

# Rates of Heat and Smoke Release of Wood in an Ohio State University Calorimeter\*

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Particleboard, Douglas fir plywood and red oak were tested for heat and smoke release rates under different heat flux levels, piloted and unpiloted conditions, and vertical and horizontal orientations in an Ohio State University calorimeter. The chamber was instrumented to obtain heat release data by both the standard thermal and oxygen consumption methods simultaneously. Heat and smoke release data obtained by both methods are reported. The heat release rates by the thermal method are consistently lower than those by the oxygen consumption method. Variability in results is consistently lower using the oxygen consumption method. The heats of combustion calculated by oxygen consumption are close to those calculated from measurements with the oxygen bomb. The heat release rates measured on particleboard using the standard thermal method are in agreement with measurements on the same material in other Ohio State University calorimeters.

## INTRODUCTION

The concept of heat release rate (HRR) calorimetry has been widely accepted in the fire research community as a method of evaluating the degree of combustibility of a material. A number of heat release calorimeters that have been developed at various locations are based on different concepts and principles.

Brenden<sup>1</sup> used a heat release calorimeter, developed at the Forest Products Laboratory (FPL), to evaluate heat release properties of some wood-based materials. Chamberlain<sup>2</sup> reviewed the calorimeters available at the time and reported heat release characteristics of various wood products using different National Bureau of Standards (NBS) calorimeters. Since the work by Chamberlain in 1982, little research has been published on HRR of wood materials, and the calorimeters used by Chamberlain have become obsolete. A database of HRR information using currently accepted calorimeters needs to be established. At FPL, we currently use an Ohio State University (OSU) heat release chamber (also called OSU calorimeter).

The design and operation of the OSU chamber are described by Smith<sup>3</sup> and also in the American Society for Testing and Materials (ASTM) E 906 standard.<sup>4</sup> According to this standard, airflow, at a fixed rate, is split so that a fraction is directed to the bottom of the chamber where it flows upward, past the specimen and out of the stack. The remaining airflow is directed to the air jacket around the upper cone section of the chamber to recover heat that is absorbed by the upper part of the chamber. The HRR from a sample is measured using the sensible heat method, by response of a thermopile. The HRR is assumed to be proportional to the temperature rise of the

fire gases leaving the stack. Smoke release rate (SRR) is quantified by optical density measurement of smoke flow out of the stack.

Many modifications to the OSU chamber have been made to obtain rate of heat release using the oxygen consumption method. This method is based on the principle that heat release is proportional to the amount of oxygen consumed. Huggett<sup>5</sup> documented that for most materials the proportionality constant is  $13.1 \text{ kJ g}^{-1}$  within  $\pm 5\%$  accuracy of oxygen consumed. Thus, by measuring the amount of oxygen depleted, the amount of heat release can be calculated. Krause and Gann<sup>6</sup> elongated the chamber stack to allow complete mixing of the air split between the internal flow and the airflow around the upper part of the chamber. They also reduced the total airflow rate to increase the oxygen concentration changes. Habrauskas<sup>7</sup> modified the operation of the chamber by allowing air to flow through the bottom of the chamber only and eliminated the airflow to the top section of the chamber. Ostman and others<sup>8</sup> used the same approach as Babrauskas. Discrepancies of 20–30% between the standard thermal and the oxygen consumption methods were observed.<sup>6-8</sup>

In this study, the OSU apparatus was instrumented to obtain HRR values using the oxygen method and the standard thermal method simultaneously. Heat and smoke release rates of some wood products were obtained at different heating fluxes and under different ignition conditions.

## EXPERIMENTAL PROCEDURES

### Instrumentation

We installed an OSU chamber following the ASTM E 906 standard. Constant airflow of  $40 \text{ l s}^{-1}$  was supplied to the chamber by a blower. To measure oxygen concentration, a paramagnetic oxygen analyzer was used. To

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avoid dilution of the combustion gases, the oxygen probe was placed in the inside shell of the chamber 15.5 in below the top of the stack. In this position, the probe was low enough to sample combustion air before it mixed with the cooling air passing around the air jacket. Also, preliminary studies with a methane flame showed that good mixing of combustion gases was obtained at the probe.

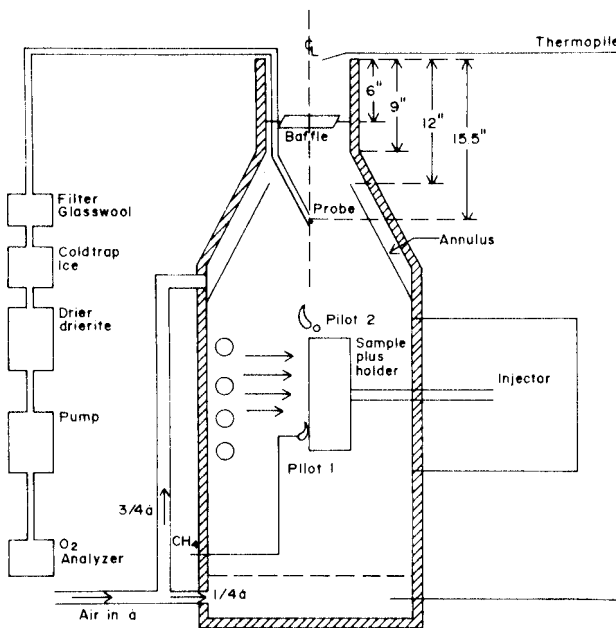
The sampled air was filtered, cooled in a cold trap and scrubbed of water before being analyzed. Carbon dioxide was not removed. The equipment setup is shown in Fig. 1.

