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MODIFICATIONS TO AN OHIO STATE UNIVERSITY APPARATUS AND COMPARISON WITH CONE CALORIMETER RESULTS

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ABSTRACT

We modified an Ohio State University (OSU) heat release apparatus to obtain piloted ignition data and heat release rate (HRR) using the oxygen Consumption method. To monitor deviation from the baseline heat flux to the sample during a test, an auxiliary heat flux meter was added to the OSU apparatus. The heat flux measured was the incident flux from the radiant panel and did not include flame flux. To obtain time to ignition, the gas phase was ignited with a pilot above the specimen. Six wood materials used in a series of room fire tests were tested at three different heating flux levels. The same materials are being tested in a Cone Calorimeter and the LIFT apparatus, but only data on Douglas-fir plywood were available for this paper. Ignition data from the three methods were in good agreement. Comparison of HRR between the OSU apparatus using the oxygen consumption technique and the Cone Calorimeter showed encouraging results. Good agreement was obtained for the first and second peaks of heat release. In the intermediate phase, the OSU apparatus gave higher HRR. Average heat of combustion was also slightly higher with the OSU apparatus. Experiments with a Cone Calorimeter holder in the OSU apparatus also showed higher heat release in the intermediate phase than in the Cone Calorimeter. The backing affected only the second peak of heat release. The difference in the intermediate phase was most likely due to the heating environment of each apparatus.

INTRODUCTION

In a joint effort to develop and validate a model for compartment fire growth, the Forest Products Laboratory (FPL) and the National Forest Products Association (NFPA) are evaluating some wood products in both bench-scale and full-scale wall/corner tests. As part of this study, bench-scale tests are conducted to provide input data to the model. The full-scale test data will then be compared with model predictions to validate the model.

Heat release rate (HRR) is one of the most important parameters controlling the rate of a developing fire. Many HRR calorimeters have been developed to quantify this parameter. Currently, two popular calorimeters are used in research and commercial testing: the Ohio State University (OSU) heat release apparatus and the Cone Calorimeter developed at the National Institute of Standards and Technology (NIST). The OSU apparatus, the ASTM E 906 standard method (ASTM, 1985), has been in use for a longer time and is available in many testing laboratories. The Cone Calorimeter is currently an ASTM proposed test method (ASTM, 1987).

These two calorimeters are of great interest because they are used in bench-scale tests to obtain input data for fire growth modeling. The OSU apparatus was used by Smith and Satija (1983) to provide data for the OSU ROOM model. The Cone Calorimeter combined with a Lateral Ignition and Flame Spread Test (LIFT) apparatus (Quintiere and Harkleroad, 1984) was used by NIST to provide data for the compartment fire models developed at NIST. The configurations, ignition modes, and sensing methods of these two apparatuses are quite different. The OSU apparatus is a semiadiabatic flow-through box, and HRR is sensed with an array of thermocouples that constitute a thermopile. The radiant source is electrically powered at a steady rate to provide the baseline heating flux to the sample. The sample is ignited by an impinging pilot flame. The Cone Calorimeter has an electrical conical heater whose temperature is controlled to provide a constant heating flux. Ignition of the gas phase is with a spark igniter. Heat release rate is calculated using the oxygen consumption technique developed by Huggett (1980) and Parker (1984).

Much has been written about comparative HRR results between calorimeters, especially these two. Babrauskas (1986) compared five types of test apparatuses, including the Cone Calorimeter and the OSU apparatus, the latter in both the standard thermal

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mode and the oxygen consumption mode. Ostman et al. (1986) compared the Cone Calorimeter with the OSU apparatus modified for the oxygen consumption method. Tran (1988) used an OSU apparatus and compared results obtained simultaneously by both the standard thermal method and a simplified oxygen consumption method. The common finding is that the HRR measurements obtained by the OSU/standard thermal method are lower than those obtained by the oxygen consumption method in the same apparatus despite some differences in the way gas samples are taken. There were conflicting reports comparing Cone Calorimeter data and data from the OSU apparatuses modified for the oxygen consumption technique. Babrauskas (1986) reported that the Cone Calorimeter gave higher first peak of heat release than did the OSU apparatus. On the other hand, Ostman et al. (1986) found that the OSU/O_2 method gave higher results than did the Cone Calorimeter.

