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(b) Experimental Data on Wood Materials

by

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INTRODUCTION

Wood is a highly diverse material. Its variability comes from numerous effects of species, the source of material, variability within each tree, and effects of processing as well as conditions of end use. Because of these sources of variability, fire properties are also affected. In the previous Section, a heat release rate model was presented which takes into account some physical and chemical properties of wood. The present Section will provide some typical ranges of experimental data and some guidelines to estimate heat release rate of wood and some wood-based products.

Most wood materials used in building construction come from trees of two broad classes, hardwoods and softwoods. The terms hardwood and softwood have little to do with the hardness of the wood. Botanically, the hardwoods are from trees with broad leaves and the softwoods are from conifers with needle-like or scale-like leaves. A more detailed description of the commercially important tree species can be found in the Wood Handbook [1]. Wood materials used in construction include untreated lumber, plywood, and particleboard. Smaller amounts comprise products which are treated with preservatives or fire retardants for specific applications. In this Chapter, the discussion will focus on materials having thickness of more than 12 mm. Most data will pertain to solid wood. Some representative data for composite materials, e.g., plywood and particleboard, and for fire-retardant treated wood are given as examples.

Many factors have been identified as key variables that affect the burning of wood. They are density, chemical composition, and moisture content. Other factors such as permeability, char contraction factor, and interactions between them should be considered in modeling of wood combustion [2]. Here, a simplified approach is presented, based on empirical correlations and parameters that are available in the literature or readily obtained.

HEAT RELEASE CALORIMETERS AND DATABASE

As discussed earlier, calorimeters used to measure rate of heat release have different designs, resulting in different exposure conditions. The heat release rate depends not only on the externaI radiant heat flux, but also on the flame flux, sample size and orientation, and mounting conditions. Therefore, the heat release data are apparatus dependent and require further analysis before they can be used for modeling purposes. The analysis would require a model such as one proposed by Parker. In this chapter, we will only examine the experimental data obtained from two well known calorimeters: the Cone Calorimeter and the OSU apparatus. A data base of different wood products tested in the Cone Calorimeter at the National Institute of Standards and Technology over the last decade is available. Some of its analysis was reported earlier by Janssens [3]. Another data base of wood products has been gathered at the U.S. Forest Products Laboratory (FPL) using the OSU apparatus, but modified sensing by oxygen consumption. The modified OSU apparatus used at FPL was described in [4]. Some materials were tested in both apparatuses for comparative purposes and will be mentioned where appropriate.

The standard sample size is different in the two calorimeters. It is 100 x 100 mm for the Cone Calorimeter and 150 x 150 mm for the OSU apparatus. In both cases, to minimize heat and mass loss to the unexposed sides, the sample is wrapped in foil and backed by ceramic fiber blanket. The sample, foil, and backing are then held in the appropriate specimen holder. The mass loss of the sample is obtained by weighing the sample before and after the test. In case of the Cone Calorimeter, mass loss is monitored continuously with a load cell. Ignition in both apparatus is achieved with a spark or a pilot flame which are designed to ignite the gas phase but impose no added flux to the sample. Heat release rate is sensed by oxygen consumption method in both cases.

Heat release rate data are available in both vertical and horizontal orientations for the Cone Calorimeter. Only vertical orientation was used for the OSU tests. Most samples were conditioned at 23°C and 50% relative humidity prior to testing, resulting in moisture contents of about 9%. Only a few oven dry samples were tested in the Cone Calorimeter to show the effect of moisture content on HRR of wood. In the following discussion, the moisture content will be assumed to be 9% unless specified otherwise.

PRESENTATION OF DATA

From the calorimeter test, an HRR curve is obtained. Heat release rate is expressed as power per unit area exposed (kW/m^2). Typically for wood materials, a sharp peak results from burning of the combustible pyrolysate soon after ignition. As the wood chars, the HRR decreases because of the insulating effect

