Effect of Crib Dimensions on Burning Rate

McAllister, S.* and Finney, M.

USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT, USA.
**Corresponding author email: smcallister@fs.fed.us*

ABSTRACT

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 to determine whether the porosity-burning rate relation in the literature holds. One set of experiments was performed to validate the testing apparatus against the known data in the literature. A second set 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. 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 third set of experiments was performed to examine 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 a 60% change for l/b =96. Future work will focus on exploring the burning rate and the effect of the crib-platform spacing for cribs with large l/b.

KEYWORDS: crib, burning rate, porosity, wood.

NOMENCLATURE

A_s	exposed stick surface area (cm^2)
A_v	area of vertical shafts (cm^2)
b	stick thickness (cm)
l	stick length (cm)
n	number of sticks per layer (-)
N	number of layers (-)
R	burning rate (g/s)
s	stick spacing (cm)
Greek	
φ	porosity (-)

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 [1-3]. It is for these

Proc. of the Seventh International Seminar on Fire & Explosion Hazards (ISFEH7), pp. xx-xx
Edited by D. Bradley, G. Makhviladze, V. Molkov, P. Sunderland, and F. Tamanini

ISBN: 978-981-08-7724-8 :: doi: 10.3850/978-981-08-7724-8_0x-0x

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. 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. 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. There are many ways to evaluate the porosity of a crib (see for example [3-6]), but perhaps the most commonly used is that of Heskestad [6]. By recorrelating the data of both Gross [4] and Block [5], Heskestad suggested that the burning rate is a function of the crib porosity given by

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

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 [4] and [5] well (±20%). However, the crib geometries tested by both Gross and Block were fairly limited. Gross only tested cubic cribs, with stick lengths equal to ten times the thickness. Block extended the length to thickness ratio of his cribs to 20. As one can imagine by looking at Eq. 1, there are seemingly endless possible ways to build a crib with a given porosity. In the wildland context, the fuels clearly are not arranged in such cubic or nearly cubic designs and may need to be represented by cribs with vastly different layouts and geometries. This work explores the burning rate of cribs with a wide variety of layouts and geometries to determine whether the above relation holds.

EXPERIMENTAL DESCRIPTION

Wood cribs of varying geometries were built using square ponderosa pine sticks with thicknesses ranging from 0.159 cm (1/16 in) to 1.27 cm (0.5 in). Table 1 shows the details of all cribs burned. Each crib layout was tested three times and the results averaged. The first set of experiments was performed to validate the testing apparatus against the known data of Gross [4]. In the second set of experiments, the effect of crib layout in the open crib regime was explored. The porosity factor of Heskestad [6] (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. 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%.

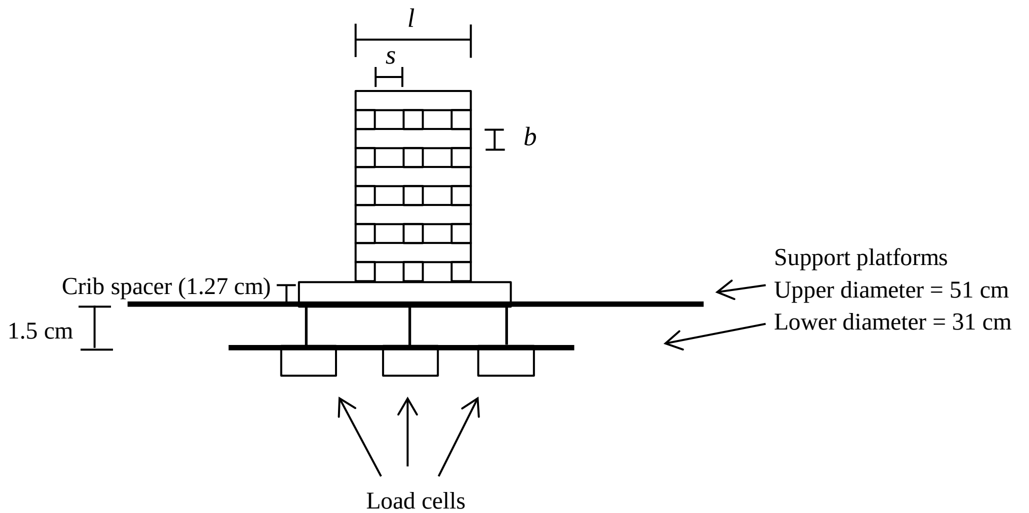

Figure 1. Sketch of apparatus for a crib with 3 sticks per layer (n = 3) and 10 layers (N = 10).

