030	1.1141	1.1540	1.1570	3.85
0.64-16-4-6	0.1284	0.7467	0.7531	0.7396	0.7465	0.90
0.64-16-5-4	0.1089	0.5926	0.5926	0.6198	0.6017	2.61
0.64-16-6-2	0.1247	0.3279	0.3492	0.3655	0.3475	5.43
0.64-24-3-27	0.1215	3.8678	4.3306	4.5316	4.2433	8.02
0.64-24-4-14	0.129	2.8798	2.7776	2.9521	2.8698	3.06
0.64-24-5-9	0.1246	2.1622	2.1000	2.2254	2.1625	2.90
0.64-24-6-6	0.123	1.7096	1.5446	1.7386	1.6643	6.29
0.64-36-8-8	0.118	3.8453	4.3561	4.4014	4.2010	7.35
0.64-48-12-6	0.119	5.6133	5.2003	6.1719	5.6618	8.61
0.32-48-6-12	0.123	1.8529	2.0239	1.6543	1.8437	10.03
0.16-96-9-10	0.119	1.1968	1.2156	1.2585	1.2236	2.58

As mentioned above, the first portion of the experiments were replicates of the experiments of Gross (1962) to validate the experimental procedure. The data from these experiments are marked in Figure 3 as solid diamond-shaped points. Heskestad's correlation fit the data of Gross (1962) and Block (1971) to within ±20% (Heskestad 1973), and the data here comfortably falls in that range. Some variation from the data of Gross is expected due to the differences in wood and moisture content of the cribs, in addition to the difference in spacing between the crib and the support platform. Gross used primarily Douglas-fir wood with average moisture content of approximately 9%, compared to the nearly dry ponderosa pine wood used here. Additionally, it appears that the separation distance used by Gross was equal to the fuel thickness (either 0.64 or 1.27 cm). A constant separation distance of 1.27 cm was used here. As mentioned above, Block noted that the burning rate changes up to 15% as the separation increase from none to a very large distance. These factors help explain the average difference 14% that was observed between the experiments here and those of Gross (1962).

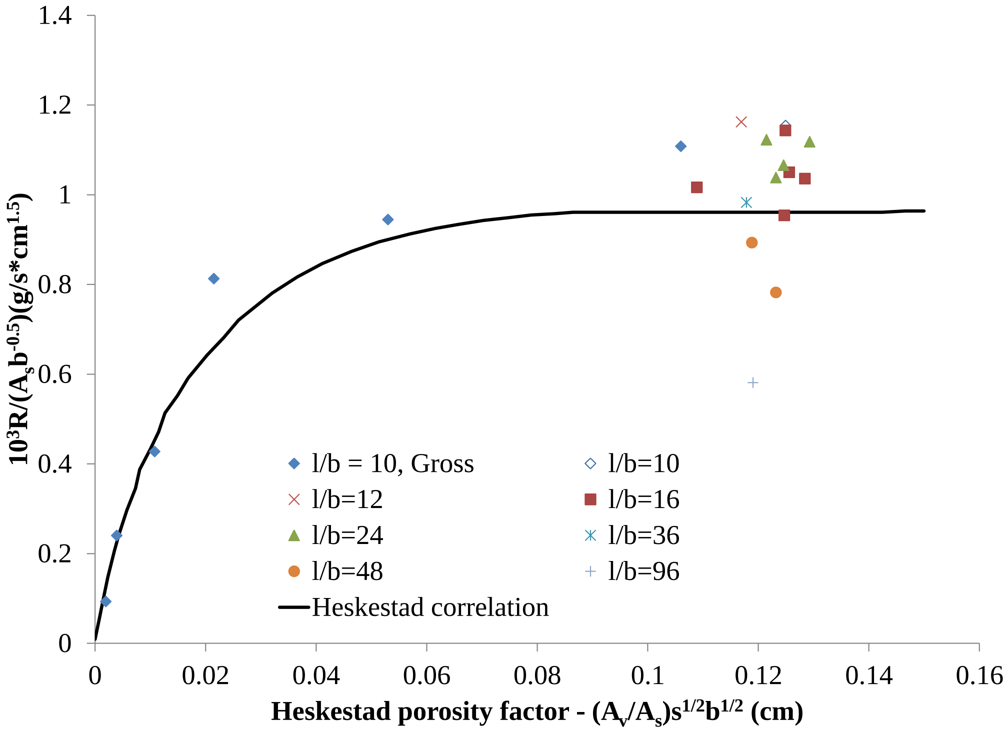

Figure 3. Burning rate results.