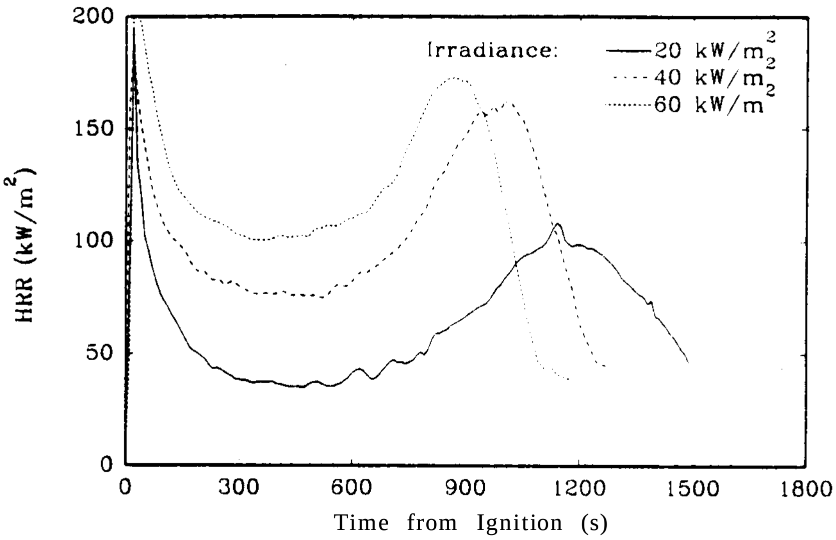

Figure 1. Heat release rate of 18 mm red oak tested in a Cone Calorimeter, vertical orientation.

of the char layer. If the wood is sufficiently thick, the HRR will stabilize to a steady rate. Normally, for materials with finite thickness, a second peak occurs near the end of the burning, as bulk temperature of the remaining material is rapidly raised to a higher value. Figure 1 illustrates the HRR curves of 18 mm thick red oak tested in the Cone Calorimeter in the vertical orientation at different levels of irradiance. The HRR curves show the first peak followed by a steady period and the second peak. Figure 2 shows the HRR curves of thick samples of

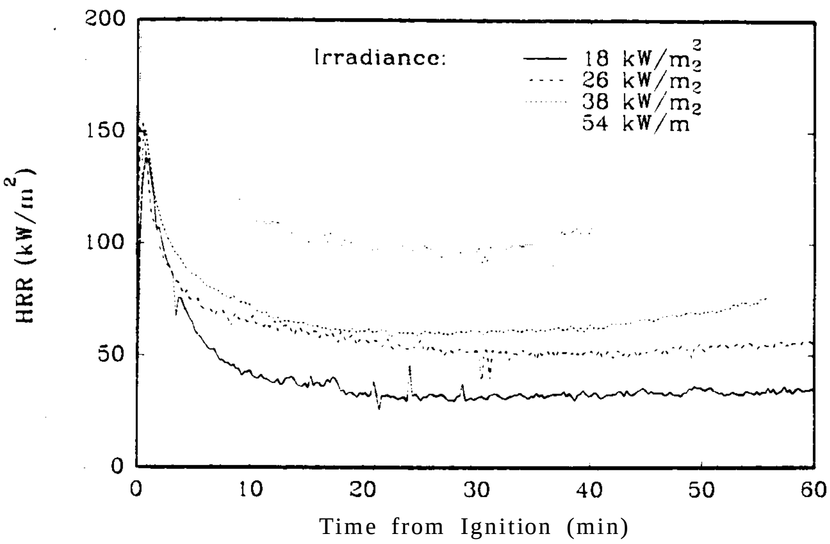

Figure 2. Heat release rate of 64 mm red oak tested in OSU apparatus, vertical orientation.

red oak (64 mm) tested in the OSU apparatus at similar irradiance. For the duration of the test (run to obtain a char depth of 36 mm), the HRR curves are flat. Generally, the part of the HRR curve before the second peak is of most interest in modeling fire growth. The second peak is dependent on unexposed face conditions. It will not be observed if the material is attached to substrate, such as gypsum board, which acts as a heat sink.

The shape of the curve poses an interesting question about how summary heat release data might be reported. At least three general types of values have been used in the literature:

(1) Peak HRR ($\dot{q}''_{peak}$). The highest value, occurring after the ignition of the sample.
(2) Average HRR, taken from ignition time over a fixed period of time, e.g., 60 s, 180 s, 300 s.
(3) Cumulative (or, total) heat release. This is usually reported for the duration of the entire test.

For charring materials specifically, Magnusson and Sundström [5] have proposed to report data in a form which takes into account the shape of the initial peak. This equation is of the form:

$$\dot{q}''(t) = \dot{q}''_{peak}e^{-\lambda(t - t_p)} \tag{1}$$

Where t_p is the time at which the peak occurs. If time t is taken as the time from t_p, the equation above is simplified further to:

$$\dot{q}''(t) = \dot{q}''_{peak}e^{-\lambda t} \tag{2}$$

Therefore, only the peak value $\dot{q}''_{peak}$ and λ are needed to characterize the heat release rate curve. The combination of these two parameters have been shown to be useful in mathematical modeling of fire growth. Some preliminary investigations aimed at characterizing the HRR curves using solely this method were abandoned, however, for two main reasons: 1) inaccuracy in obtaining $\dot{q}''_n$ and 2) for most wood products, the method is only adequate to describe the first peak, which comprises only the first minute or two of the total HRR curve.