The differences between results from the two calorimeters are often attributed to two factors associated with the design of the OSU apparatus. Since the OSU box is not perfectly insulated, a fraction of heat release is lost to the surroundings. Part of the radiative heat loss is accounted for in the calibration with the methane gas burner. However, the radiative fraction of heat losses from the flame and the heated specimen surface in real tests is different (mostly higher). Therefore, there is a net radiative heat loss unaccounted for using the thermal method. On the other hand, thermal feedback from the burning sample surface to the radiant panel and walls of the apparatus and back to the sample results in higher heating flux than the baseline heating flux. This increase in heating flux may cause the sample to pyrolyze faster and yield higher heat release. The two factors work in opposite directions, and the errors could be compensating. The deviation from baseline heating flux due to thermal feedback is recognized but not well quantified.

Because the OSU apparatus is being used widely in the evaluation of materials and because of interest in comparing it with the Cone Calorimeter, which is gaining acceptance as the new standard, a careful comparison of the two apparatuses is again needed. This study was designed for two purposes: (1) establishing a data base of bench-scale heat and smoke release data for six wood products used in a series of room fire tests and (2) comparing HRR data between an OSU apparatus at FPL and a cone calorimeter at NIST on the same materials. To make the comparison meaningful, the following modifications of the ASTM E 906 standard method were made:

1. Additional instrumentation to obtain HRR by oxygen consumption technique
2. Addition of a heat flux meter to monitor changes in heating flux to the sample
3. In addition to the standard ignition mode, remote (gas phase) ignition with a pilot flame above the specimen for some tests

Preliminary work by Tran (1988) showed the feasibility of adding the oxygen consumption technique to the OSU chamber. The method is refined in this study using an improved probe, a complete gas sample analysis system, and modifications 2 and 3.

EXPERIMENTAL PROCEDURES

Instrumentation

Features of the modified OSU apparatus used in this work are shown in Figure 1. It was operated as much in accordance with the ASTM E 906 as possible in the standard thermal mode. The modifications are additions to the method and should not interfere with the standard procedure. Constant airflow was supplied by a blower. Total airflow was monitored with a volumetric flow meter and found to be constant. Air entering the chamber was split in the fashion described in the standard method. Approximately 1/4 of that air went to the bottom of the chamber and flowed upward through the combustion chamber. The remaining air flowed around the pyramidal section of the chamber and mixed with the combustion products in the stack. For the oxygen consumption technique, a sample of exhaust gases was continously drawn from a point 25 mm below the top of the inner pyramidal section. This position was found to be optimum to obtain an undiluted sample of the exhaust gases. To ensure a mixed sample, the T-shaped probe was designed with three holes 25 mm apart in the horizontal plane and facing upward, with the center hole at the centerline of the stack. The sample was filtered and analyzed for O_2, CO, CO_2 , and H_2O vapor. The three gases, O_2, CO, and CO_2, were measured on a dry basis because water was scrubbed from the lines leading to these analyzers.