The vertical runs were conducted following standard procedures. For the horizontal runs, we used a stainless steel reflector, 0.05 in thick, instead of the foil recommended by the ASTM standard, because the foil does not retain its shape and would require frequent changing.

Using a personal computer, the signals from the thermopile, oxygen analyzer, smoke detector, airflow meter and thermocouples monitoring the incoming and stack air were recorded every 3 s. The millivolt signal from the thermopile was amplified and recorded as a percentage of an arbitrary scale.

### Calibration

The radiant heat was controlled by regulating the power input to the four Globar\* heater elements. The radiant heat flux to the specimen was measured using a Hy-Cal total heat flux gauge for the vertical specimens and a Hy-Cal pyrheliometer for the horizontal specimens. The heat



ML88 5444

**Figure 1.** The Ohio State University calorimeter with oxygen measurement (not to scale). (ML88 5444)

\* The use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service. Available from the Carborindum Co., Globar Division, Niagara Falls, NY, USA.

flux gauges have view angles of 180°. The heat flux gauges were situated at the center of corresponding samples.

Heat release response factors  $K$  for the thermopile were obtained using a methane diffusion flame following the standard ASTM E 906 procedure. Square waves of heat input were obtained by quickly varying the methane flow rate between 0.1 and 0.5 stdft<sup>3</sup> min<sup>-1</sup>, corresponding to 1.58 and 7.92 kW of net heat release, respectively. The thermopile response difference between the low and the high methane flow rate divided into 6.34 kW determined the response factor  $K$ . We found that  $K$  increased with the radiant heat flux to the vertical specimen: the hotter the chamber, the less responsive the thermopile (Fig. 2).

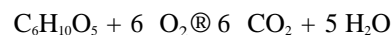
For a fixed heat flux from the Globars,  $K$  was found to vary also with the heat release rate. A methane flame was varied at increments of 0.1 stdft<sup>3</sup> min<sup>-1</sup> (1.58 kW of net HRR). The recorded response of the thermopile at 35 kW m<sup>-2</sup> of flux setting is shown in Fig. 3. From the response of the thermopile,  $K$  values for different increments in HRR were constructed (Fig. 4). Note in Fig. 4 that the  $K$  value increases with increasing HRR level. This indicates that by using the  $K$  values determined by the standard method we may overestimate HRR of low heat-releasing materials by as much as 10%.

### Oxygen consumption calculations

As mentioned, water was scrubbed from the sample gas. Carbon dioxide was not scrubbed because it was difficult to tell when the base (Ascarite) was exhausted, and the scrubber tended to clog the line. We decided to leave carbon dioxide in the sample gas and use the following assumptions in our calculation.

In complete combustion, the stoichiometric relations for wood and its carbohydrate fractions are as follows:

Cellulose:



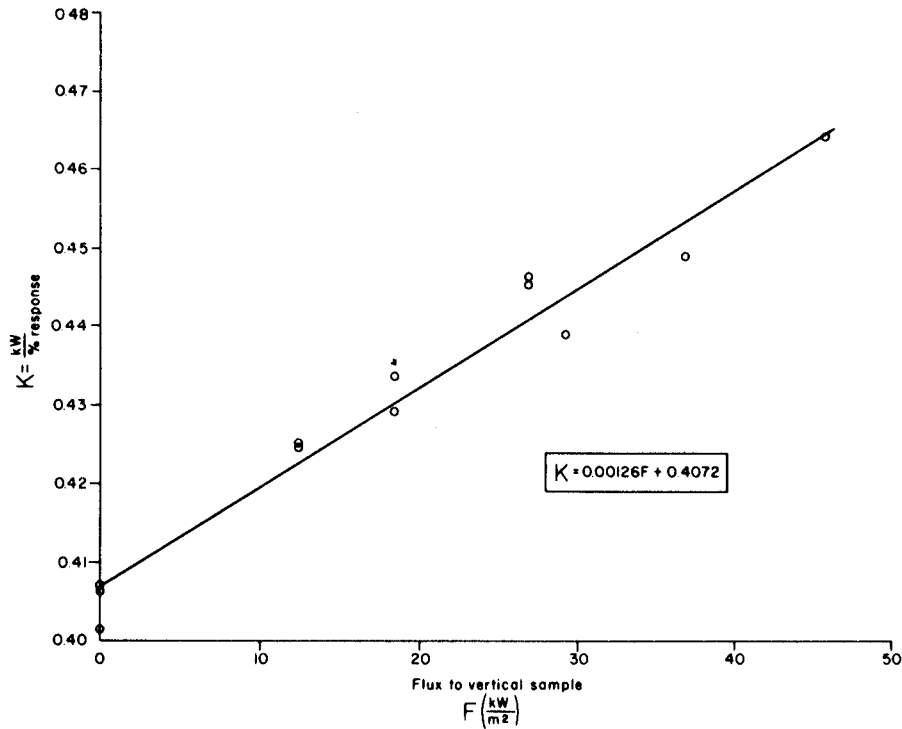
Hemicellulose:



Wood:

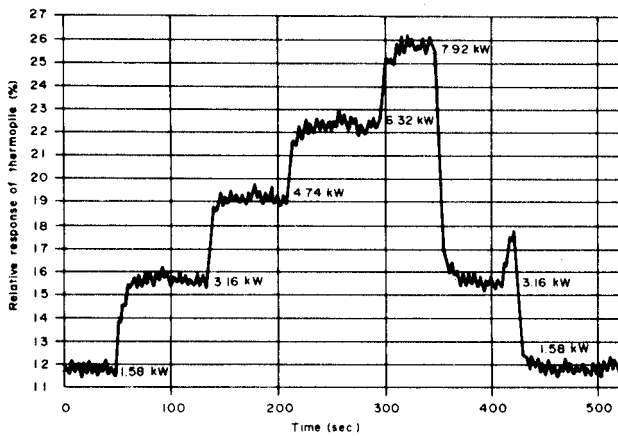


For every mole of oxygen consumed, there is about 1 mole of carbon dioxide produced. Thus, we can assume a constant flow of noncondensable gases through the chamber. The oxygen concentration measured by the analyzer is proportional to molar flow rate of oxygen in the stack. Using this simplification, assuming an HRR of 13.1 kJ g<sup>-1</sup> of oxygen consumed (as suggested by Huggett<sup>5</sup>) and the known flow rate of air into the chamber, we then calculated the HRR values of the materials. This assumption may not be accurate for incomplete combustion because the stoichiometry of combustion is not known. Data obtained by Nakaya<sup>9</sup> on yield rate of carbon dioxide and depletion rate of oxygen in compartment fires using wood fuel confirmed that this assumption is valid for a wide range of wood fuel/air equivalent ratios. Note that this assumption may be acceptable for wood, but is not always useful for other materials.



ML88 5445

Figure 2. Relative response of the thermopile ( $K$ ) as a function of heat flux ( $F$ ). (ML885445)



ML88 5446

Figure 3. Relative response of the thermopile as a function of a methane flame. (ML88 5446)

**Materials**

Particleboard, Douglas-fir plywood and red oak were used (Table 1). The particleboard was provided by Weyerhaeuser Company for between-lab comparison. The composition of this particleboard is not known and immaterial. For Douglas-fir plywood and red oak, the vertical specimens were  $6 \times 6 \times \frac{3}{8}$  in. For the horizontal runs, only plywood was used. Samples were  $6 \times 4 \frac{3}{8} \times \frac{3}{8}$  in.

The specimens were preconditioned at 25°C and 50% relative humidity.

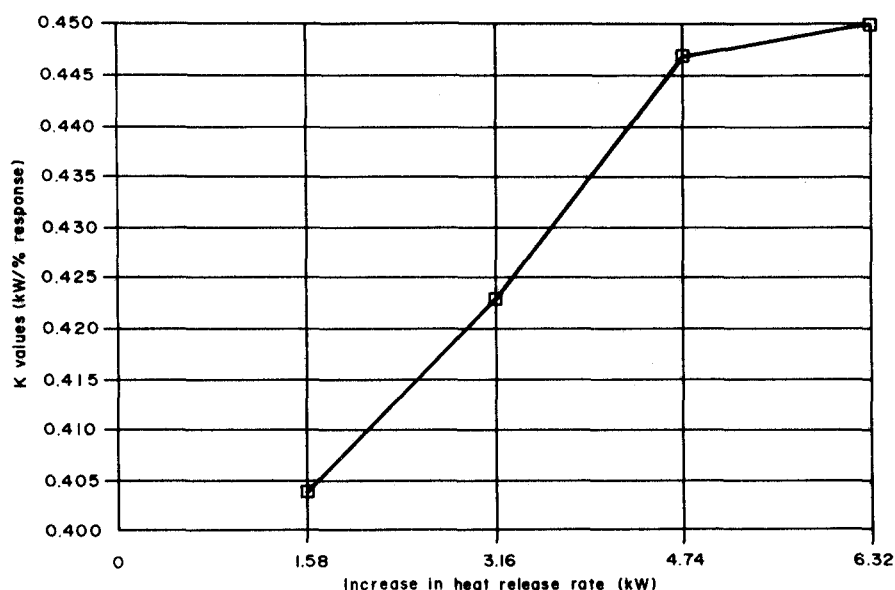
**Test conditions**

Particleboard was tested at only one flux level ( $35 \text{ kW m}^{-2}$ ). This same material was used to compare our instrument with three other similar OSU chambers in other organizations.

Plywood and red oak were run at three flux levels and under both piloted and unpiloted conditions. Plywood was tested at  $25 \text{ kW m}^{-2}$  in the horizontal orientation to compare with the vertical situation. The typical number of replicates was three for plywood and two for red oak, except for a few cases where additional runs were conducted to verify the operating conditions. The test conditions are summarized in Table 2.

In the piloted and vertical mode, a premixed methane pilot flame impinged on the specimen, and three methane diffusion flames above the specimen were used to ensure complete combustion of volatiles. In the piloted horizontal mode, only the premixed methane flame was used.

Each specimen was mounted in a holder as specified in ASTM E 906. It was wrapped in two layers of foil, backed by 0.5-in layer of Kaowool insulation. The holder was mounted on a shaft and injected into the chamber. Before injecting the specimen, the computer data acquisition was initiated for 45 s to obtain baselines for the thermopile, the oxygen analyzer and the smoke meter. For each specimen, the specimen plus the holder were weighed before and after each run to determine weight changes.



ML88 5447

Figure 4. K values as a function of heat release rate (HRR). (ML88 5447)

Table 1. Wood materials tested

Material	Size (in)	Mean	Weight (g)		Average moisture content (%)
			Standard deviation	Average	
Particleboard	6 x 6 x $\frac{1}{2}$	209.4	4.4		7.63
Douglas-fir plywood	6 x 6 x $\frac{3}{8}$	119.8	5.0		7.76
Red oak	6 X 6 x $\frac{3}{8}$	154.7	5.6		6.80

## RESULTS AND DISCUSSION

The HRR values obtained by the thermal and oxygen methods were calculated from the responses recorded on the computer. The results are reported in kilowatts per square meter of exposed surface area and as a function of time starting from injection. The areas beneath the HRR curves were integrated to give cumulative heat release expressed in megajoule per square meter as a function of exposure time. The SRR values were calculated using the procedure outlined in ASTM E 906 standard and reported in  $SMOKE\ min^{-1}$  per square meter. By integrating the areas under the SRR curves, the cumulative smoke release (SR) is reported in  $SMOKE$  per square meter units. The definition of  $SMOKE$  is given in the ASTM E 906 standard.<sup>4</sup>

In the piloted mode, most specimens exhibit a first peak of heat release when the surface of the specimen is enveloped in flame. This maximum is normally reported as characteristic of the tested material.