In the following analysis of the data base, HRR will be characterized with particular emphasis on two parameters: the 60 s and 300 s average HRR.

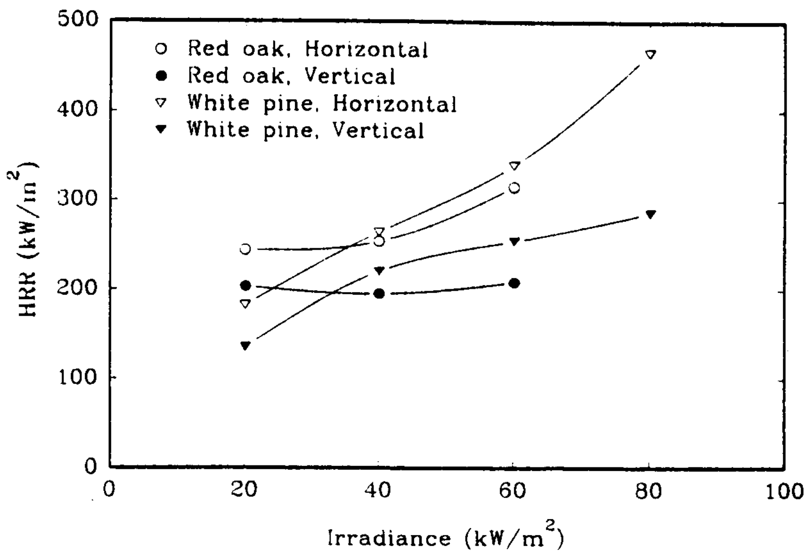

Figure 3. Peak heat release rate of red oak and white pine tested in a Cone Calorimeter.

EFFECT OF ORIENTATION

of the materials in the data base, red oak and white pine were tested in the Cone Calorimeter in both horizontal and vertical orientations at radiant flux levels ranging from 20 to 80 kW/m^2. The peak HRR, the 60 s average, and the 300 s average are shown in Figures 3 to 5, respectively. In all cases, HRR increases

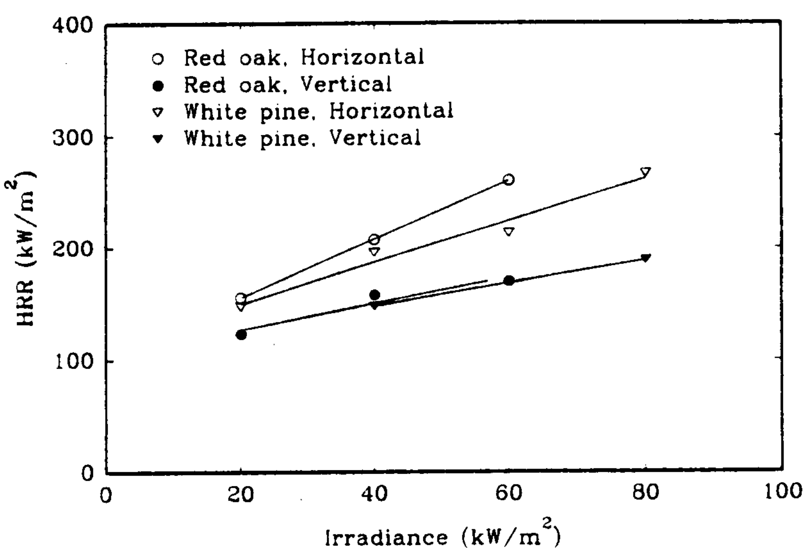

Figure 4. One-minute average heat release rate of red oak and white pine tested in a Cone Calorimeter.