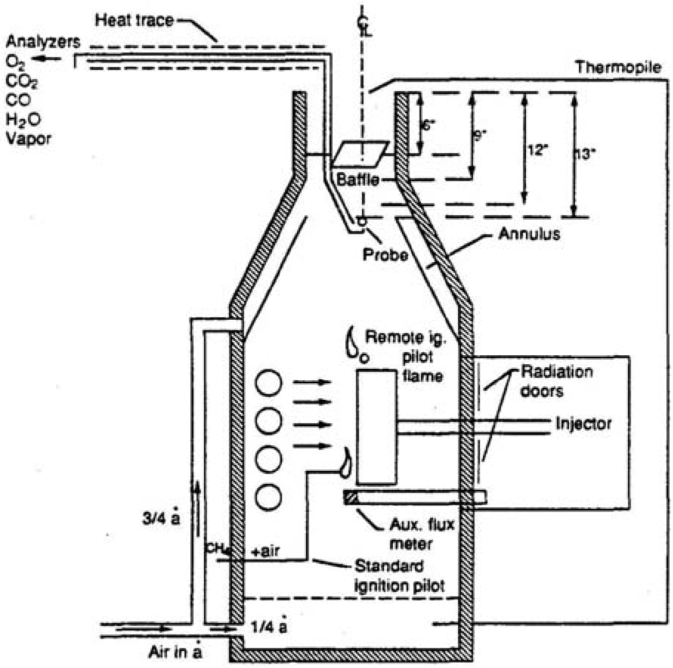

Figure 1. Features of the modified OSU apparatus.

To monitor the heating flux to the sample surface, an auxiliary heat flux meter was mounted in a pipe attached to the lower radiation door so that when the door was closed, the surface of the heat flux meter was fully exposed and parallel to the surface of the specimen. The heat flux meter was located 25 mm to the side and 25 mm downward from the bottom edge of the specimen. The surface of this meter was 12 mm ahead of the specimen surface so that it did not see the radiation from the flame. It did not see the convective heat from the burning sample because it was below the sample. The meter was of the Schmidt-Boelter type, having a 180° view angle.

The pilot flame used in the experiments used a premixed methane-air mixture as specified in the standard. In the remote ignition mode, the pilot flame was situated 12 mm above the sample and 12 mm recessed from its surface so that the tip of the flame was in the boundary layer of the pyrolysis products coming from the specimen. The fuel contribution from the pilot was assumed to be negligible.

The data collected included ambient and stack temperatures and voltages from the thermopile, the analyzers, and the auxiliary heat flux meter. A microcomputer was used to log data every 3 s.

Materials

The six materials of this study were used in a series of room tests conducted at FPL. All these materials were conditioned at 23°C and 50% relative humidity prior to testing. Average thickness, ovendry density, and moisture content of the materials are given in Table 1. The materials were selected based on their relative flame spread classification in the ASTM E 84 test (ASTM, 1988). According to this test, materials are classified into three classes based on their flame spread index (FSI). The classes are FSI 0-25 for class I, 26-75 for class II, and 76-200 for class 111. From the information available to us, fire-retardant-treated (FRT) plywood is class I. Redwood lumber is class 11. Douglas-fir (DF) plywood and southern yellow pine (SYP) plywood are in the lower range of class 111. Particleboard and oriented strandboard (OSB) are in the high range of class III.

The redwood lumber was tongue and groove. The DF plywood was five-ply CD grade. The SYP plywood was three ply. The FRT plywood was the SYP plywood treated with fire-retardant chemicals. Particleboard and OSB were composite products of proprietary compositions. Since only HRR and ignition data from the DF plywood were available from NIST, a great part of the paper is devoted to the comparison using this material.

Calibration

The heating flux to the specimen was calibrated using a total heat flux meter having a 180° view angle situated at the center of the virtual surface of the specimen. This meter was used to set the power so that the desired "baseline" flux was obtained. Baseline flux is defined as the flux measured by this meter prior to injection of the specimen. Since this flux meter was not present when a specimen was tested, the correlation between the flux to the center of the specimen and the auxiliary flux meter was required to determine heat flux to the sample during testing. Note that heating flux refers only to the flux from the radiant panel and does not include flame flux. To relate the heating flux to the specimen to the auxiliary heat flux meter, their responses were recorded simultaneously during a heatup period.

