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# Experiments on the Burning of Cross Piles of Wood

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Experiments have been performed in which geometrically scaled, unenclosed, cross piles of wood were burned under controlled conditions. For sticks of square cross section ranging in size from 0.16 to 9.15 centimeters, the typical weight-time curve illustrated the three characteristic stages: ignition, active combustion, and decay. For the active combustion stage, the maximum rate of burning (rate of weight loss) was determined and all the test data were correlated in terms of a porosity factor involving the vent area of the pile and the exposed surface area of the sticks. The correlation between the scaled rate of burning and the porosity factor may be simply considered in terms of three regions:

a. Diffusion-limited combustion, in which the scaled rate of burning is very nearly proportional to the porosity factor,

b. free combustion, in which the scaled rate of burning is independent of the porosity factor, and

c. nonsustained combustion, in which the openness of the pile prevents the maintenance of combustion.

Similarity considerations of flame height and radiant intensity data indicate that a simple model may adequately describe the natural convection burning of cross piles of wood of the type and size range investigated.

## Table of Nomenclature

| | | |
|---|---|---|
| $A_s$ | = initial total exposed surface area of sticks, $2nb^2[N(21-n)+n]$ | $cm^2$ |
| $A_v$ | = initial open (vent) area of vertical shafts, $b^2(10-n)^2$ | $cm^2$ |
| $b$ | = stick width | cm |
| $c$ | = heat capacity of wood | joule/g °C |
| $c_g$ | = heat capacity of gas | joule/g °C |
| $D$ | = pile size, $10b$ | cm |
| $F$ | = thermal diffusivity factor, $\frac{\alpha \text{ (Douglas fir)}}{\alpha \text{ (test wood)}}$ | |
| $g$ | = gravitational constant | 980 $cm/sec^2$ |
| $h$ | = height of pile | cm |
| $H$ | = maximum flame height | cm |
| $J$ | = radiant intensity (maximum) | watt/steradian |
| $k$ | = weight ratio for complete combustion, exhaust gas/fuel | |
| $L$ | = stick length | cm |
| $M$ | = weight of pile | g |
| $M_0$ | = initial weight of pile | g |
| $n$ | = number of sticks per layer | |
| $N$ | = number of layers | |
| $N_{FR}$ | = modified dimensionless Froude number, $\frac{\rho_1}{\rho_0-\rho_1}\frac{v^2}{gh}$ | |
| $N_{\text{Rad}}$ | = radiation group, $\frac{J}{krc_g\Delta T}$ | |
| $r$ | = maximum rate of burning | g/sec |
| $R$ | = maximum rate of burning | percent/sec |
| $t$ | = time | sec |
| $T$ | = temperature | °K |
| $T_0$ | = cold gas temperature | °K |
| $\Delta T$ | = gas temperature rise | deg C |
| $v$ | = gas velocity | cm/sec |
| $V$ | = volume of wood in pile | $cm^3$ |
| $\alpha$ | = thermal diffusivity, $\frac{\lambda}{c\rho}$ | $cm^2/sec$ |
| $\lambda$ | = coefficient of thermal conductivity | watt/cm °C |
| $\rho$ | = density of wood | $g/cm^3$ |
| $\rho_0$ | = density of cold gas | $g/cm^3$ |
| $\rho_1$ | = density of hot gas | $g/cm^3$ |
| $\varphi$ | = porosity factor, $N^{0.5}b^{1.1}\frac{A_v}{A_s}$. | |

## 1. Introduction

The lack of basic knowledge on the growth and propagation of fires in building structures has hampered efforts to evaluate quantitatively the importance of the interior finish or lining material. The costs involved in performing an extensive number of full-scale tests of room and building size are considerable, and, in addition, such tests are usually performed in the open where they are subject to uncontrollable weather conditions. Although full-scale tests are indeed necessary, it appears likely that basic understanding of the mechanism involved in fire spread can be achieved through experimentation on a reduced geometric scale.[1]

In using the model-study approach to research on fire growth, it is possible to achieve a compilation of results based on systematically varying the physical, chemical, and geometrical properties of combustible and surroundings under more reproducible conditions. Of even more significance is the opportunity for analyzing and studying the effect of the model parameters on the processes involved in the burning of combustible material. Although the ultimate goal is the use of models for analysis of fires in enclosed rooms and building structures, the initial tests were limited for the most part to simple, symmetrical, unenclosed piles of sticks.