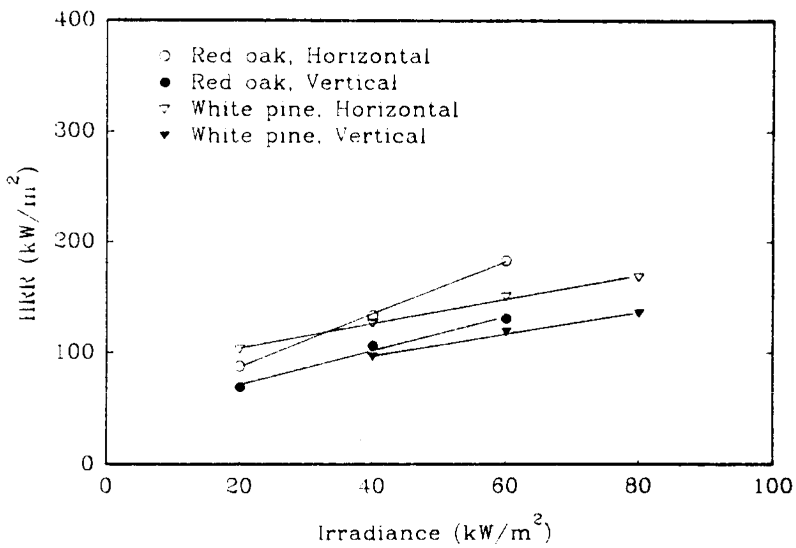

Figure 5. Five-minute average heat release rate of red oak and white pine tested in a Cone Calorimeter.

with irradiance. The average HRR is a linear function of irradiance, (Figs. 4 and 5), but the peak HRR is not (Fig. 3). The non-linearity of the peak HRR values, as a function of irradiance, is attributed mainly to inaccuracies in obtaining the peak value. The peak HRR is often difficult to obtain accurately from the data, since, for wood products, it tends to be in a steep regions of the HRR curve, and also since the data collection is usually only available at intervals of 3 to 10 s. The 60 s average is, consequently, more representative of the peak area. Average HRR for 180 s to 300 s periods, then, take into account both the first peak and the subsequent plateau. Analysis indicates that, for wood materials of more than 12 mm thickness, the 300 s average is a good representation.

The horizontal orientation consistently gave about 30% higher HRR than the vertical orientation. The higher HRR in the horizontal orientation can be explained by the effect of flame flux. In the vertical orientation, the flame forms a thin sheet that covers the pyrolyzing surface. Most of the burning of the gas phase occurs above the upper edge of the sample. On the other hand, the flame assumes a conical shape above the horizontal sample. The flame volume is much greater, resulting in significantly more radiative feedback to the sample.

EFFECT OF EXTERNAL HEAT FLUX

As shown in Figures 3 to 5, HRR can be related to irradiance for each material and orientation. The following analysis attempts to derive empirically rules of

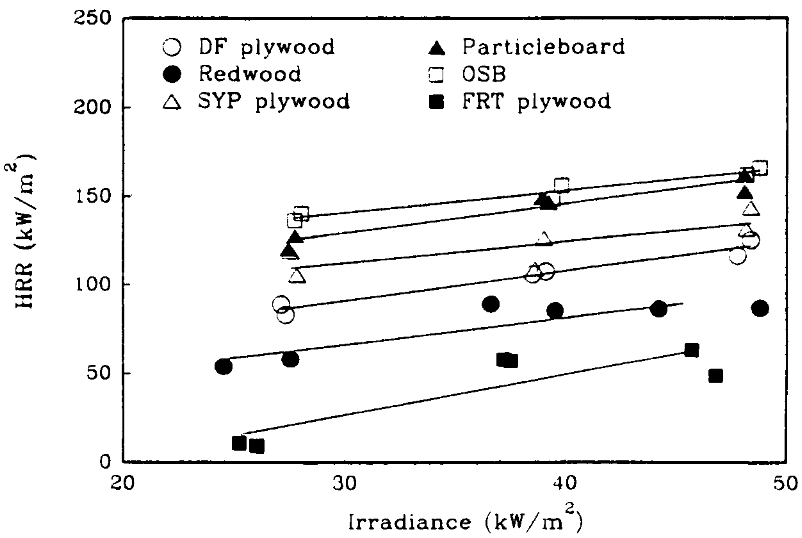

Figure 6. Five-minute average heat release of six materials tested in OSU apparatus.

thumb that could be used to estimate the HRR at various irradiances, if one value of HRR of a material is known at a particular irradiance.

In our data base, 6 materials were tested in both the Cone Calorimeter and the OSU in the vertical orientation for comparative purposes [4]. The 6 materials are redwood, Dougias-fir (DF) plywood, Southern pine (SP) plywood, particleboard, oriented strand board (OSB), and a fn retardant treated (FRT) plywood. All of