Table 1. Crib dimensions.

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

The cribs were burned in a very large experimental chamber (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 Fig. 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. The cribs were placed on two steel spacers of 1.27 cm (0.5 in) to allow air to flow to the bottom of the crib. 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 Fig. 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.

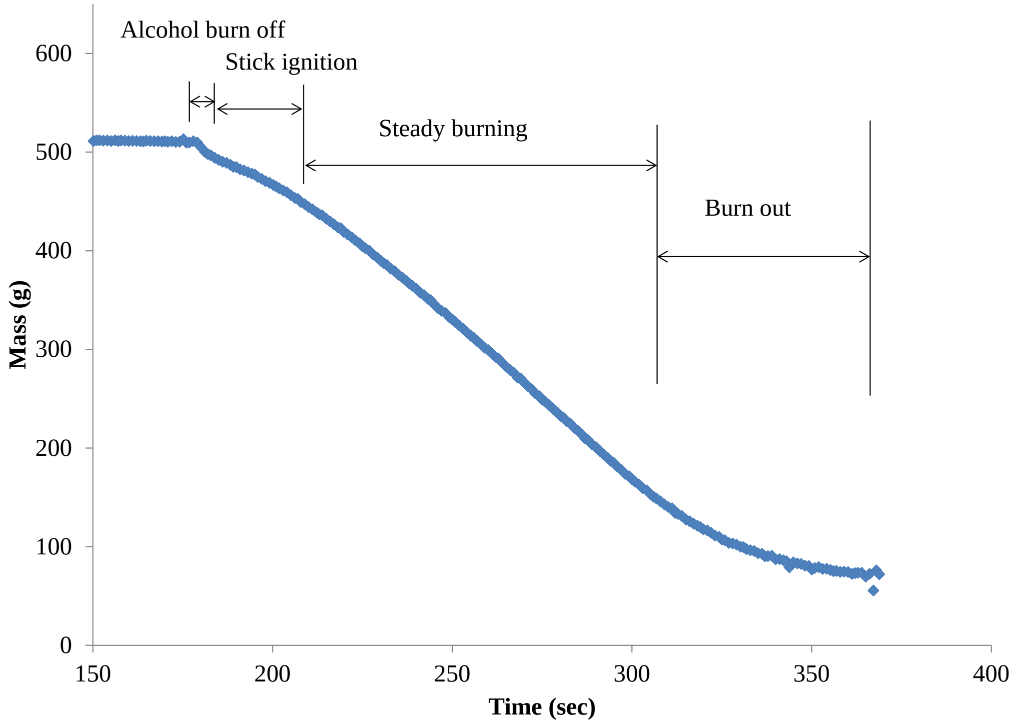

Figure 2. Sample raw data for 1.27-12-3-14 crib.

RESULTS AND DISCUSSION

The burning rates of all cribs are listed in Table 2. As mentioned above, three replicates of each crib fire were performed. The average and standard deviation from these replicates are also shown in Table 2. 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 Fig. 3. using the form of Eq. 1. The black line in Fig. 3 is the correlation from Heskestad [6].

Table 2. Burning rate results.

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 set of experiments were replicates of the experiments of Gross [4] to validate the experimental procedure. The data from these experiments are marked in Fig. 3 as solid diamond-shaped points. Heskestad's correlation fit the data of Gross [4] and Block [5] to within ±20% [6], 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. 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.

Because the layout of the cribs from the second set of experiments varied so widely, the burning rate results in Fig. 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 Fig. 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.