This paper presents some experimental results on the burning characteristics of geometrically scaled cross piles of wood, and includes correlations of these results in terms of the important model parameters.

## 2. Experimental Details

The wood used for the majority of these experiments was Douglas fir (*Pseudotsuga menziesii*), D grade, clear, kiln-dried lumber. The wood was cut to size and conditioned to equilibrium in an atmosphere maintained at 23 °C and 50 percent rh yielding an equilibrium moisture content of 9.2 ±1.5 percent based on the oven-dry weight. The mean density, when conditioned, was approximately 0.48 g/cm$^3$ although considerable density variation was observed. Several experiments were also performed using mahogany, ash, and balsa woods to explore the effects of density and thermal properties on the maximum rates of burning.

The sticks were of square cross section and had a length $L$ equal to 10 times the width $b$. The construction of the pile was identical to that employed by Folk [1][2] and consisted of $N$ layers (usually 10) each containing $n$ sticks, with successive layers laid crosswise. A pile configuration was designated by the thickness of the stick, the number of sticks per layer and the number of layers, or $b$-$n$-$N$. The range explored is listed in table 1.

The pile was ignited by burning normal heptane in a square fuel pan centered at a distance equal to $b$ beneath the pile (see fig. 1). In several experiments, alcohol was used in place of normal heptane. No appreciable difference in the results was noted for either the two fuel types or the quantity supplied as long as there was sufficient fuel to initiate burning of the pile. For almost all tests, the size of the pan was scaled according to the pile size and contained a quantity of fuel corresponding to 8 percent or less of the initial pile weight. With this percentage, the fuel was completely exhausted before any appreciable weight loss of the pile occurred and therefore the fuel weight is not included in the weight of the pile.

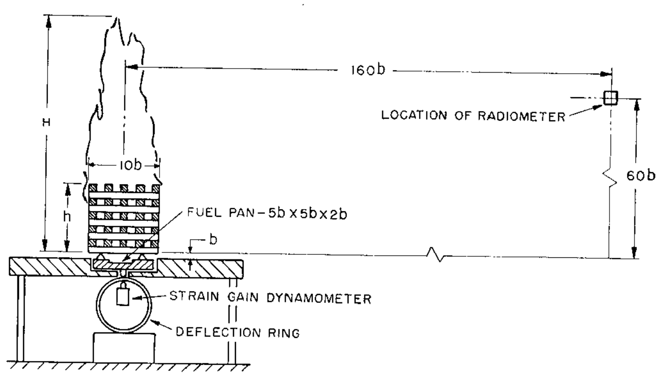


FIGURE 1. *Schematic drawing of experimental arrangement with specimen supported on platform.*

For stick sizes up to 1.90 cm, a dynamometer of the resistance strain gage type was used for obtaining a continuous weight record. The dynamometer was arranged to operate in either of two ways: (a) Directly supporting a suspended coarse wire mesh basket containing the pile, or (b) internally mounted to measure the deflection of the ring supporting the pile on a platform. The type of mounting had no noticeable effect upon the results except that shielding the dynamometer assembly from radiation was much simpler with the platform support. For stick sizes 1.90 cm and larger, conventional platform scales were used. In some tests, measurements were made of the time for balance after removing one of several small weight increments while in other tests, the pile weight was read directly from a calibrated dial.

All tests were conducted within large, high-ceilinged, essentially closed rooms to minimize effects of wind and draft. Figure 2 shows the active combustion stage of a pile of 9.15 cm thick wood arranged seven pieces per layer. The similarity to an actual building fire is evident.