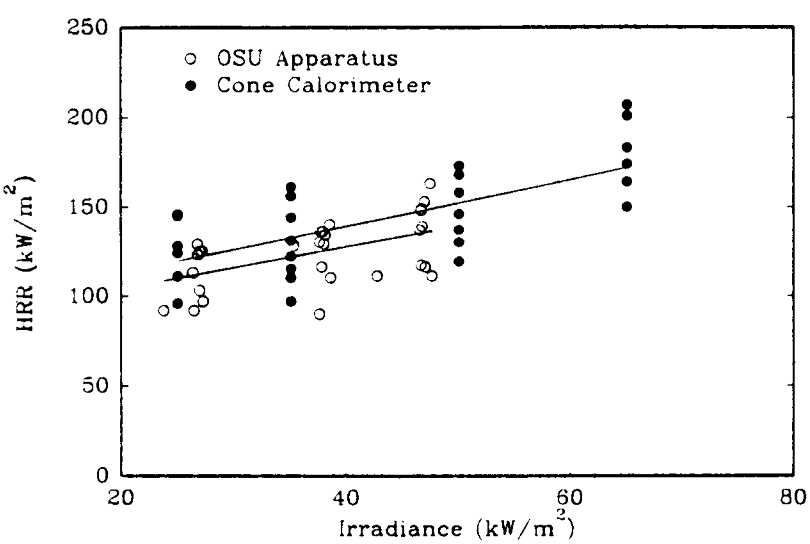

Figure 7. One-minute average heat release rate of five materials in the OSU and Cone Calorimeters.

Table 1
Average Heat Release Rate versus Radiant Heat Flux[a]

Material	Cone calorimeter						OSU apparatus					
	1 min			5 min			1 min			5 min		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
DF plywood	0.72	86	0.42	1.43	22	0.91	−0.1	130	0.02	1.68	41	0.96
Redwood	1.19	76	0.82	1.49	16	0.94	0.70	77	0.27	1.50	21	0.77
SP plywood	1.13	86	0.64	2.40	33	0.91	0.65	74	0.32	1.22	76	0.62
Particleboard	1.73	55	0.94	1.73	55	0.99	1.65	80	0.66	1.65	80	0.92
OSB	1.32	95	0.98	1.88	60	1.00	1.49	69	0.76	1.25	103	0.95
FRT plywood	1.73	55	0.61	1.26	19	0.49	1.65	80	0.41	2.31	−43	0.75

[a] Linear regression of the form $Y = aX + b$, where Y is the average HRR (kW/m^2) and X is the heat flux (kW/m^2).

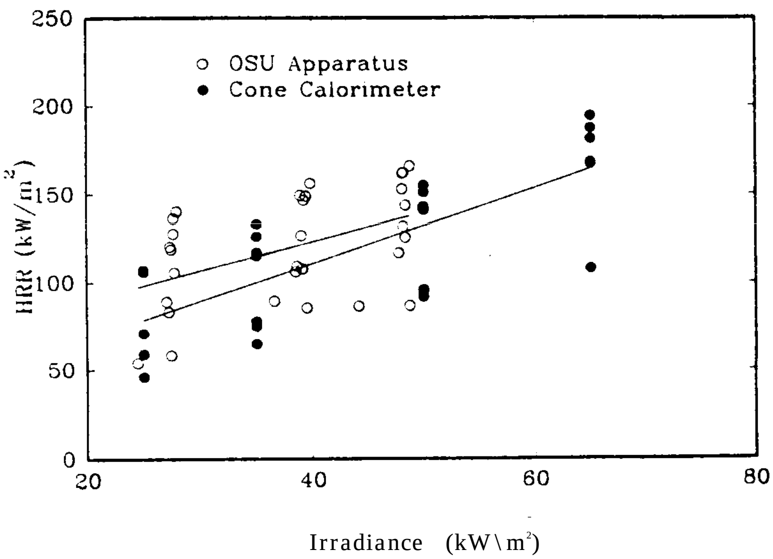

Figure 8. Five-minute average heat release rate of five materials in the OSU and Cone Calorimeters.

them were tested in the vertical orientation under irradiances of 25 to 65 kW/m^2. As shown in Figures 4 and 5, the average HRR depends linearly on the irradiance. The 300s average HRR of the materials tested in the OSU apparatus are shown in Figure 6 as an example. Linear regression results of the average HRR for these six materials are summarized in Table 1.