Because the layout of the cribs from the second set of experiments varied so widely, the burning rate results in Figure 3 were grouped by their length to thickness ratio (*l*/*b*) which ranged from 10 to 96. As listed in Table 1, a fairly wide variety of crib layouts for *l*/*b* ranging from 10 to 24 were tested. The burning rates from these cribs are shown in Figure 3 as diamonds for *l*/*b* =10, x's for *l*/*b* = 12, squares for *l*/*b* = 16, and triangles for *l*/*b* = 24. Interestingly, it appears that the burning rate of cribs within this range of *l*/*b* can be reasonably predicted with the Heskestad correlation, regardless of the crib layout. However, even though the porosity of all the cribs tested was approximately constant (and within the loosely-packed regime), the burning rate appears to decrease as the length to thickness ratio (*l*/*b*) further increases. For *l*/*b* less than or equal to 36, the burning rate is consistently above the Heskestad correlation. For *l*/*b* equal to 48, the burning rate falls below the Heskestad correlation by 7-19%, which is still in the noted range of variability of the correlation. However, for *l*/*b* equal to 96, the burning rate falls 40% below that of the correlation. Interestingly, this decrease in burning rate also corresponded to a visual change in burning regime. As this *l*/*b* ratio increased to 36 and above, it was observed that the cribs no longer burned simultaneously, but rather burned as propagating region from the outside edges inward as shown in Figure 4. A similar behaviour was noted when burning the densely-packed cribs in the first portion of the experiments. In other words, these loosely-packed cribs behaved like densely-packed cribs of a much lower porosity and the availability of oxidizer is controlling the burning rate as the *l*/*b* ratio increases. Thus, it appears that the crib porosity is also a function of the length to thickness ratio above some critical value of *l*/*b*.

Fig 4. Crib with l/b = 48 burning from the outside edges inward.