### Particleboard testing

Three piloted and three unpiloted runs were conducted on the particleboard specimens at a heating flux of

Table 2. Test conditions

Species	Orientation <sup>a</sup>	Irradiance (kWm <sup>-2</sup> )	Mode <sup>b</sup>	Number of replicates
Particleboard	V	35	P	3
			U	3
			P	3
Douglas-fir plywood	V	25	U	3
			P	6
			U	6
		45	P	3
			U	3
			P	6
Red oak	V	25	U	2
			U	2
			P	2
		35	U	2
			P	2
			U	2

<sup>a</sup>V denotes vertical; H horizontal.

<sup>b</sup>P denotes piloted; U unpiloted.

35 kWm<sup>-2</sup>. The HRR values obtained from the three piloted runs by the thermopile method were almost identical with those obtained at Weyerhaeuser Company, Boeing and OSU. This agreement indicated that our apparatus was operating in accordance with other extensively used chambers. To evaluate repeatability between tests, the triplicate results with particleboard are compared in Table 3.

For the piloted runs, the mean maximum HRR of particleboard by the standard thermal method is 150 kWm<sup>-2</sup> at about 83s after sample injection. The cumulative heat release at 10 min is about 58 MJm<sup>-2</sup> with a coefficient of variation (COV) of 2.4%. For this particleboard, which is fairly uniform, the repeatability

**Table 3. Particleboard results from standard thermal method evaluating repeatability**

Result	Unit	Mean of triplicates	Coefficient of variation (percentage of mean)
<i>Piloted condition, 35 kW m<sup>-2</sup></i>			
Maximum HRR <sup>a</sup>	kW m <sup>-2</sup>	150.0	0.0
Time of maximum HRR	S	83.3	6.9
HRR			
1 min	kW m <sup>-2</sup>	126.7	9.1
3 min		110.0	7.9
5 min		82.3	3.1
10 min		118.3	2.4
HR <sup>b</sup>			
1 min	MJ m <sup>-2</sup>	2.2	15.7
3 min		17.6	3.9
5 min		29.2	2.4
10 min		58.2	1.8
Maximum SRR <sup>c</sup>	SMOKE min <sup>-1</sup> m <sup>2</sup>	40.8	9.4
Time of maximum SRR	S	90.0	0.0
SRR			
1 min	SMOKE min <sup>-1</sup> m <sup>2</sup>	20.0	0.0
3 min		9.3	12.4
5 min		2.0	50.0
10 min		15.0	13.3
SR <sup>d</sup>			
1 min	SMOKE m <sup>-2</sup>	5.0	20.0
3 min		53.3	7.8
5 min		59.7	8.4
10 min		93.3	11.1
<i>Unpiloted condition, 35 kW<sup>2</sup> m<sup>-1</sup></i>			
Maximum HRR	kW m <sup>-2</sup>	NA <sup>e</sup>	NA
Time of maximum HRR	S	NA	NA
HRR			
1 min	kW m <sup>-2</sup>	-6.7	22.9
3 min		3.7	87.7
5 min		3.7	95.8
10 min		10.0	43.6
HR			
1 min	MJ m <sup>-2</sup>	-0.5	34.6
3 min		-0.3	100.0
5 min		0.3	200.0
10 min		2.8	61.9
Maximum SRR	SMOKE min <sup>-1</sup> m <sup>2</sup>	50.0	17.3
Time at maximum SRR	S	170.0	10.2
SRR			
1 min	SMOKE min <sup>-1</sup> m <sup>2</sup>	-2.7	173.2
3 min		38.3	7.5
5 min		3.3	45.8
10 min		3.0	120.2
SR			
1 min	SMOKE m <sup>-2</sup>	-4.3	93.3
3 min		45.0	33.3
5 min		79.7	12.6
10 min		86.7	22.4

<sup>a</sup>HRR heat release rate  
<sup>b</sup>HR cumulative heat release  
<sup>c</sup>SRR smoke release rate  
<sup>d</sup>SR cumulative smoke release  
<sup>e</sup>NA no apparent maximum

between samples is excellent. The maximum SRR was 40.8 SMOKE min<sup>-1</sup> m<sup>2</sup> at 90s after injection. The COV of smoke measurement is much higher than heat release (cumulative SR at 10 min has a COV of 11.1%). One explanation of this large variation is the stack configuration, which allows smoke to come out without confining

it to a fixed light path. The light path is taken as the stack width, which sometimes is much different from the actual smoke light path.

In the unpiloted mode, there was no apparent peak of heat release because the specimens did not ignite. There were some initial heat losses (negative heat release)

followed by slow rates of heat release. Because of small levels of heat release, the COV values are high. Variability of smoke measurement was generally high.

The HRR values of particleboard at  $35\text{ kW m}^{-2}$  of heating flux under piloted conditions obtained by both methods are shown in Fig. 5. The methods differed consistently by 20--30%.