The linear regressions shown in Table 1 have acceptable R^2 values for 5 min average HRR with exception of the FRT material, which has a much lower R^2. This is explained by the fact that ignition of this material is difficult to determine, causing uncertainties in the average values of HRR. The R^2 values of 1 min average HRR are not as good simply because of the limited number of data points taken for the averaging. The parameter of interest here is the slope (a). The value of a allows the calculation of HRR at various irradiances, once a pair of known HRR and given irradiance (Y_o, X_o) is available. The HRR (Y) at irradiance (X) is estimated as follows:

$$Y = a(X - X_o) + Y_o \qquad (3)$$

The slopes for the first 5 materials of Table 1 are similar. To generalize the slope of the HRR versus irradiance function, their data were pooled together. Data for FRT plywood were left out because of the uncertainty in their accuracy. Linear regression of the pooled data are shown in Figures 7 and 8. Generally speaking, the data from the two calorimeters are within reasonable agreement. The regression equations are:

Cone Calorimeter:

1 min average HRR:	$Y = 1.31\ X + 86$	**(4)**
5 min average HRR:	$Y = 2.14\ X + 25$	**(5)**

OSU apparatus:

1 min average HRR:	$Y = 1.17\ X + 80$	**(6)**
5 min average HRR:	$Y = 1.66\ X + 56$	**(7)**

The slopes given by these relationships can then be used in Eq. 3 for estimating the HRR.

EFFECT OF DENSITY

Wood varies significantly between species. A subset of the data base having a range of species tested in the vertical orientation at the same 40 kW/m^2 irradiance is summarized in Table 2. In Table 2, the materials are separated into two classes of hardwoods and softwoods and listed in order of average oven dry density. The data base of hardwoods is more substantial than softwoods for the main reason that hardwoods are more commonly used for interior finishes than softwoods. The data in Table 2 are plotted in Figure 9 to examine the effect of density on HRR.

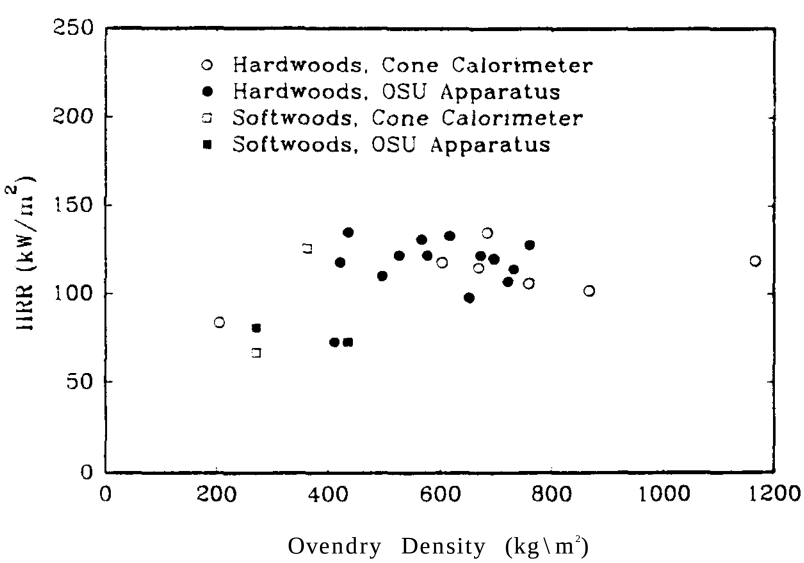

Figure 9. Five-minute average heat release rate at 40kW/m^2 heat flux versus ovendry density.

Table 2
Five-Minute-Average HRR at 40 kW/m² Heat Flux. Vertical Orientation

Material	Density (kg/m³)	Cone calorimeter	OSU apparatus
Hardwoods			
Balsa	205	84	—
Yellow poplar	410	—	73
Aspen	420	—	118
Alder	435	—	135
Red maple	495	—	110
Black ash	525	—	122
Cottonwood	565	—	131
Hackberry	575	—	122
Birch	602	118	—
Sweet gum	615	—	133
Sugar maple	650	—	98
Afromosia	667	115	—
White ash	670	—	122
Rosewood	683	135	—
Hickory	695	—	120
White oak	720	—	107
Beech	730	—	114
Red oak	759	106	128
Purpleheart	867	102	—
Letterwood	1166	119	—
softwoods			
Redwood	271	67	81
White pine	362	126	—
Douglas fir	435	—	73

For the materials in the present data base, density does not appear to have a predictable effect on HRR.

On the assumption that, for the materials in the present data base, density does not affect HRR significantly, a comparison can be made between the values obtained in the two calorimeters. For hardwoods, 300 s average HRR values of the species tested in the vertical orientation at 40 kW/m² (Table 2) are 111 kW/m² with a coefficient of variation of 14% in the Cone Calorimeter, and 117 kW/m² with 14% coefficient of variation in the OSU apparatus. Despite expected problems due to apparatus dependency of HRR data, the results are in within reasonable agreement between the two calorimeters. No conclusion can be drawn for softwoods based on the limited data base.