[1] The importance of this problem was emphasized at the Fourth Session (Fire Research and Fire Models) of the First Fire Research Correlation Conference sponsored by the Nat. Acad. of Sci.-Natl. Research Council, November 1956.
[2] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1.

| Material | Density [a] | Heat capacity [a] | Thermal conductivity [b] | Configuration | Weight of pile [c] | Maximum burning rate r | Maximum burning rate R | Maximum flame height H | Radiant energy (max) Radiometer distance | Output Rdg. | Irradiance | Radiant intensity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | g/cm³ | Joule/g °C | Watt/cm °C | | g | g/sec | Percent/sec | cm | cm | mv | Watt/cm² | Watt/steradian |
| Douglas fir | 0.428 | 1.37 | 0.00110 | 0.16-3-10 | 0.62 | 0.0248 | 3.98 | 5 | | | | |
| | | | | .16-5-10 | 1.15 | .00343 | 0.30 | 3 | | | | |
| | | | | .16-7-10 | 1.58 | .00233 | .15 | 5 | | | | |
| | | | | .32-3-10 | 4.55 | .128 | 2.83 | 44 | 50 | 0.35 | 0.00105 | 2.71 |
| | | | | .32-5-10 | 7.7 | .070 | 0.93 | 24 | 50 | .17 | .000485 | 1.25 |
| | | | | .32-7-10 | 10.4 | .048 | .46 | <12 | 50 | .10 | .000239 | 0.617 |
| | | | | .64-3-10 | 37.2 | .443 | 1.19 | 76 | 100 | .24 | .000723 | 7.47 |
| | | | | .64-5-10 | 62.2 | .333 | 0.54 | 65 | 100 | .177 | .000513 | 5.30 |
| | | | | .64-7-10 | 86.3 | .150 | .18 | 36 | 100 | .064 | .000119 | 1.23 |
| | | | | 1.27-3-10 | 286 | 1.24 | .43 | 77 | 200 | .125 | .000329 | 13.6 |
| | | | | 1.27-5-10 | 477 | 1.98 | .42 | 165 | | | | |
| | | | | 1.27-7-10 | 670 | 0.83 | .125 | 64 | 200 | .080 | .000167 | 6.90 |
| | | | | 1.90-3-3 | 272 | (*) | (*) | | | | | |
| | | | | 1.90-5-3 | 454 | .98 | .215 | | | | | |
| | | | | 1.90-7-3 | 652 | 1.34 | .205 | | | | | |
| | | | | 1.90-3-5 | 445 | (*) | (*) | | | | | |
| | | | | 1.90-5-5 | 752 | 1.69 | .225 | | | | | |
| | | | | 1.90-7-5 | 1052 | 1.56 | .148 | | | | | |
| | | | | 1.90-3-7 | 638 | 1.34 | .210 | | | | | |
| | | | | 1.90-5-7 | 1067 | 2.38 | .223 | | | | | |
| | | | | 1.90-7-7 | 1498 | 1.70 | .113 | | | | | |
| | | | | 1.90-3-10 | 906 | 1.97 | .217 | | | | | |
| | | | | 1.90-5-10 | 1535 | 3.40 | .222 | | | | | |
| | | | | 1.90-7-10 | 2118 | 1.90 | .090 | | | | | |
| | | | | 2.54-3-10 | 2570 | 3.58 | .139 | | | | | |
| | | | | 2.54-5-10 | 4150 | 5.58 | .134 | | | | | |
| | | | | 2.54-7-10 | 5970 | 4.23 | .071 | 140 | 400 | .095 | .000220 | 36.3 |
| | | | | 3.81-3-10 | 7520 | (*) | (*) | | | | | |
| | | | | 3.81-5-10 | 13570 | 10.3 | .076 | | | | | |
| | | | | 3.81-7-10 | 18640 | 9.88 | .053 | | | | | |
| | | | | 9.15-7-10 | 262000 | 57.5 | .022 | 460 | 1100 | .32 | .000970 | 1170 |
| | | | | 9.15-8-10 | 315000 | 55.7 | .018 | 365 | 1100 | .26 | .000787 | 904 |
| Ash | .660 | 1.37 | .00156 | 1.27-3-10 | 442 | 1.98 | .450 | 100 | 200 | .136 | .000367 | 15.2 |
| | | | | 1.27-7-10 | 1030 | 0.92 | .088 | 58 | 200 | .112 | .000282 | 11.7 |
| Mahogany | .375 | 1.37 | .000987 | 1.27-3-10 | 252 | 1.44 | .572 | 96 | | | | |
| | | | | 1.27-7-10 | 586 | 0.68 | .117 | 70 | | | | |
| Balsa | .190 | 1.37 | .000619 | 1.27-3-10 | 127 | 1.28 | 1.01 | 90 | 200 | .106 | .000258 | 10.7 |
| | | | | 1.27-7-10 | 281 | 0.48 | 0.170 | 70 | 200 | .094 | .000218 | 9.02 |
| Fir [d] | .428 | 1.37 | .00110 | 1.02-4-10 | 190 | .90 | .467 | | | | | |
| | | | | 1.02-5-10 | 250 | .82 | .333 | | | | | |
| | | | | 1.02-7-10 | 330 | .40 | .117 | | | | | |