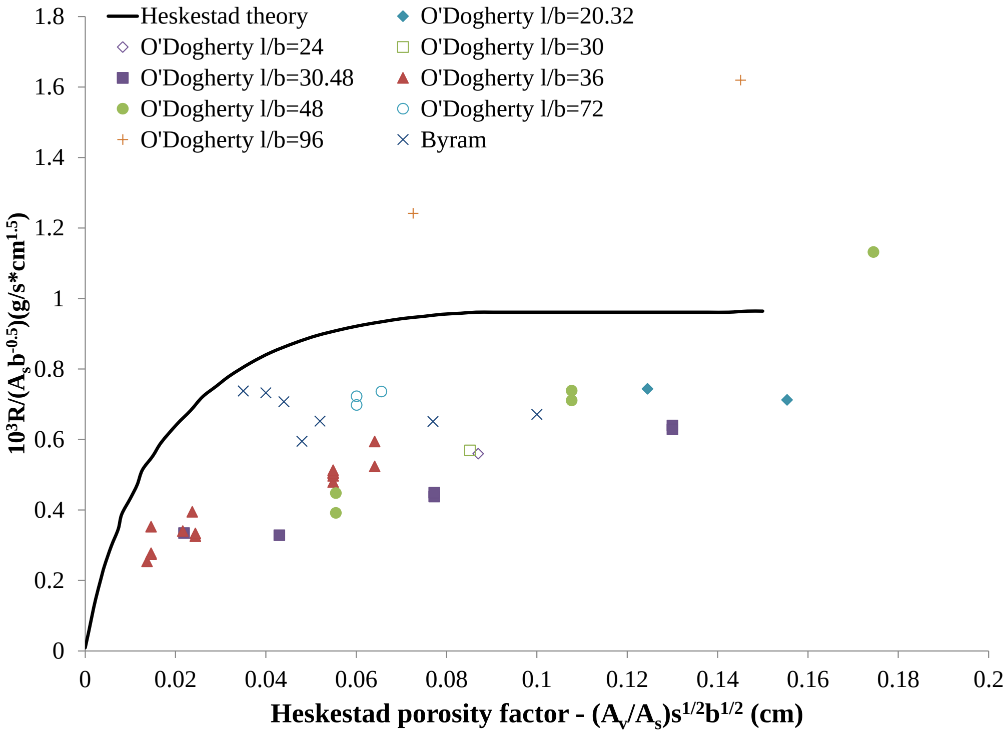

Figure 5. Burning rate data from O'Dogherty and Young (1964) and Byram et al. (1964).

To help clarify whether the porosity is a function of the length to thickness ratio, the results from O'Dogherty and Young (1964) and Byram *et al*. (1964) are considered. These are the only studies found in the literature that consider cribs with *l/b* greater than 40. Figure 5 shows the data of both O'Dogherty and Young (1964) and Byram *et al*. (1964) along with the Heskestad correlation. O'Dogherty and Young used white pine of 12% moisture content with *l/b* from 20.2 to 96. As mentioned earlier, their data was poorly predicted by the Heskestad correlation and the data is considerably scattered. The burning rate for cribs with (*l/b*) = 96 is significantly larger than the others and there is no clear trend in their data with (*l/b*). Byram *et al*. tested cribs of white fir with 10% moisture content. No spacing between the crib and support platform appears to have been used. In this study the stick spacing (*s*) and crib height were kept constant as the length of the sticks was increased. Consequently, the porosity of these cribs increased from a densely-packed crib to a loosely-packed crib as *l*/*b* increased from 9.1 to 61.4. As shown in Figure 5, when considered in the form of Heskestad and Eq. 1, the transformed burning rate was relatively constant for all cribs considered. The densely-packed crib results with lower *l*/*b* ratios are reasonably close to the Heskestad correlation. However, as the *l*/*b* ratio increases above 25 (porosity of 0.048 cm) and the beds become more porous, the burning rates fall considerably below the Heskestad correlation. Interestingly, neither work mentions the spacing distance used between the crib and the support platform. The majority of the data from both studies falls below the Heskestad correlation suggesting that no spacing between the cribs and the platforms was used. Thus it is clear that a more thorough sampling of the burning rates from cribs with *l*/*b* greater than approximately 30 is needed to clarify whether a critical *l*/*b* ratio exists.

Though the studies of O'Dogherty and Young and Byram *et al*. don't help to clarify whether the porosity is a function of the length to thickness ratio, the low burning rates suggest that the spacing between the crib and the support platform could have a greater effect that that listed by Block (1971).

4. Effect of spacing distance between the crib and support platform

The results of the tests with variable spacing distance between the crib and the support platform are shown in Table 4 and Figure 6. As shown, the burning rate of cribs with *l*/*b* equal to 12 is virtually insensitive to the spacing between the crib and the support platform. In fact, a slight decrease in the burning rate was seen for the largest spacing distance tested (7.62 cm), possibly due to increased convective or radiative heat losses. As the ratio of *l*/*b* increases, however, the effect of that spacing drastically increases. In fact, at *l*/*b* equal to 96, the difference is over 60%. As in the experiments above, this decrease in burning rate is seen visually as well. As shown in Figure 7, cribs with a *l/b* ratio equal to or greater than 48 burn as a propagating region from the outside edges inward when the spacing between the crib and the support platform is small (0 to 1.27 cm). As the crib-platform spacing distance increases, the cribs begin to burn simultaneously, in a similar fashion to the cribs with *l/b* less than 48. It is quite apparent that as the *l*/*b* ratio increases, a significant portion of the required oxidizer comes from the bottom of the crib, even for supposedly loosely-packed cribs.

Table 4. Burning rate results for crib-platform spacing tests.