For calibration of the thermopile response factor k, three heating flux levels, 25, 35. and 45 kW/m^2, were selected. A higher upper limit was desired but could not be accomplished because of limitations in the power supply to the radiant panel. Three calibrations were done corresponding to the three selected flux levels. This procedure is different from the ASTM E 906 standard, which specifies that calibration is done without power to the radiation source. However, we found that k increased with power to the apparatus and calibration at the corresponding flux levels is more appropriate. Pure methane was metered through the standard calibration T burner at flow rates of 2,820 and 14.160 cm^3/min (0.1 and 0.5 ft^3/min) in a "square wave" fashion. The difference in HRR between the high and low methane flows divided by the difference in the thermopile response is the k factor used in HRR calculation using the thermopile method. The three calibrations at the three flux levels resulted in three different k factors. The k factor increases with higher heating flux. This relationship between k and heat flux was shown in an early work by Tran (1988).

Table 1. --Materials

Material	Thickness (mm)	Ovendry density (kg/m^3)	Moisture content (%)
Redwood	19	389	7.9
Fire-retardant-treated southern yellow pine plywood	12	653	9.2
Douglas-fir plywood	12	526	9.1
Southern yellow pine plywood	11	580	8.8
Particleboard	13	788	7.1
Oriented strandboard	12	644	7.3

The exact flow rate of air entering the combustion chamber is crucial in the HRR calculation with the oxygen consumption method. Because the air supply to the OSU chamber is distributed to the combustion chamber and around the pyramidal section by pressure drop across drilled holes, the split ratio is not well defined, although it can be assumed to be fixed. The airflow rate through the combustion chamber was calculated on the basis of known methane gas flow rates to the T burner and the species concentrations using equations described by Parker (1984).

The airflow rate was calculated at different flow rates of methane and was found to be constant regardless of heating flux and methane flow rate. This flow rate was used to calculate HRR of materials. In all three calibrations, the calculated airflow rate was consistent at 0.0086 m^3/s (20°C basis).

Test conditions

Three heating flux levels were selected: 25, 35, and 45 kW/m^2. Duplicates of the six materials were tested under two ignition modes, standard piloted ignition with the pilot flame impinging on the specimen and remote ignition with the pilot above the specimen. Unexposed surfaces of each specimen were covered with two layers of aluminum foil. A ceramic fiberboard was tightly pressed against the back of the sample to approach adiabatic boundary condition of the unexposed side. The specimens were tested in the vertical orientation. Ignition time in the remote ignition mode was measured from insertion of the sample to the time at which the flame attached to the specimen surface. Each specimen and specimen plus holder were weighed before and after the test for mass loss. The tests were terminated after the second peak of heat release had occurred to ensure that the specimens were completely charred.

To establish repeatability data, four additional tests were made with particleboard at 35-kW/m^2 heating flux in the standard ignition mode. The total number of particleboard tests under these conditions is six. Particleboard was chosen because it had the

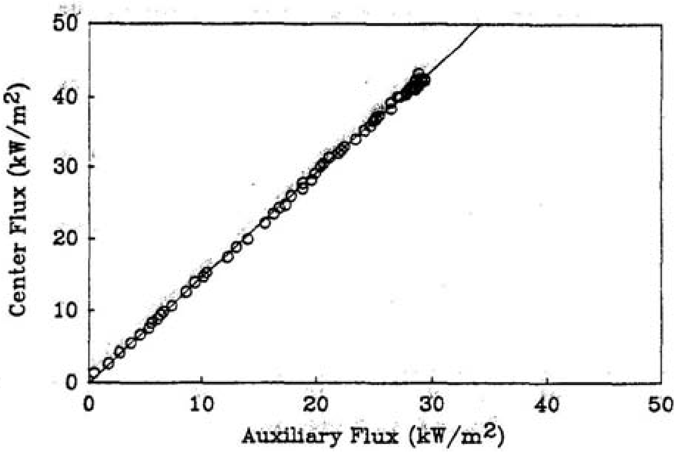

Figure 2. Correlation between heat flux meters.