Quite a few years earlier, the effect of density on HRR was explored by Chamberlain [9]. While the measuring technology available to him was not as refined as that available in the present day, he was, nonetheless able to examine a significantly greater number of wood species, albeit only at a single irradiance of 60 kW/m^2. His findings can be summarized as follows. If the heat release rate $\dot{q}''_o$ is known at a certain density ρ_o, then the heat release rate $\dot{q}''$ at another density, p, is given as:

$$\dot{q}'' = \dot{q}''_o + b(\rho - \rho_0) \tag{8}$$

where b=0.092 for the peak $\dot{q}''$ values, 0.060 for 60 s average values, and 0.102 for 300 s values. This relationship is, of course, limited in that it was not explored for any irradiance values other than 60 kW/m^2.

More generally, the effect of density is related to the chemical composition of wood. As shown in the previous section, the lignin content plays a significant role in the rate of pyrolysis of whole wood. Hardwoods in general have about 23% lignin ± 3% whereas softwoods have about 30% ±3%. Lignin pyrolyses at higher temperatures than the carbohydrate fractions of wood [6]. It is, therefore, expected that woods with higher lignin content would release less heat than those with less lignin under the same heating conditions. A sample of chemical composition of selected hardwoods and softwoods was already given earlier in the Chapter. A complete list of chemical composition of woods from over the world has been documented by Pettersen [7]. However, one cannot estimate HRR based on lignin content alone. For example, several extratives in wood, especially resins in pine species can significantly increase HRR.

EFFECT OF MOISTURE CONTENT

It may be intuitively obvious that increasing the moisture content of a material should act to reduce its HRR. To check and to quantify this assumption, 4 softwood and 4 hardwood materials were tested at 50 kW/m^2 irradiance in the vertical orientation in the Cone Calorimeter to examine the effect of moisture content on HRR. Moisture content is defined as the percentage of mass of water per unit mass of oven dry wood. Tests were done with conditioned wood and oven dry wood. The 60 s and 300 s HRR data are summarized in Table 3 for comparison.

Again, the data show that HRR values of softwoods are generally lower than those of hardwoods, except for southern pine which is rather resinous. The lower values for softwoods is most likely due the effect of higher lignin content. As

Table 3
Average HRR of Conditioned and Oven-dry Wood and Percentage Difference

Material	1 min Average HRR			5 min Average HRR		
	Cond.	Oven-dry	% Diff.	Cond.	Oven-dry	% Diff.
Hardwoods						
Basswood	141	163	16	141	171	21
Yellow poplar	136	159	17	103	156	51
Red oak	134	153	14	113	156	38
Hard maple	133	178	34	125	189	51
Average	136	163	20	120	163	40
softwoods						
Redwood	105	143	36	72	101	40
Red cedar	83	106	28	62	95	53
Spruce	107	117	9	70	92	31
Southern pine	106	140	32	107	154	44
Average	100	126	26	78	110	42

shown in the percent difference between conditioned and the oven dry materials, the effect of moisture content is very significant in HRR of wood products. A 9% moisture content is responsible for about 23% change in the 60 s HRR and 41 % change in the 300 s HRR. The data base is certainly not adequate to characterize the effect of moisture content satisfactorily. However, based on the information available, we propose that an adjustment of 2.59o for the 60 s HRR and 4.590 for the 300 s HRR be made for each 1% change in moisture content. Thus, the following equation is recommended to estimate HRR at moisture content M (in %) if one set of data is available for moisture content MO :

$$\dot{q}''_M = \dot{q}''_o[1 - a(M - M_o)] \tag{9}$$

where a is 0.025 and 0.045 for 60 s and 300 s HRR, respectively.

HEAT OF COMBUSTION

The gross heat of combustion can be obtained in an oxygen bomb calorimeter. White documented some typical heat of combustion values for selected hardwoods and softwoods, both unextracted and extracted of extraneous materials [8]. The heat of combustion obtained was found to depend on lignin content, however, the typical gross heat of combustion averaged around 20 MJ/kg for oven dry wood.

Table 4
Effective Heat of Combustion (MJ/kg) Obtained in OSU Apparatus

Material	28 kW/l^2 irradiance		40 kW/l^2 irradiance		50 kW/l^2 irradiance	
	Actual	Dry	Actual	Dry	Actual	Dry
DF plywood	11.7	13.3	13.1	14.7	13.5	15.1
Redwood	11.7	14.0	12.5	14.2	13.2	14.7
SP plywood	12.4	13.8	13.2	14.8	13.2	14.7
Particleboard	11.0	12.6	12.8	14.2	12.8	14.0
OSB	11.8	13.0	—	—	13.2	14.4
FRT plywood	5.7	6.8	8.0	9.3	7.9	9.1

In fires, the actual heat of combustion observed is not the gross value, measured for complete combustion. Wood degrades by first pyrolyzing, then later charring. During the early, pyrolyzing period, when mostly flaming combustion occurs, the effective heat of combustion is about 13 MJ/kg. After flaming ceases, char oxidation becomes the more dominant mode and heat of combustion would rise to that of carbon (31 MJ/kg). A typical curve of heat of combustion for white pine obtained in the Cone Calorimeter was shown by Janssens [3].