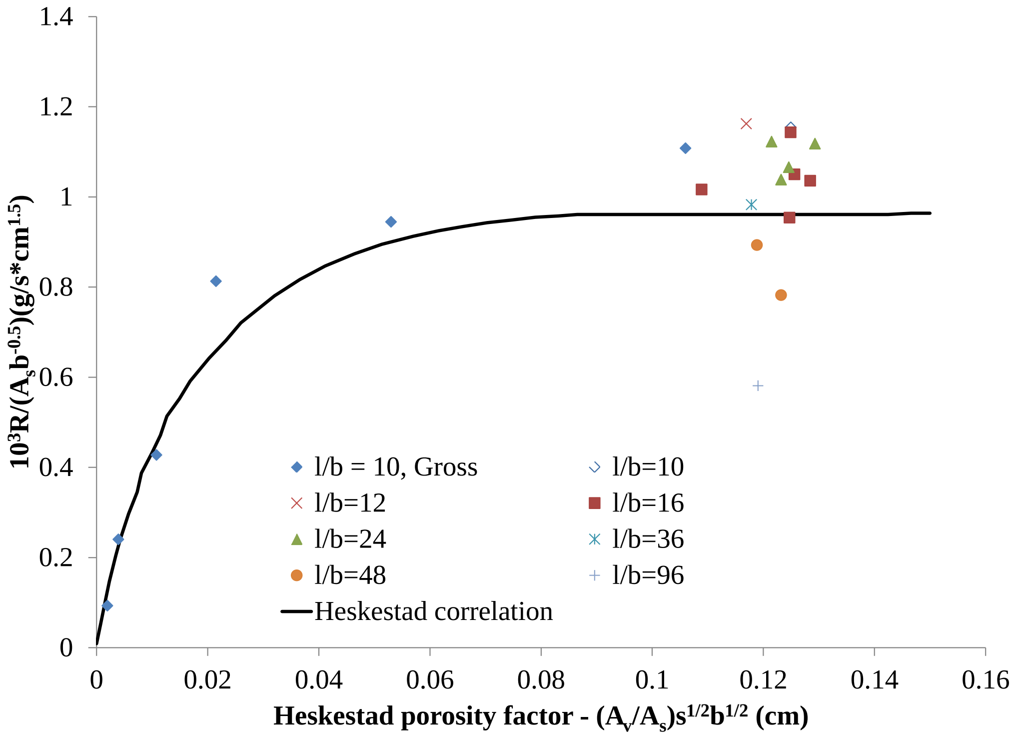

Figure 3. Burning rate results.

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 Fig. 4. A similar behavior was noted when burning the densely-packed cribs in the first set of 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*.

O'Dogherty and Young [7] and Byram et al. [2] 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 [7] and Byram et al. [2]. O'Dogherty and Young used white pine of 12% moisture content with *l*/*b* from 20.2 to 96. However, the spacing between the crib and support platform used by O'Dogherty and Young is not mentioned and there is considerable scatter in their data. 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*). The majority of their data falls below the Heskestad correlation suggesting that no spacing between the cribs and the platforms was used. 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 Fig. 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. This reduced burning rate may be partly due to the lack of separation between the crib and the support platform. 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.

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

The low burning rates of O'Dogherty and Young's cribs suggest that the spacing between the crib and the support platform could have a greater effect that that listed by Block [5]. A short series of experiments was performed with a subset of the cribs with a spacing of 0, 0.64, and 1.27 cm to explore this idea. The cribs tested and resulting burning rates are listed in Table 3.

The differences in burning rate of the no spacing and 0.64 cm spacing cases relative to the 1.27 cm spacing case are plotted in Fig. 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. However, as the ratio of *l*/*b* increases, 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. Cribs that burn simultaneously with a 1.27 cm spacer burn from the outside edges in with a 0.64 cm spacer, and especially so with no spacer. 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. Block [5] noted a critical spacing of about 1.5 cm beyond which the burning rate of his cribs (*l*/*b* = 10-20) did not change. A wider range of spacers should be tested to see if there is such a threshold spacer for cribs with *l*/*b* larger than that tested by Block.