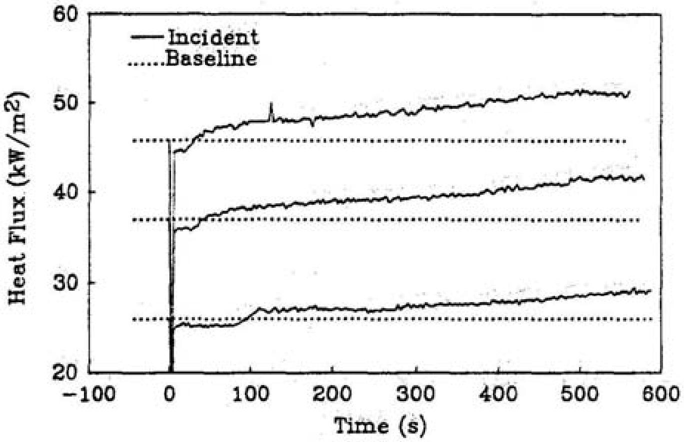

Figure 3. Deviation from baseline flux for Douglas-fir plywood.

least variance in physical properties and its results may be a better indicator of repeatability of the method.

A Cone Calorimeter holder was also used in the OSU apparatus to investigate the effect of the holder in the OSU environment. The major differences between the two holders are size and mass. The OSU holder allows for a 150- by 150-mm specimen area and weighs 186 g. The Cone Calorimeter holder accommodates a 100- by 100-mm specimen area and weighs about 700 g. The latter is much bulkier per unit specimen area.

RESULTS AND DISCUSSION

Correlation Between Heat Flux Meters

Incident heat fluxes to the virtual center of the specimen are plotted against those to the auxiliary heat flux meter in Figure 2. The resulting linear relationship is very useful to infer heating flux to the specimen knowing flux to the auxiliary meter during a test.

Deviations From Baseline Heating Flux

Using the linear relationship between the two heat flux meters, heating flux to the center of the specimen was calculated from the auxiliary flux. Three typical heat flux curves corresponding to three nominal flux levels are shown for DF plywood in the remote ignition mode in Figure 3. The 30-s baselines are stable. The dip in heating flux is an artifact due to opening of the radiation doors, which moved the auxiliary flux meter out of position. After the radiation doors closed, the flux remained lower than the baseline flux because the cold sample absorbed heat, causing the panel temperature to drop. After ignition, flux increased due to feedback effects.

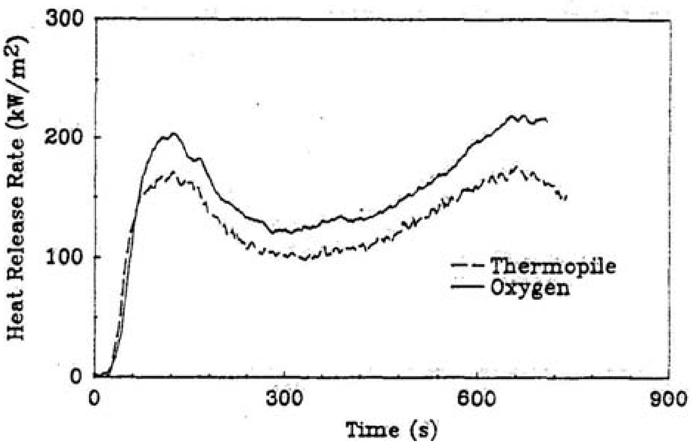

Figure 4. Heat release rate for particleboard at nominal 35 kW/m^2, standard ignition mode.

Increase in heating flux was as high as 5 kW/m^2, especially near the end of the test. Because the baseline heating flux also drifted as the chamber heated up from test to test, the three target flux levels are referred to hereafter as "nominal" heating flux levels.