*No sustained burning.
[a] Assumed values, oven dry.
[b] Based on formula MacLean (11) for oven-dry wood.
[c] Not including weight of igniting fuel.
[d] Data from Folk (1).

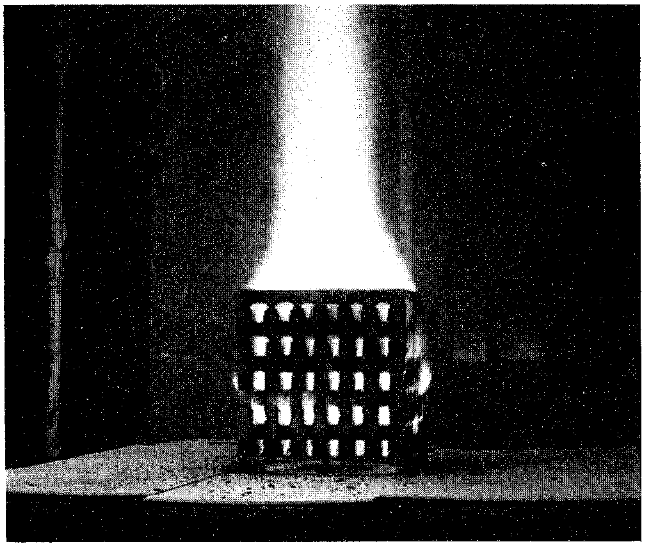

FIGURE 2. *Active combustion stage in burning of cross pile of wood.*

9.15 cm thick wood, 7 sticks per layer, 10 layers high.

## 3. Results

Typical weight-time curves are shown in figure 3, from which three characteristic stages may be noted: (a) The ignition stage corresponding to a gradually increasing rate of weight loss, (b) the active combustion stage corresponding to a maximum and relatively constant rate of weight loss, and (c) the decay stage corresponding to the exhaustion of the pile attended by its collapse into glowing embers and ultimate extinction. The maximum rate of burning is taken as the maximum slope of the smoothed weight-time curve.

*Shielding effects.* Investigation of the effects of some conditions external to the pile was limited to one pile configuration, 1.27–7–10. It was found that: (a) There was no appreciable effect on the mode or the maximum rate of burning when a horizontal floor shield, up to 5 times the pile size on a side, was placed at the base level (or 1.27 cm below the base) of the pile, as compared with that for a pile suspended in a wire basket with only the fuel pan underneath. For uniformity, however, a square floor shield was used in most tests, its size being 2 to 5 times the pile size on a side, as shown in figure 1. (b) The maximum burning rate was reduced over 50 percent by a vertical shield placed so as to restrict air flow to the pile. The shield consisted of a square tube of black iron sheet twice the height of the pile and providing 7.62 cm clearance on all sides of the pile. It was placed in position after ignition of the pile was established. (c) There was no appreciable difference in the maximum rate of burning when the floor shield at the base of the pile had either a highly reflective aluminum foil surface or a carbon-blacked, highly absorptive surface.

*Flame height.* Visual observations were made of the maximum height of the flames measured above the base of the pile. The data are given in table 1.

*Temperature.* For a number of tests, temperatures in and around the pile were measured and recorded by means of bare chromel-alumel thermocouples (0.051 cm diam wire) and multipoint potentiometric recorders. Figure 4 illustrates typical temperature records for 12.7, 25.4, and 91.5 cm piles measured in each case at a point in the air near the central vertical axis. For the 12.7 and 25.4 cm piles, the thermocouple was located a distance of $b$ above the base, while for the 91.5 cm pile, it was situated a distance $2b$ above the base. Except where the thermocouple came in close contact with the wood surface or was otherwise shielded from direct flame