Shorthand (b-l/b-n-N)	l/b [ ]	Porosity (φ) [cm]	Mean R (g/s) 0 cm	Mean R (g/s) 0.64 cm	Mean R (g/s) 1.27 cm	Mean R (g/s) 2.54 cm	Mean R (g/s) 7.62 cm
1.27-12-3-14	12	0.117	3.1546	3.1582	3.1036	3.2086	2.9653
0.64-24-4-14	24	0.129	2.2923	2.7081	2.8698	2.8966	2.769
0.64-48-12-6	48	0.119	-	5.0705	5.6618	7.164	7.777
0.32-48-6-12	48	0.123	1.0354	1.5545	1.8437	1.9799	2.3513
0.16-96-9-10	96	0.119	0.4555	0.8644	1.2236	1.3297	1.3425

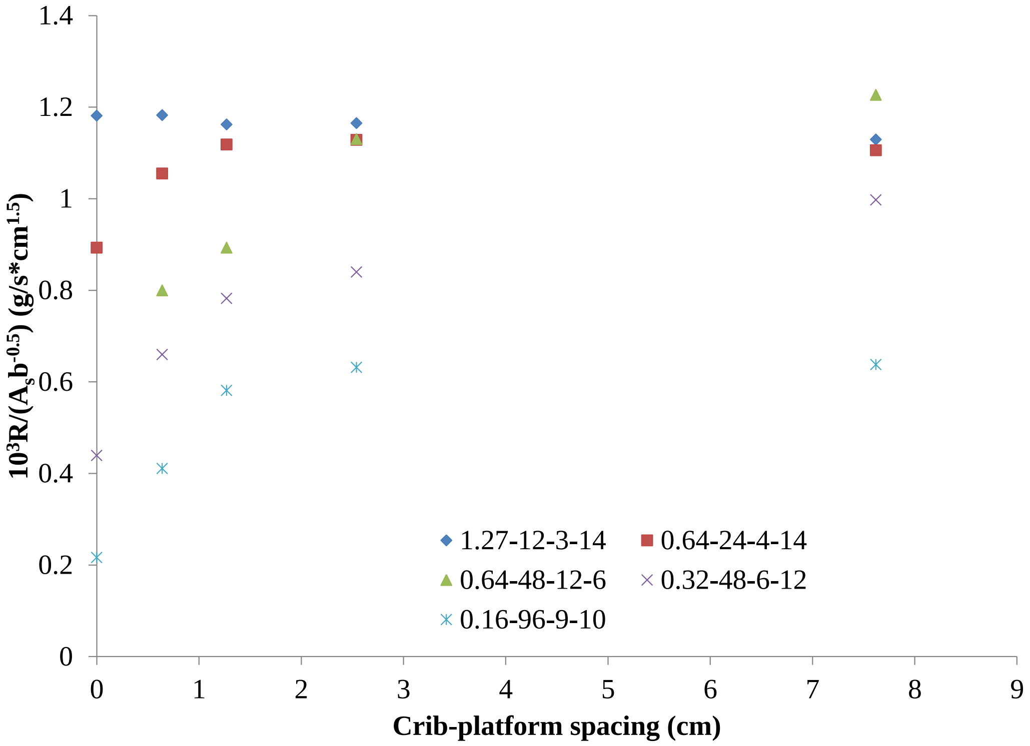

Figure 6. Effect of crib-platform spacing.