Oxygen Consumption and Thermopile Methods

A typical set of HRR curves obtained for a particleboard test is shown in Figure 4. The oxygen consumption method yielded an approximately 20% higher result. This is consistent with previous findings that the thermopile method underaccounts for the heat release (Babrauskas, 1986; Tran, 1988). There was no consistency in terms of the percentage difference between the sensing methods due to the "sooting" of the thermopile in any series of tests. The difference is more severe toward the end of the series.

Repeatability

Results from six particleboard tests at nominal 35 kW/m^2 in the standard ignition mode are shown in Table 2. Deviation from baseline heating flux was on the average of 3 kW/m^2. Except for the average HRR over the first minute, coefficients of variation for the oxygen method are much smaller than for the thermopile method. Smoke release rate as specific extinction area (as defined by Babrauskas (1988)) is much less repeatable than HRR, with a coefficient of variation of about 18%.

Ignition Time

Remote ignition time was defined as the time from insertion of the sample to that at which the flame became attached to the specimen. In some cases, especially with FRT plywood, "flashes" resulted when gas phase combustion occurred when not enough combustible volatiles were present to sustain flaming. Results are consistent with the finding of Janssens (1989) that the inverse of ignition time to

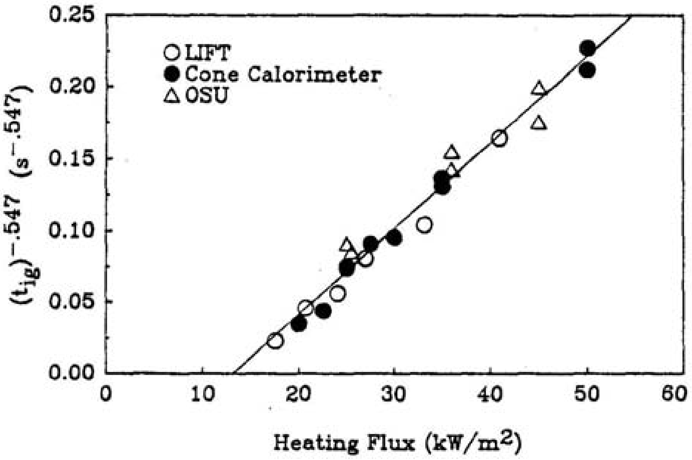

Figure 5. Ignition data for OSU apparatus, Cone Calorimeter, and LIFT apparatus for 12.7-mm Douglas-fir plywood.

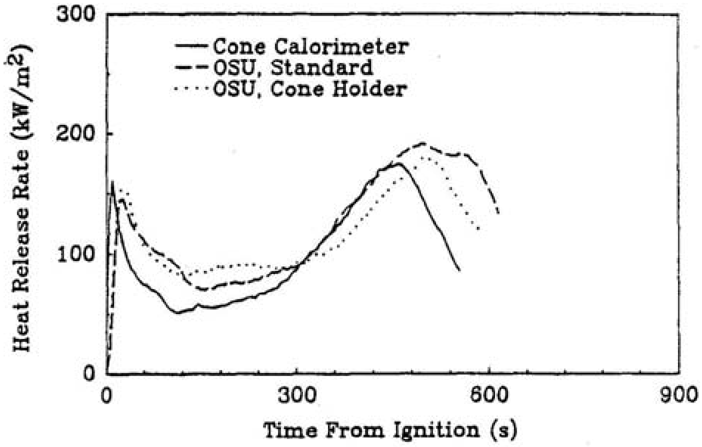

Figure 7. Comparison of OSU apparatus and Cone Calorimeter for Douglas-fir plywood at 35 kW/m^2.