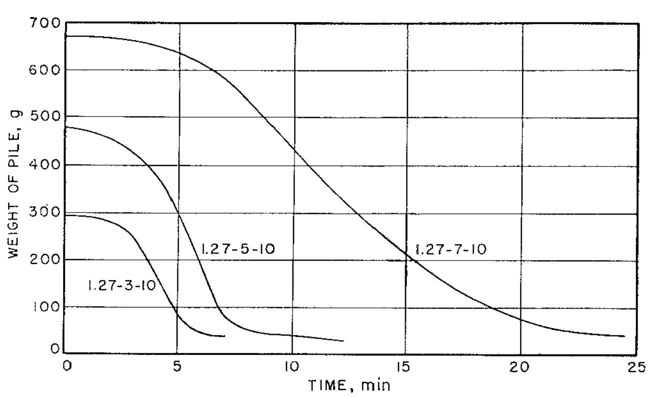


FIGURE 3. *Weight-time curves for cross piles of wood.*

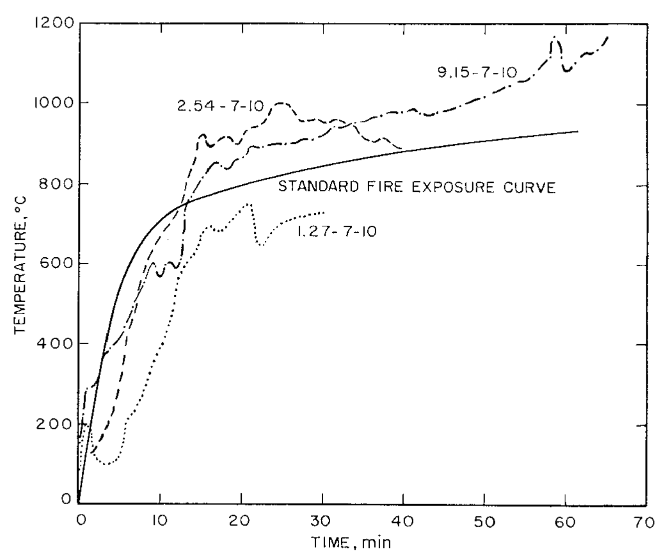


FIGURE 4. *Typical temperature-time records of burning cross piles of wood.*

Thermocouple location: near central vertical axis, distance $b$ (12.7 and 25.4 cm piles) or $2b$ (91.5 cm pile) above the base.

radiation, the exact location was not considered to be of major importance. The maximum temperatures measured within the pile were of the order of 800, 1000, and 1200 °C for piles composed of 1.27, 2.54, and 9.15 cm sticks respectively, although the maximum temperatures for a given size stick appeared, from all data obtained, to be somewhat dependent upon the structure of the pile. The prescribed temperature-time curve of a standard fire exposure test [2] is also shown in figure 4 from which a general agreement may be noted.

*Radiant energy.* Measurements were also made of the radiant flux from the pile incident on a single receiver. The radiometer consisted of a multiple-junction total radiation thermopile taken from a commercial radiation pyrometer. It had a thin mica window, a wide-angle field of view and was of moderate response speed (98% within 2 sec). It was horizontally mounted and arranged to view the pile plus the entire area of flaming according to the scheme in figure 1. The radiometer was calibrated by measuring emf output as a function of distance from a small blackbody source of known radiant intensity. The results are summarized in table 1. Figure 5 is a plot on logarithmic coordinates of the maximum radiant intensity as a function of the maximum rate of burning. The ordinate was calculated on the basis of the inverse square law (considering the fire as a point source) and refers to a unit solid angle from the source in the direction of the radiometer as shown in figure 1. The error introduced by the inverse square law assumption was considered negligible when the radiometer to source distance was five or more times the maximum fire dimension. A straight line of unit slope (direct proportionality) yielded a good fit to the data. There appeared to be a slight tendency, however,