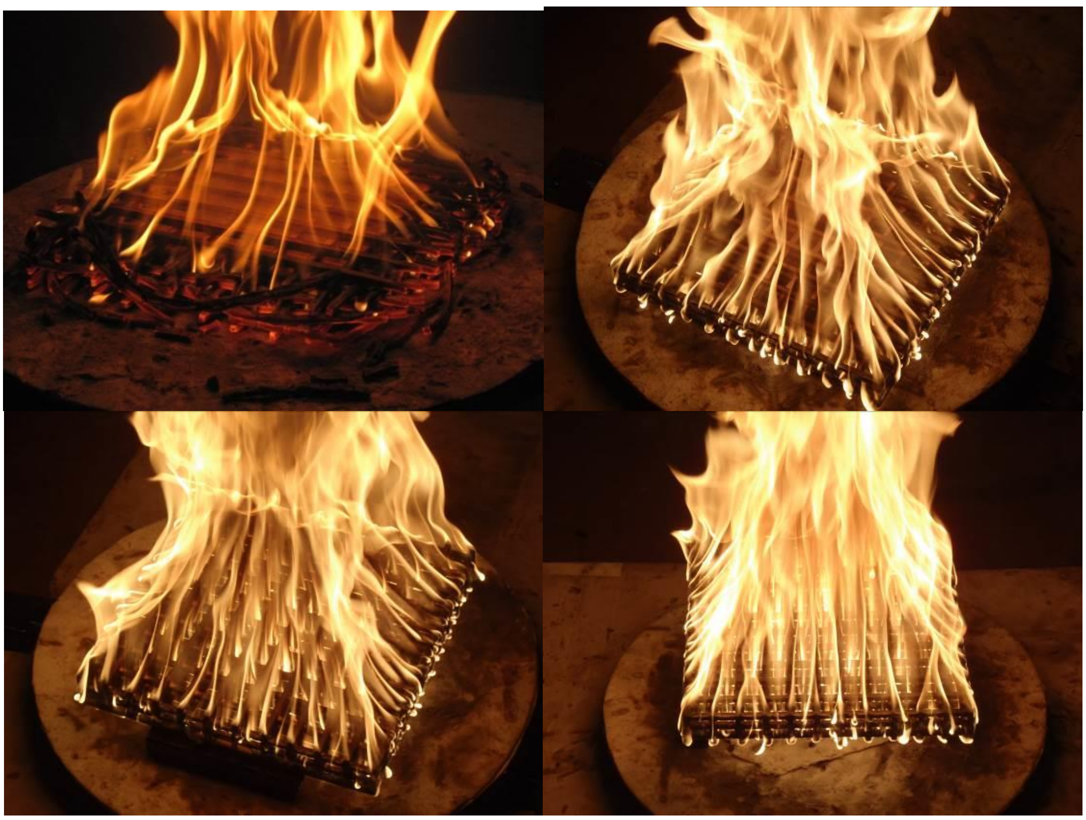

Figure 7. Visual change in burning regime for various crib-platform spacings for the 0.64-48-12-6 crib design. Top left: 0 cm spacing; Top right: 1.27 cm spacing; Bottom left: 2.54 cm spacing; Bottom right: 7.62 cm spacing.

Block (1971) noted a critical spacing of about 1.27 cm beyond which the burning rate of his cribs with *l/b* equal to ten did not change. By looking at Figure 6, this critical spacing distance seems reasonable for cribs up to *l/b* up to 24. For larger length to thickness ratios, however, the critical spacing distance is larger. For the cribs tested here with *l/b* of 48, the critical spacing distance appears to be over 2.5 cm. For these cribs, the burning rate increased by 7% for the 0.64-48-12-6 cribs and 15% for the 0.32-48-6-12 cribs as the spacing increases from 2.54 cm to 7.62 cm. Further tests are required at even larger spacing distances to identify the actual critical spacing distance, but it is clear that the change in burning rate is beginning to level off a value much larger than that identified by Block. Interestingly, the change in burning rate for the crib tested with a length to thickness ratio of 96 seems to level off earlier than the cribs with *l/b* of 48. In fact, the critical spacing distance seems to be around 2.54 cm. Because only one crib design with l/b of 96 was tested, it is difficult to know whether the reduction in the critical spacing distance as *l/b* goes from 48 to 96 is real or some artefact of the crib design, in particular the stick thickness. Either way, the critical spacing distance between the crib and the support platform is clearly a function of the length to thickness ratio and can be quite a bit larger than previously thought.