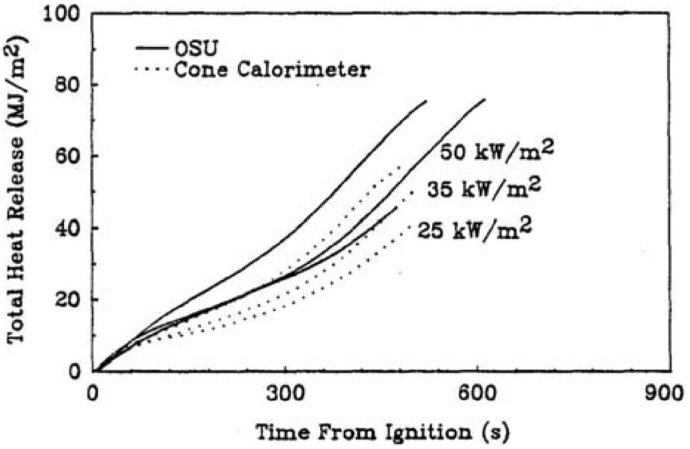

Figure 6. Comparison of OSU apparatus and Cone Calorimeter for Douglas-fir plywood at three flux levels.

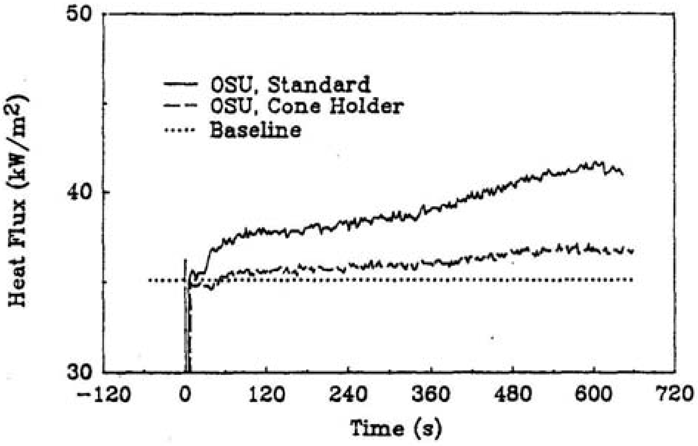

Figure 8. External heat flux to specimen surface for Douglas-fir plywood at 35 kW/m^2.

the power of 0.547 should be linear with heating flux for thermally thick specimens. The relationships are shown in Figure 5 for DF plywood tested in the OSU apparatus, Cone Calorimeter, and LIFT apparatus. Data from the LIFT apparatus tend to deviate from the regression line, especially toward higher fluxes (greater than 50 kW/m^2). The reason is that the LIFT apparatus has a gas panel that is not temperature controlled. Upon injection of a cold sample, a significant drop in heat flux occurs, which results in longer ignition time. The LIFT data in the high flux range were not included. The excellent agreement in ignition times among the three methods gives us confidence in the calculated heat flux using the auxiliary flux meter.

Comparison of Heat Release Rates With Cone Calorimeter Data

Only the data for DF plywood were available from both the OSU apparatus and the Cone Calorimeter. The total heat release at three flux levels (25, 35, and 50 kW/m^2) obtained from the Cone Calorimeter were compared to those at similar flux levels from the OSU apparatus (Fig. 6). The OSU data are significantly higher. This same order of magnitude in the difference was noted by Ostman et al. (1986).

The HRR curves of averaged duplicates for DF plywood from the Cone Calorimeter, the OSU apparatus, and the OSU with the Cone Calorimeter holder at 35 kW/m^2 of heat flux were compared (Fig. 7). Very good agreement in the first and second peaks was obtained despite deviations in heat flux in the OSU apparatus (Fig. 8). Note that the deviation in heat flux with the OSU standard holder (150- by 150-mm sample) was much greater than that with the Cone Calorimeter holder (100- by 100-mm sample). In the intermediate phase, heat release is lowest with the Cone Calorimeter data and highest with the same holder in the OSU apparatus.