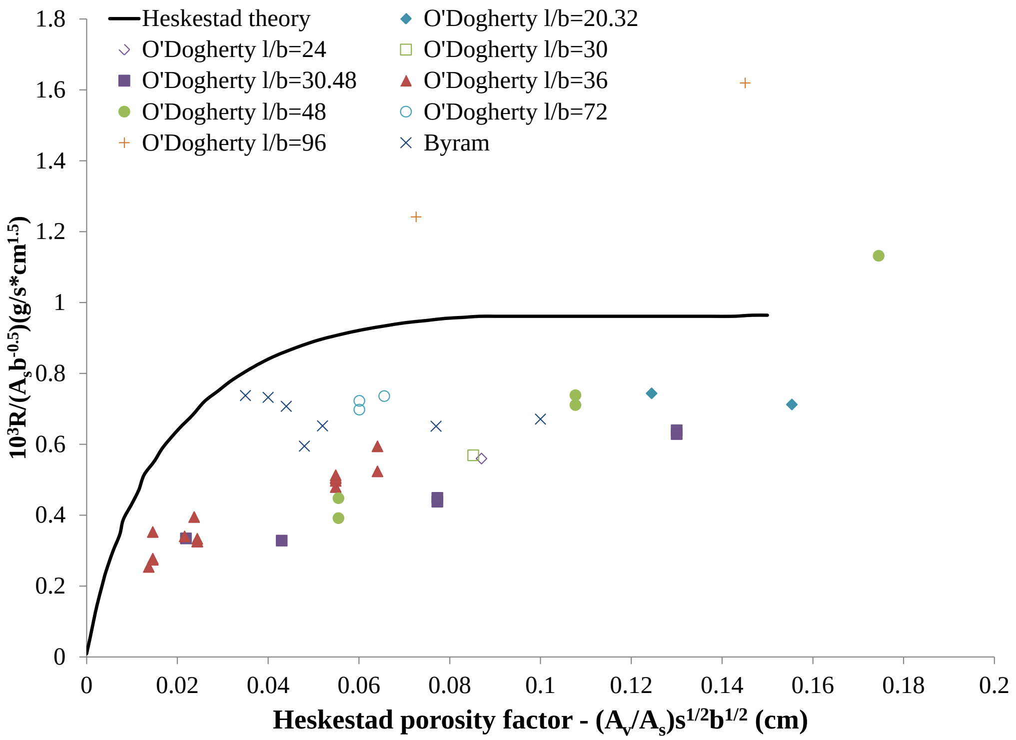

Figure 5. Burning rate data from O'Dogherty and Young [7] and Byram et al. [2].

Table 3. Burning rate results with variable crib-platform spacing.

Shorthand (b-l/b-n-N)	l/b [ ]	Porosity (φ) [cm]	Mean burning rate 0 cm space [g/s]	Mean burning rate 0.64 cm [g/s]	Mean burning rate 1.27 cm [g/s]
1.27-12-3-14	12	0.117	3.2125	3.2279	3.1036
0.64-24-4-14	24	0.129	2.2923	2.7531	2.8698
0.64-24-5-9	24	0.1246	1.6886	-	2.1625
0.64-36-8-8	36	0.118	2.5748	3.2772	4.2010
0.64-48-12-6	48	0.119	3.0394	4.2565	5.6618
0.32-48-6-12	48	0.123	1.0354	1.6300	1.8437
0.16-96-9-10	96	0.119	0.4555	0.8644	1.2236