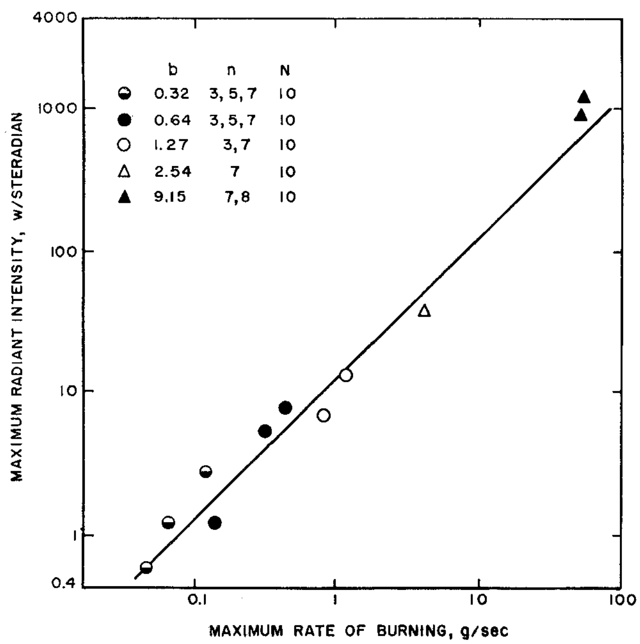


FIGURE 5. *Relationship of maximum radiant intensity to maximum rate of burning.*

for the more open piles ($n=3$) to have a relatively higher maximum radiant intensity than the closely packed piles ($n=7$).

*Air velocity.* Some observations were made of the velocity of air approaching the pile. Measurements were limited to exploratory tests using both titanium tetrachloride smoke (for visual demonstration) and heated thermocouple anemometors.

## 4. Analysis and Discussion

The rate of burning data appeared to be most effectively correlated in terms of a power relation of the scale size. When the rate of burning, expressed in percent per second, was multiplied by the stick width raised to the 1.6 power, it was found that the maximum values of $Rb^{1.6}$ were all equal to about 0.62. A plot of the scaled rate of burning $Rb^{1.6}$ as a function of pile size for three configurations is shown in figure 6.

It is interesting to note that experiments conducted by Bryan [3] led him to the conclusion that the fundamental law governing the combustion of his wood cribs was the dependence of mass change and heat emission upon the 3/2 power of the scale size. Furthermore, measurements of heat conduction in bodies subjected to standard fire exposure tests [2] have shown that the time for a certain temperature to be reached is approximately dependent upon the 1.6 power of the thickness. This has also been verified by means of measurements on electrical models arranged to represent the analogous thermal situation [4, 5]. Whereas the rate of burning of a stick of square cross section should properly be considered a two-dimensional system, this 1.6 power relation is based upon one-dimensional heat flow. However, in the actual burning, all sides are not uniformly affected by the developing fire and the assumption of a one-dimensional heat flow may not be unreasonable. Since the rate of burning depends upon the absorption of heat within a body with resultant release of combustible decomposition products, it is reasonable to expect

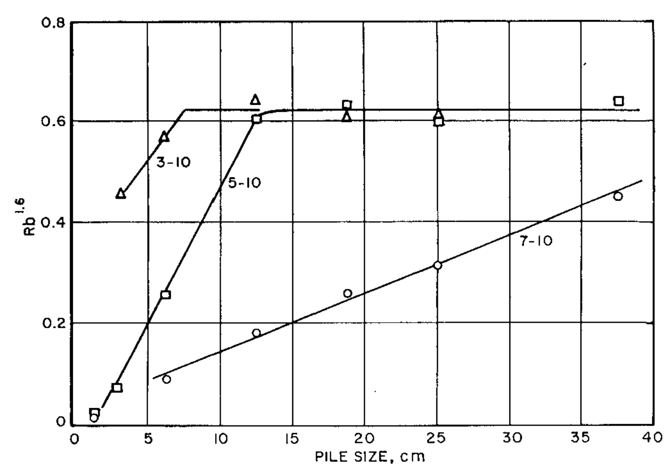


FIGURE 6. *Scaled rate of burning as a function of pile size.*

something like a 1.6 power scaling effect upon the rate of burning.