Here, we will focus on the effective heat of combustion during the flaming period, which is of main interest in fire growth. This value can be especially useful since it can be used to crudely calculate the HRR when only the mass loss rate of burning wood material is known. The HRR, then, is simply determined as the product of mass loss rate and effective heat of combustion.

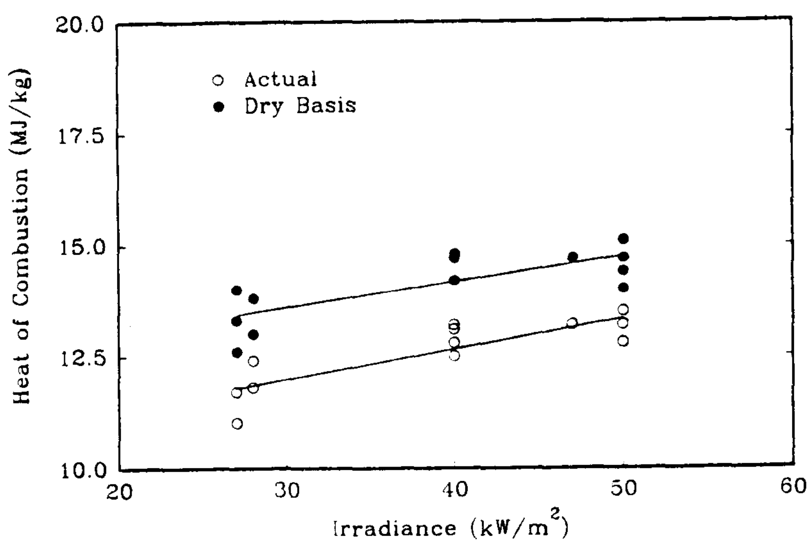

Figure 10. Effective heat of combustion of five materials in OSU apparatus.

In the calorimeter tests, samples are normally weighed before and after test. The total heat release divided by the mass lost gives the average heat of combustion for that burning period. Most tests are terminated soon after the flaming ceases before char oxidation becomes dominant. It is assumed that effective heat of combustion is constant in this period. The effective heat of combustion is complicated by the moisture content in wood, which has been vaporized almost completely when the flaming ceases. For most wood samples, the residual char is about 20% of the original mass. The effective heat of combustion for some materials (Table 1) based on mass loss based on actual and dry mass loss obtained in the OSU apparatus are given in Table 4. Similar data were obtained for the same materials in the Cone Calorimeter within 5% difference. As shown, effective heat of combustion increases with heat flux. Except for the FRT material which has lower heat of combustion, the remaining 5 materials can be grouped together to obtain an average trend. Figure 10 shows average heat of combustion as a function of flux for the 5 materials.

The linear regression of effective heat of combustion for the range of heat flux from 20 to 50 kW/m^2 gave:

Actual basis:

$$\mathbf{Y} = 0.068\ x + 9.95 \qquad (10)$$

Dry Basis:

$$Y = 0.057\ x + 11.88 \qquad (11)$$

where X is heat flux in kW/m^2 and Y is effective heat of combustion (MJ/kg).

ADDITIONAL GUIDELINES

The present data base is not adequate to exhaustively characterize all factors that may affect HRR. However, based on the empirical analysis of the data base, some guidelines are proposed

1. When testing wood products, it is important to measure moisture content, and note any available physical and chemical data.
2. The orientation of sample in testing must be carefully chosen to represent real life application. As a general rule, the horizontal orientation gives 30% higher HRR result than the vetical orientation.
3. To estimate HRR at various irradiances, Eqs. 3 to 7 can be used if one set of data is available.
4. Variations due to density variation may be estimated by using Eq. 8.
5. To estimate HRR at different moisture content if one is known, use Eq. 9.
6. To estimate HRR when only mass loss data is available, use effective heat of combustion from Eqs. 10 and 11.

It should be reemphasized that the variability of wood and wood products is high. It is still the best procedure to actually test the materials using reliable calorimeters. The guidelines provide help to fill in the gaps where data are not readily available.

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