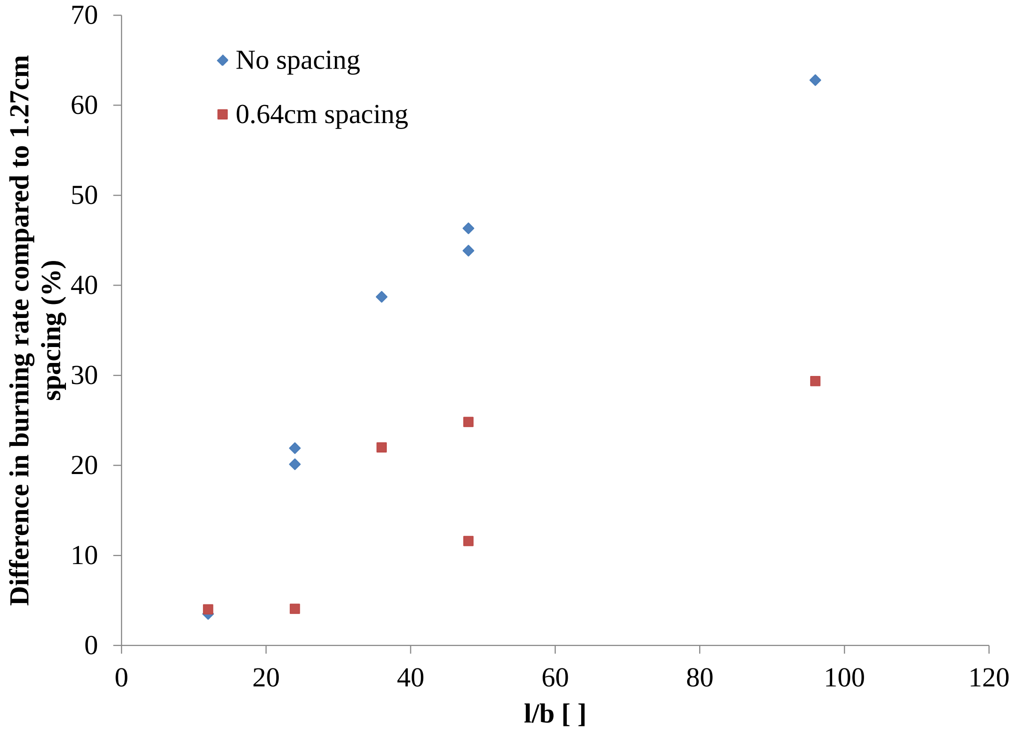

Figure 6. Effect of crib-platform spacing compared to 1.27 cm spacing.

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 the 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 [4] or a fairly limited range of the stick length to thickness ratio (*l/b* = 10-20 in [5]). However, there are seemingly endless possible ways to build a crib with a given porosity. 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 in [6] holds. One set of experiments was performed to validate the testing apparatus against the known data of Gross [4] and good agreement was found. A second set 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 [6], 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. A third set of experiments was performed to examine 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. It is possible that the 1.27 cm spacing used in the second set of experiments was insufficient for cribs with large l/b to allow enough oxidizer to flow within the crib. Consequently, it is possible that with a larger crib-platform spacing the burning rate of these cribs may increase and be closer to the Heskestad correlation. Thus, the next step in this work will be to increase the crib-platform spacing for these large l/b cribs. 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. Understanding these effects 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).

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.

REFERENCES

1. W.L. Fons, H.B. Clements, and P.M. George. “Scale effects on propagation rate of laboratory crib fires,” *Symposium (International) on Combustion* 9(1): 860-866 (1963).
2. G.M. Byram, H.B. Clements, E.R. Elliott, and P.M. George. “An experimental study of model fires,” Technical Report No. 3, Forest Service, USDA Southeastern Forest Experiment Station, 1964, 36 pp.
3. H.E. Anderson. “Relationship of fuel size and spacing to combustion characteristics of laboratory fuel cribs,” Research Paper INT-424, Intermountain Research Station, USDA Forest Service, July 1990, 9 pp.
4. D. Gross. “Experiments on the burning of cross piles of wood,” Journal of Research of the National Bureau of Standards –C. Engineering and Instrumentation, vol 66c, no 2, April-June 1962, pg 99-105.
5. J.A. Block. “A theoretical and experimental study of nonpropagating free-burning fires,” *Symposium (International) on Combustion* 13:971-978 (1971).
6. G. Heskestad. “Modeling of enclosure fires,” *Symposium (International) on Combustion* 14:1021-1030 (1973).
7. M.J. O’Dogherty, and R.A. Young. “Miscellaneous experiments on the burning of wooden cribs,” Fire Research Note No. 548, Fire Research Station, Boreham Wood. Herts. 1964, 11 pp.