Burning at a rate below the maximum value is a result of the limitation by the pile structure on air flow into (or gas flow out of) the pile. Consideration of the important parameters affecting air flow led to a definition of a porosity factor which provided a good correlation for all pile configurations tested, namely,

$$\varphi = N^{0.5} b^{1.1} A_v / A_s.$$

The initial total exposed area of the sticks is given by

$$A_s = 2nb^2[N(21-n)+n].$$

The vent area of the pile may be considered the area of the vertical shafts only or of some unknown fraction of the total vent area comprising the top, four sides and bottom of the pile. For simplicity, the initial open area of the vertical shafts has been taken and is expressed as

$$A_v = b^2(10-n)^2.$$

It was evident from visual observations that significant flaming issued from many of the side openings as well as from the top. Several experiments may be suggested to investigate this point, e.g., using a solid slab roof as the top layer, offsetting sticks in alternate layers to obstruct the flue effect, setting the pile directly on the floor after ignition, closing off all or part of the side openings, etc. In tests with a solid slab roof, approximately a 20 percent reduction in the maximum rate of burning was obtained and this suggests that the area of the vertical shafts was only partially limiting.

All the available data, including that of Folk, have been plotted in figure 7 as a function of the porosity factor $\varphi$. To take into account the effect of thermal properties in the tests with mahogany, ash and balsa woods, the scaled rate of burning ordinate, $Rb^{1.6}$, has been multiplied by a factor $F$ which is the ratio of the thermal diffusivity of Douglas fir to that of the wood under test. For these data points, the greater scatter probably results from lack of appropriate information on the thermal properties of the different woods. It is realized that the formulation of abscissa groups other than $\varphi$ might yield equally satisfactory correlation. However, the porosity factor $\varphi$ chosen served as a useful means for gaging the effect of the porosity or openness of the pile. Plotting the data on this basis, the combustion is considered to consist of essentially three regions:

a. Diffusion-limited combustion, in which the scaled rate of burning is nearly proportional to the porosity factor $\varphi$.

b. free combustion, in which the scaled rate of burning is independent of the porosity factor, and

c. nonsustained combustion, in which the openness of the pile prevents the maintenance of combustion.

*Dimensionless correlation.* Analysis of the natural convection fire problem is simplified if it is assumed that the flame temperatures for model and prototype are identical. Furthermore, Hottel [6] has shown that modeling is impossible if allowance must be made for the interaction between radiation and flow. If, instead, it is assumed that radiation is sufficiently small so as not to affect the flow pattern, this still permits modeling of the reception of fire radiation by the surroundings. Experimental flame height and radiant intensity data may be analyzed on the basis of these considerations.

If, in the fluid dynamic regime, the rate is gravity-controlled, the dimensionless Froude group will be the criterion for similarity. Assuming the rate of burning to be directly related to the mass flow of gas,

$$r = \frac{1}{k} \rho_1 v D^2.$$

The modified Froude number based upon buoyancy may then be written:

$$N_{FR} = \frac{\rho_1}{\rho_0 - \rho_1} \frac{v^2}{gh} = \frac{T_0}{\Delta T} \frac{k^2 r^2}{g \rho_1^2 D^4 h}.$$

A good correlation, figure 8, of the data from this investigation has been achieved between the dimensionless flame height $H/D$ and the modified Froude number. Also shown is a line representing the data