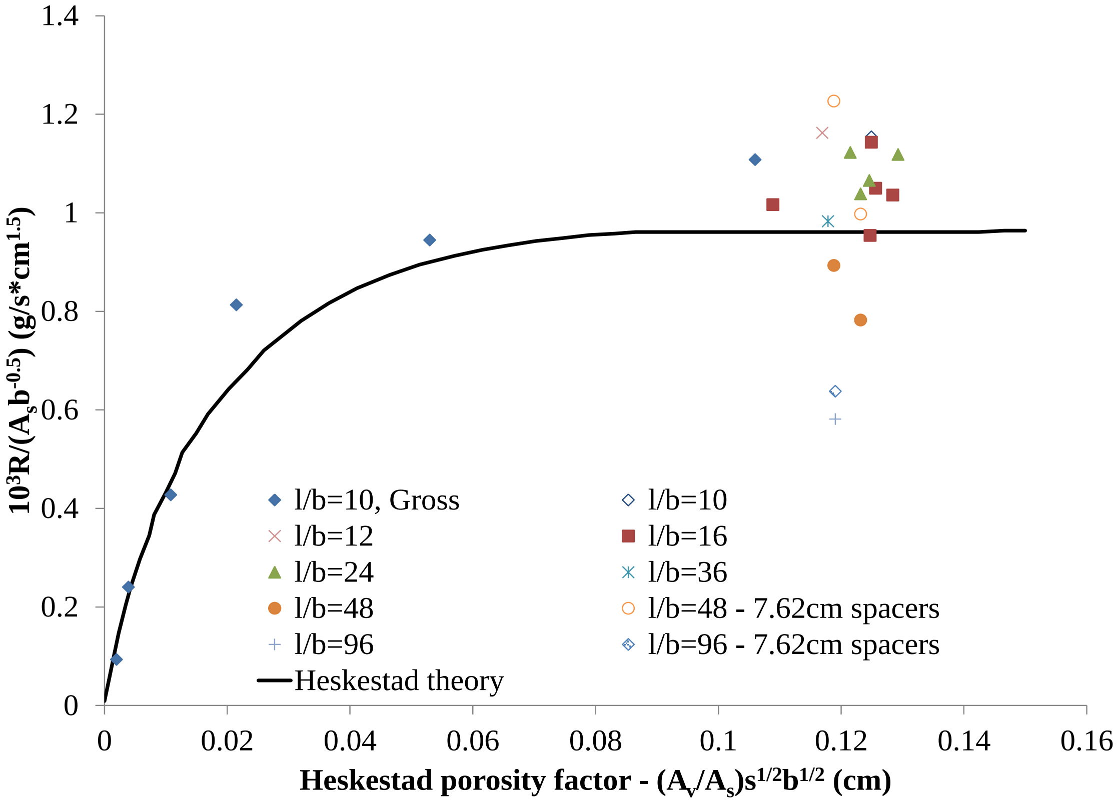

Figure 8. Burning rate including effect of crib-platform spacing.

Because such a large change in the burning rate for cribs with a large *l/b* ratio was seen with the increase in the crib-platform spacing, the Heskestad correlation was reconsidered to determine if the burning rate of these cribs would more closely match the correlation with a larger crib-platform spacing. Figure 8 shows the transformed burning rate as a function of the porosity with both the data from Figure 3 with a crib-platform spacing of 1.27 cm along with the data for cribs with *l/b* of 48 and 96 taken with a crib-platform spacing of 7.64 cm. As shown, the burning rates for the cribs with *l/b* of 48 and crib-platform spacing of 7.64 cm have indeed increased such that they are within the range of burning rate values measured for cribs with smaller *l/b*. However, the critical crib-platform spacing for crib design tested with *l/b* of 96 was much closer to the spacing used in the original series of tests, so the burning rate for this crib design did not increase much and remains significantly below the Heskestad correlation. It is unknown whether this low burning rate is a real effect of the crib design, due possibly to the extremely thin sticks, or is the result of some effect of the experiment design. Because the sticks are so thin, the steady burning regime is very short (on the order of ten seconds), so it is possible that not all of the liquid fuel is immediately burned off. The measured burning rate would thus be dictated by the liquid fuel and not the sticks themselves and thus not as susceptible to changes in crib design. Additionally, the rate of data logging was fixed at 2 Hz, so fewer data points are available to perform a linear regression on so the error in these measurements may be larger. More crib designs with this stick thickness should be performed, particularly with smaller *l/b* ratios, to determine whether these results are due to the experimental protocol or are a true indication of the behaviour.