### Effect of flux and ignition mode on the heat release of Douglas-fir and red oak

Heat release data of representative runs (smoothed) obtained by the standard thermal method are used to demonstrate qualitatively the effect of flux and ignition mode on HRR values. Figure 6 shows HRR values and cumulative heat release of Douglas-fir plywood under piloted and unpiloted conditions. Figure 7 shows those of red oak. Under piloted conditions, a higher maximum HRR was reached sooner with a higher heating flux (Figs 6(a) and 7(a)). Cumulative heat release is also higher for higher heating flux (Figs 6(b) and 7(b)). Under unpiloted conditions, ignition is definitely a function of heat flux. For Douglas-fir plywood, ignition times were about 12, 7 and 1 min with no pilot for heat fluxes of 25, 35 and  $45\text{ kW m}^{-2}$ , respectively (Figs 6(c) and 6(d)). For red oak, the specimens did not ignite at  $35\text{ kW m}^{-2}$  heating flux and below. At  $45\text{ kW m}^{-2}$ , red oak ignited within 2 min from the beginning of the exposure (Figs 7(c) and 7(d)).

Also note that there is a second peak, which is associated with the insulated rear surface. The insulation caused a heat buildup within the specimen that increased the rate of pyrolysis. Another explanation is the involvement of the back surface in flaming combustion. For most purposes, HRR in the first 5 min of exposure is characteristic of the materials. The HRR in the later part of the curve is a function of the thermal thickness of the specimens and should be ignored, unless the test is specifically designed for that kind of information. In our tests, the rear insulation effect was observed at 5 min at  $45\text{ kW m}^{-2}$  of heating flux. To observe the effects of flux levels, we tabulated maximum HRR values and the

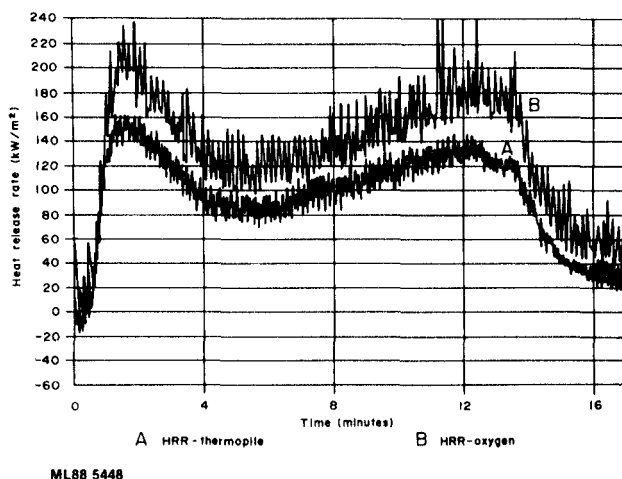


Figure 5. Heat release rate of Weyco particleboard at  $35\text{ kW m}^{-2}$  of heat flux under piloted, vertical conditions. (ML88 5448)

cumulative heat release at 5 min, obtained by both methods, as well as the maximum SRR values and cumulative SR at 5 min of exposure (Table 4).

We observed a definite difference between the heat release data generated by the two methods (Table 4). The discrepancies range from 20% to 35%, with the oxygen depletion method normally generating higher values for maximum HRR and HRR at 5 min. Variation in results was generally lower for oxygen depletion. This difference was observed earlier by Krause and Gann,<sup>6</sup> Babrauskas<sup>7</sup> and Ostman and others.<sup>8</sup> There is a consistent trend that the higher the heat flux, the higher the maximum HRR and cumulative heat release. Note that Douglas-fir plywood in the horizontal orientation has a substantially higher HRR peak but almost the same cumulative heat release by 5 min when compared to the vertical specimens at the same flux of  $25\text{ kW m}^{-2}$ . The difference in peak HRR values between the orientations is consistent with results obtained from the NBS Cone Calorimeter.<sup>8</sup>

In contrast, SR variations are less predictable. There is a general trend that cumulative SR increases with heating flux under both piloted and unpiloted conditions. The first peak of SR is not as consistent as that of heat release and cannot be used to characterize the wood materials. The cumulative SR data are inconsistent with respect to which condition (piloted or unpiloted) produces more smoke. We concluded that, because of the configuration of the stack, the smoke measurement is not very reproducible. Also, the SRR sometimes became negative. Our smoke system may have malfunctioned, therefore smoke data were suspect.