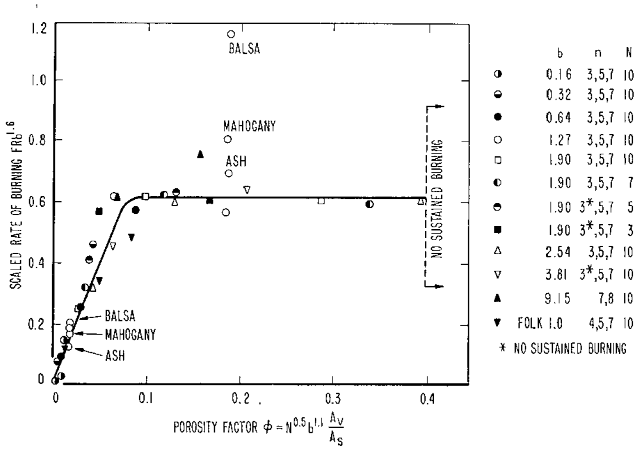


FIGURE 7. *Effect of porosity on the scaled rate of burning.*

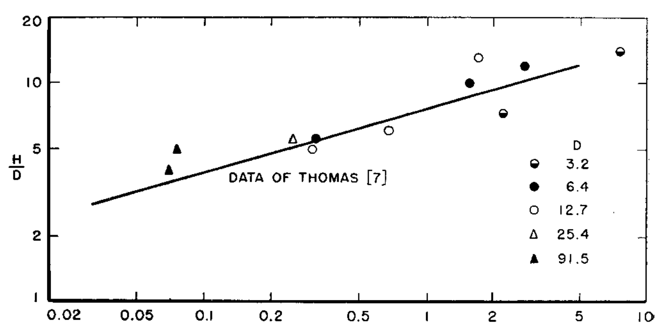


FIGURE 8. *Dimensionless plot of flame-height data.*

of Thomas [7] on white spruce (*Picea glauca*) in piles ranging in size from 25.4 to 152.4 cm. The plot is based upon the following approximate values:

$$k=6.1, \text{ see Kawagoe [8, p. 5]},$$
$$\rho_1=0.00028$$
$$g=980$$
$$T_0=300$$
$$\Delta T=1000.$$

One limitation on the correlation appears to be that the same type of flow pattern be maintained. Except for the smallest pile ($D$=1.59 cm), a predominantly turbulent pattern was obtained. It is interesting to note that a similar correlation was obtained from model experiments with cross piles of sticks within an enclosure, only one side of which was open [9].

For a flow system involving radiation, a condition for similarity is that the ratio of the radiative to the convective transport of heat shall be constant. This may be expressed in a "radiation group" which is essentially the inverse of a group employed by Thring [10]. In terms of the measured quantities, $N_{\text{Rad}}=\frac{J}{krc_g\Delta T}$. Since the integrated radiation was not measured, the maximum radiant intensity $J$ based on measurements at a single point was used. Figure 9 is a plot of this radiation group as a function of the modified Froude number based upon the following values:

$$k=6.1, \text{ as before}$$
$$c_g=1.25$$
$$\Delta T=1000.$$

It is possible to fit a nonhorizontal straight line through all the data points with the exception of the 91.5 cm pile size. Thus, for pile sizes up to 25.4 cm, the radiation group increased slightly with ln $N_{FR}$. Temperature scale effects alone do not appear to provide an explanation for the pattern observed. However, since the radiation group only varies by a factor of about 3 for a 100-fold change in the modified Froude number, it may be considered essentially independent of the Froude number.

## 5. Summary

This report describes experiments performed over a period of several years to obtain fundamental information on the burning characteristics of cross piles of wood. This is one of the initial steps in an overall investigation of the applicability of model techniques to the study of the development and growth of fires in buildings.

From the results of the experiments to date, it has been found that weight-time records can be considered in terms of three characteristic stages: Ignition, active combustion, and decay. For the active combustion stage, the maximum rate of burning data have been found to correlate in terms of a porosity factor involving the vent area of the pile and the total exposed area of the sticks. This correlation may be simply considered in terms of three regions on the porosity scale: Diffusion-limited combustion, free combustion, and nonsustained combustion.

Flame height data have been correlated on a dimensionless basis with the modified Froude number. It was also found that the ratio of the radiative to the convective transport of heat was essentially independent of the modified Froude number. These results indicate that a simple model may adequately describe the natural convection burning of cross piles of wood.

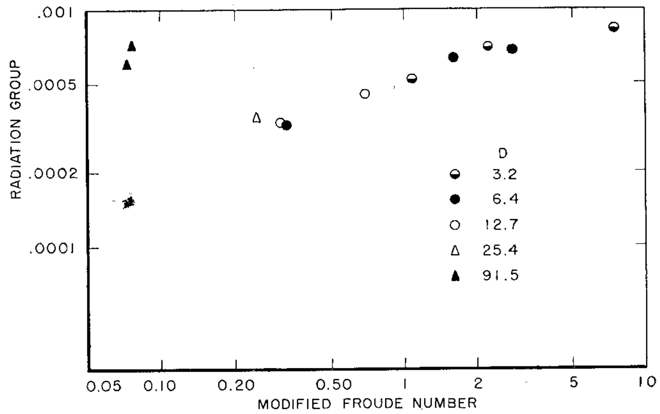


FIGURE 9. *Radiant intensity data*

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The experimental work was performed through the cooperative efforts of many members of the Fire Research Section. Credit for the bulk of the experimental work is due to the following part-time student aids, K. N. Berk, T. Burns, P. F. Eastman, and R. H. Speier.

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