5. Summary and future work

Wood cribs are often used as ignition sources for room fire tests. A fundamental understanding of the mechanisms that govern the burning rate of a wood crib may also have applications to wildland fires. The burning rate of unconfined cribs has long been identified to occur in two regimes: the densely-packed regime where the burning rate is proportional to the crib porosity and the loosely-packed regime where the burning rate is independent of porosity. The cribs used to define these burning regimes were fairly limited in their design – either cubic (Gross 1962) or a fairly limited range of the stick length to thickness ratios (*l/b* = 10-20 in Block 1971). However, there are seemingly endless possible ways to build a crib with a given porosity. The first part of this work explored the burning rate of cribs with a wide variety of geometries to determine whether the porosity-burning rate relation defined by Heskestad (1973) holds. One round of experiments was performed to validate the testing apparatus against the known data of Gross (1962) and good agreement was found. A second round of experiments explored the effect of crib layout in the loosely-packed crib regime. The porosity was kept approximately constant while the number of sticks per layer, number of layers and the length to thickness ratios (*l*/*b*) were varied from 10 to 96. For *l*/*b* less than 36, the burning rate of all cribs matched the porosity-burning rate relation from Heskestad (1973), regardless of layout. For larger *l*/*b*, the burning rate was considerably reduced, indicating that there is an insufficient flow of oxidizer inside the crib even though the defined porosity indicates that it should in the loosely-packed regime. This implies that the crib porosity could be function of *l*/*b* above some critical threshold. The second part of this work explored the effect of the spacing distance between the crib and the support platform. The effect of spacing distance is strongly dependent on *l*/*b*, with no difference seen for *l*/*b* = 10 and over a 60% change for *l*/*b* = 96. From these experiments it was clear that cribs with a large *l/b* ratio require a significant amount of oxidizer to flow through the bottom of the crib. The critical spacing distance was shown to be larger than previously thought and a function of the length to thickness ratio. For the cribs with *l/b* = 48, a larger crib-platform spacing the increased the burning rate of these cribs so that the burning rate was closer to the cribs with smaller *l/b*. For cribs with *l/b* = 96, the burning rate was still well below the predicted value, even for large crib-platform spacing.
Because the number of cribs with *l*/*b* = 36 or larger was limited, future work will explore a wider variety of crib layouts with large *l*/*b* to see if the trends seen here hold and to determine if there is a threshold *l*/*b* where the porosity becomes dependent on *l*/*b*. As wildland fuels tend to be quite thin, more cribs with stick thickness of 0.16 cm should be tested. Understanding the effects explored here will be vital when applying crib theory to wildland fires. For example, the effect of crib spacing above the platform will be important when considering ground fuels versus crown fuels. The effect of (*l/b*) will be important when considering different fuel types (needle litter versus slash fuels will change *b*) and flame zone depths (will change *l*).

6. Acknowledgements

The authors wish to thank James McGuire for his 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.

7. References

Anderson HE (1990) Relationship of fuel size and spacing to combustion characteristics of laboratory fuel cribs. USDA Forest Service, Intermountain Research Station Research Paper INT-424, 9 pp.

Block JA (1970) A theoretical and experimental study of nonpropagating free-burning fires. Ph.D. Thesis, Harvard University, Cambridge, MA.

Block JA (1971) A theoretical and experimental study of nonpropagating free-burning fires. *Symposium (International) on Combustion* **13**, 971-978.

Byram GM, Clements HB, Elliott ER, George PM (1964) An experimental study of model fires. USDA Forest Service. Southeastern Forest Experiment Station Technical Report No. 3, 36 pp.

Fons WL, Clements HB, George PM (1963) Scale effects on propagation rate of laboratory crib fires. *Symposium (International) on Combustion* **9**(1), 860-866.

Gross D (1962) Experiments on the burning of cross piles of wood. *Journal of Research of the National Bureau of Standards –C. Engineering and Instrumentation* **66c**(2), 99-105.

Heskestad G (1973) Modeling of enclosure fires. *Symposium (International) on Combustion* **14**, 1021-1030.

O'Dogherty MJ, Young RA (1964) Miscellaneous experiments on the burning of wooden cribs. Fire Research Station, Fire Research Note No. 548. (Boreham Wood. Herts.)

Smith PG, Thomas PH (1970) The rate of burning of wood cribs. *Fire Technology* **6**(1), 29-38.

Thomas PH (1973) Behavior of fires in enclosures – some recent progress. *Symposium (International) on Combustion* **14**, 1007-1020.