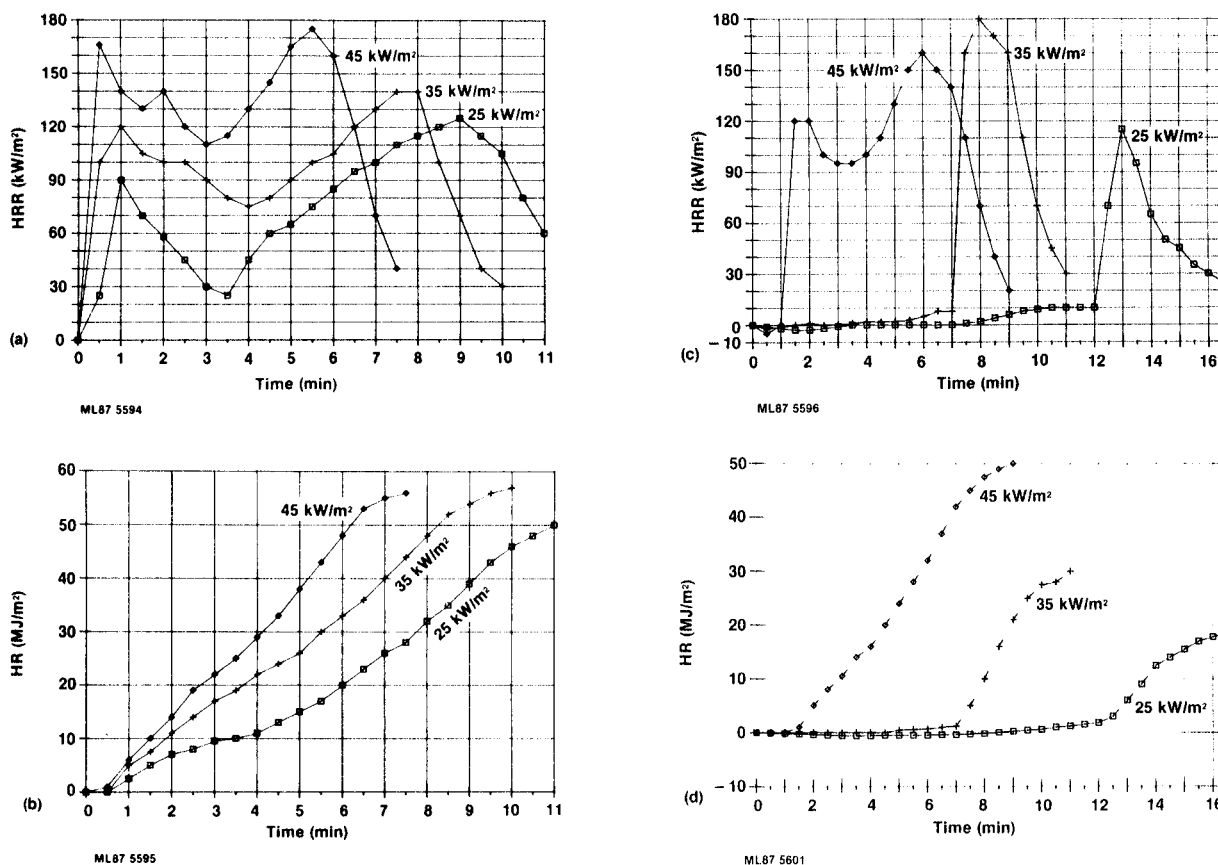
### Heat of combustion analysis

To gain more confidence in the heat release measurement we conducted an analysis to estimate heat of combustion of the specimens based on the heat release data obtained. In the tests the specimens were withdrawn from the chamber when they were reduced to a glowing char and HRR had dwindled to a very low value (Fig. 5). The residual char weight was derived from the original specimen weight minus the mass loss, which is the difference between the weights of the specimen and holder before and after the test. In most of the tests, the char weight constituted about 15--25% of the original oven-dry weight.

Using the average moisture contents of the various species we calculated the oven-dry weights of the original specimens and the amounts of water present. We then calculated the oven-dry mass losses based on the original oven-dry weights and the dry char residues.

The following assumptions were made to complete the analysis:

- (1) The char residue is bone dry. This assumption is good because the holder and residues were weighed hot to avoid moisture pickup by the char.
- (2) All char residues have a net heat of combustion of  $11,387\text{ Btu lb}^{-1}$  or  $26.53\text{ MJ kg}^{-1}$  as determined by Brenden and Chamberlain.<sup>11</sup>
- (3) In the standard thermal method, part of the heat of combustion of the volatiles was used to evaporate the moisture in the wood. Thus, the heat of combustion must be corrected using heat of vaporization of water



**Figure 6.** Data from Douglas-fir plywood at different fluxes using the standard thermal method. (a) Heat release rate and (b) cumulative heat release under piloted conditions; (c) heat release rate and (d) cumulative heat release under unpiloted conditions. (ML87 5594, ML87 5595, ML87 5596, ML87 5601)

of 2.25 MJ kg<sup>-1</sup>. The measured heat release by the oxygen consumption method is the total chemical energy of combustion and is not affected by moisture in wood.

For the oxygen consumption method the average heat of combustion of the volatiles was obtained by the total heat release accumulated over each run (megajoules) divided by the oven-dry mass loss. Prior to the division, the heat release by the thermal method was corrected by adding the heat to vaporize the moisture in the wood. To determine the average heat of combustion of wood, the total heat release of the volatiles is added to the heat content of the char and divided by the original oven-dry wood.

Table 5 summarizes the average heat of combustion of volatiles (corrected for moisture content for the thermal method) and the calculated heat of combustion of wood for the piloted runs. We only used the piloted runs because complete combustion is approached. The heats of combustion of volatiles and of whole wood obtained by the standard thermal method are always lower than those by the oxygen method (Table 5). Heats of combustion of Douglas-fir plywood range from 15.2 to 16.1 MJ kg<sup>-1</sup> in vertical tests by the thermal method compared to a range of 17.8–21.1 MJ kg<sup>-1</sup> by the oxygen method. Red oak results are 14.9–16.9 MJ kg<sup>-1</sup> and 18.1–22.0 MJ kg<sup>-1</sup> for

the thermal and oxygen methods, respectively. We cannot explain why, but both the thermal and oxygen methods gave very low heats of combustion for Douglas-fir plywood in the horizontal orientation.

Literature values of gross heat of combustion of Douglas-fir and red oak are 21.8 and 21.4 MJ kg<sup>-1</sup>, respectively. These are high-heating values and therefore must be corrected to net heating values (water resulting from combustion did not condense in the chamber). For wood with a formula of C<sub>1.7</sub>K<sub>2.5</sub>O, about 1.3 MJ kg<sup>-1</sup> of that wood evaporates the water. Thus, the net heating values of Douglas-fir and red oak are about 20.5 and 20.1 MJ kg<sup>-1</sup> of oven-dry wood. Compared to the values in Table 5, the oxygen method gave better agreement with heat of combustion of whole wood than the thermal method.

## CONCLUSIONS

In this study we obtained HRR values by using both standard thermal and oxygen consumption methods simultaneously. In our apparatus the rates of heat release by both methods are quite reproducible for the same wood materials but smoke measurements are less so. Maximum rates of heat release and cumulative heat

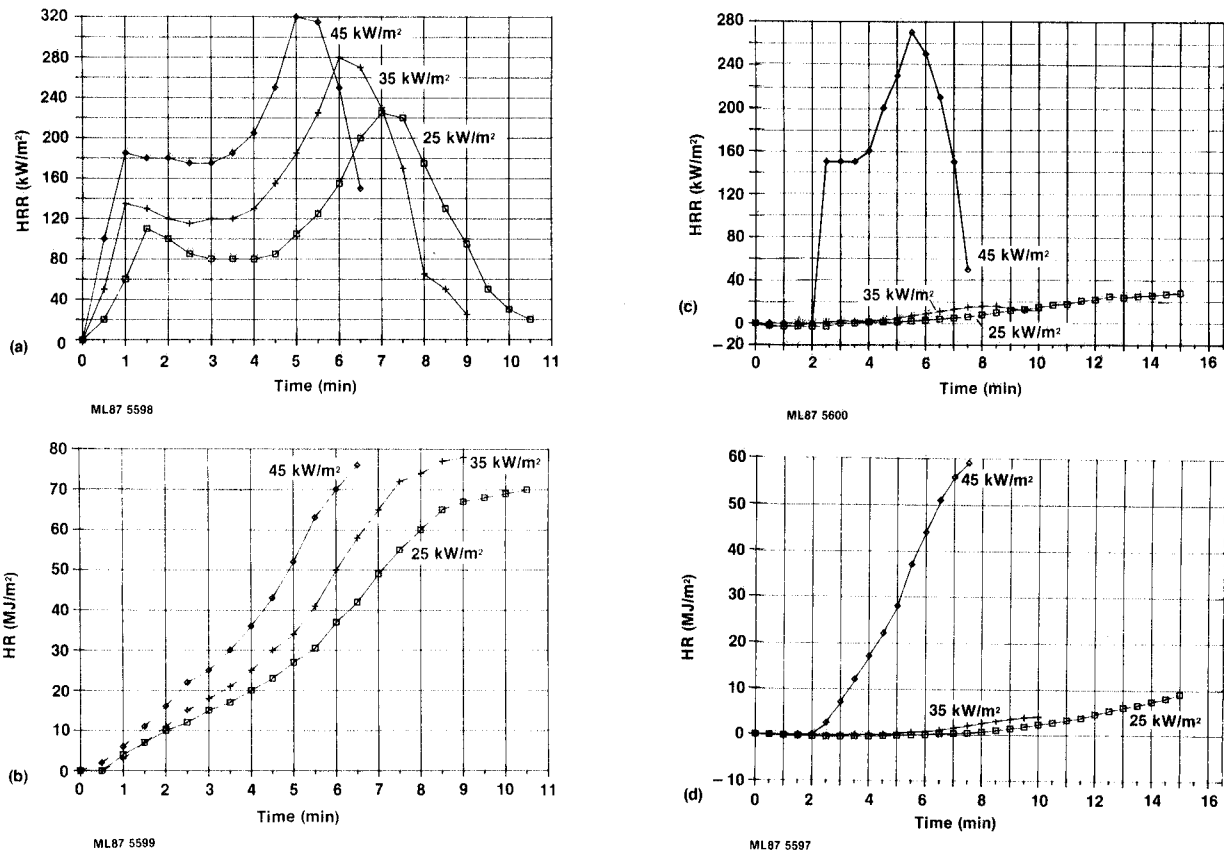


Figure 7. Data from red oak at different fluxes using the standard thermal method (a) Heat release rate and (b) cumulative heat release under piloted conditions, (c) heat release rate and (d) cumulative heat release under unplotted conditions (ML87 5598, ML87 5599, ML87 5600, ML87 5597)

Table 4. Means and coefficients of variation of heat and smoke release

Material	Mode <sup>a</sup>	Flux (kW m <sup>-2</sup> )	Heat release												
			Thermal method						Oxygen method						
			Maximum HRR <sup>b</sup> (kW m <sup>-2</sup> )		HR (5min) <sup>c</sup> (MJm <sup>-2</sup> )		Maximum HRR (kW m <sup>-2</sup> )		HR (5-min) MJm <sup>-2</sup>		Smoke release				
			Mean	COV <sup>f</sup>	Mean	COV	Mean	COV	Mean	COV	Maximum SRR <sup>d</sup> Maximum SRR <sup>d</sup>	COV	SMOKE <sub>min</sub> <sup>e</sup> SR (5min) <sup>e</sup>	COV	
Particleboard	V, P	35	150.0	0	29.2	2	211.5	3	41.9	3	40.8	9	59.7	8	
	V, U	35	NA <sup>g</sup>		0.3	200	NA		33	24	50.0	17	79.7	13	
	Douglas-fir plywood	H, P	25	120.0	11	19.1	9	173.8	9	23.1	4	43.0	13	66.0	55
	H, U	25	NA		4.0	73	NA		56	50	NA	NA	31.0	64	
	V, P	25	88.3	3	15.5	12	116.5	10	22.9	5	NA	NA	11.0	24	
	V, U	25	NA		-0.3	67	NA		2.2	81	NA	NA	47.3	14	
	V, P	35	145.7	9	24.9	14	207.9	6	35.8	13	24.3	23	30.0	41	
	V, U	35	NA		0.6	130	NA		27	5	37.3	30	88.0	17	
	V, P	45	163.3	5	38.0	5	252.7	6	54.8	2	39.0	4	125.0	14	
	V, U	45	113.3	26	25.0	7	220.4	9	38.3	11	38.0	27	81.7	34	
	Red oak	V, P	25	112.5	3	23.5	3	142.5	3	31.2	5	NA	NA	19.0	30
	V, U	25	NA		-0.4	35	NA		3.5	120	NA	NA	7.5	47	
	V, P	35	135.0	0	34.0	0	185.5	2	44.1	0	18.0	16	44.5	8	
	V, U	35	NA		0.1	141	NA		2.4	9	NA	NA	87.5	12	
	V, P	45	187.5	6	53.7	3	258.0	0	69.4	5	42.5	8	157.0	15	
	V, U	45	155.0	— <sup>g</sup>	28.0	—	193.5	—	—	—	40.0	—	120.0	—	

<sup>a</sup> V denotes vertical orientation; H horizontal orientation; P piloted; U unplotted conditions.

<sup>b</sup> HRR: heat release rate.

<sup>c</sup> HR: cumulative heat release.

<sup>d</sup> SRR: smoke release rate.

<sup>e</sup> SR: cumulative smoke release.

<sup>f</sup> COV: coefficient of variation.

<sup>g</sup> NA: no apparent first peak associated with front surface combustion.

—: no data available.



**Table 5. Heat of combustion analysis, means and coefficients of variation (piloted condition)**

Material	Mode <sup>a</sup>	Flux (kWm <sup>-1</sup> )	Thermal method				Oxygen method			
			Heat of combustion of volatiles (MJkg <sup>-1</sup> )		Heat of combustion of wood		Heat of combustion of volatiles (MJkg <sup>-1</sup> )		Heat of combustion of wood	
			Mean	COV <sup>b</sup>	Mean	COV	Mean	COV	Mean	COV
Particleboard	V	35	12.9	3.2	16.0	2.0	18.2	2.4	20.0	2.0
Douglas-fir	H	25	9.6	4.7	11.2	6.8	10.0	— <sup>c</sup>	12.4	— <sup>c</sup>
plywood	V	25	12.3	11.5	15.2	7.0	15.5	6.4	17.8	4.4
	V	35	13.2	3.0	16.0	2.1	18.5	9.9	20.2	7.3
	V	45	13.3	5.0	16.1	3.2	19.6	5.0	21.1	3.6
Red oak	V	25	12.2	0.3	14.9	0.6	16.1	2.3	18.1	1.9
	V	35	12.6	1.3	15.2	0.6	16.6	0.6	18.4	0.3
	V	45	14.0	13.3	16.9	2.4	20.8	19.2	22.0	15.8

<sup>a</sup>V denotes vertical; H horizontal

<sup>b</sup>COV: coefficient of variation.

<sup>c</sup>—: inadequate data.

release are functions of heating flux and can be used to characterize wood. In this study we did not look at other variables that influence heat release characteristics of wood, such as moisture content, density and chemical composition. A larger database is needed to establish these relationships.

The standard thermal method gave results 20–35% lower than those by the oxygen consumption method. An analysis of heat of combustion indicates that the oxygen method is in agreement with literature values of the heat of combustion of wood. This observation supports the criticism that the standard thermal method fails to account for all the heat release.

There are two possible explanations of the discrepancy between the standard thermal and the oxygen consumption methods:

- (1) Heat was absorbed by the holder and was lost to the shaft by conduction.
- (2) Radiation heat losses from the surface of the burning specimen are not present when the methane burner is used for calibration. The calibration only addresses radiation losses of the flames, assuming that methane and wood flames have similar emissivities.

Heat absorbed by the holder is much smaller than the 20–35% difference. We plan to quantify the radiation heat losses from the surface of the burning specimen.

One major feature of the OSU chamber, which makes it very convenient to convert to the oxygen consumption method, is the known and constant flow rate of air into the chamber. This feature makes the calculations much simpler than when flow rates have to be measured in the stack and corrected for temperature and increased molar flow because of chemical reaction, as in a free-burning configuration. The calculations can be further simplified by scrubbing carbon dioxide from the sample gas and using the constant flow rate of nitrogen as the tie component. Then it is no longer necessary to assume that the drop in oxygen concentration is balanced by an equal increase in the carbon dioxide concentration. Another alternative is to measure the carbon dioxide and figure it in the calculations.

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### REFERENCES

1. J. J. Brenden, Wood-based building materials: rate of heat release. *J. Fire Flammability* **6**, 274–93 (1975).
2. D. L. Chamberlain, Heat release rate properties of wood-based materials. US department of Commerce, Center for Fire Research, *NBSIR 82-2597* (1982).
3. E. E. Smith, Release rate tests and their application. *J. Fire Flammability* **8**, 309–23 (1977).
4. Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products. Test Method E 906-83, American Society for Testing and Materials, Philadelphia, PA (1985).
5. C. Huggett, Estimation of rate of heat release by means of oxygen consumption measurements. *Fire and Materials* **4** (2), 61–5 (1980).
6. R. A. Krause, Jr, and R. G. Gann, Rate of heat release measurements using oxygen consumption. *J. Fire Flammability* **12**, 117–30 (1980).
7. V. Babrauskas, Comparative rates of heat release from five different types of test apparatuses. *J. Fire Science* **4**, 148–9 (1986).
8. E. A. L. Östman, I. G. Svenson and J. Blomquist, Comparison of three test methods for measuring rate of heat release. *Fire and Materials* **9** (4), 176–84 (1985).
9. I. Nakaya, Prediction model of CO, CO<sub>2</sub>, and O<sub>2</sub> concentrations in compartment fires using wood fuel. *Fire and Materials* **11**, 173–8 (1987).
10. J. J. Brenden and D. L. Chamberlain, Heat release rates from wall assemblies. *Res. Pap. FPL-RP-476*, US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI (1986).
11. P. J. Ince, How to estimate recovery heat energy in wood or bark fuels. *Gen. Tech. Rep. FPL 29*, US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI (1979).