We explored the possible effect of the backing by comparing the OSU data for both holders with different boundary conditions of the backside. The standard boundary condition is with the low-density ceramic fiberboard. The other two conditions are no backing and two layers of DF plywood. The results for the two holders are shown in Figures 9 and 10. The effect of the backing for the thickness of this material comes

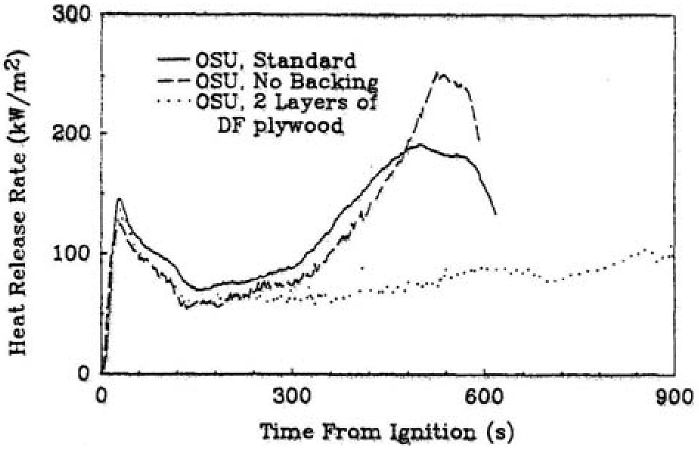

Figure 9. Effect of backing on rate of heat release in OSU apparatus for Douglas-fir plywood at 35 kW/m^2.

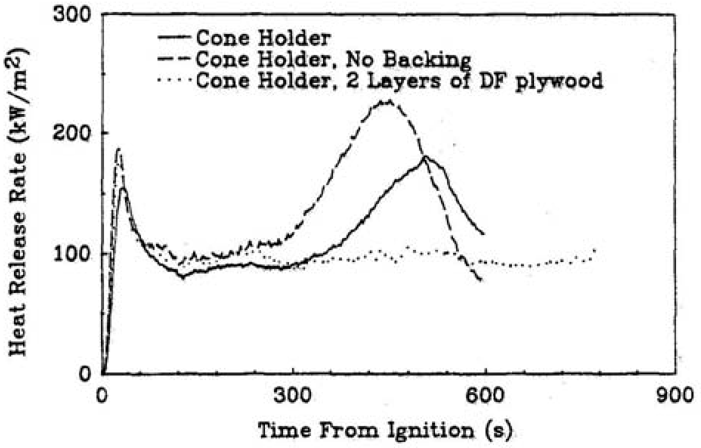

Figure 10. Effect of backing on rate of heat release in Cone Calorimeter for Douglas-fir plywood at 35 kW/m^2.

into play only after 5 min of exposure. The shape and size of the first peaks and the intermediate phase are virtually unchanged. Thus, for the first 5 min of the test, the intermediate phase of HRR does not depend on the backing for the 12-mm DF plywood.

We cannot explain the difference in heat release during the intermediate phase based on the sample size alone. Nussbaum and Ostman (1986) used the Cone Calorimeter with two sample sizes, 200 by 200 mm and 100 by 100 mm, in the horizontal orientation. The larger sample size resulted in higher peak HRR for all the products tested although the difference was not significant for wood products. This indicates that at least for wood products, the sample size does not have a large effect in the range of 100 to 200 mm in the Cone Calorimeter environment. We found that in the OSU apparatus, the smaller sample (Cone holder) resulted in higher HRR than the standard holder although heat flux to the smaller sample was less than the standard holder (Fig. 8):

By the process of elimination, the difference in HRR during the intermediate phase between the two apparatuses must be due to the boundary conditions around the sample holder. In the OSU apparatus, the sample and holder are heated in an enclosure, whereas they are open to ambient environment in the Cane Calorimeter. Heat transfer through the sides of the holder are opposite in the two apparatuses. We hypothesize that the net effect is the difference in temperature, which affects the rate of heat release. Temperature affects HRR in two ways: rate of reaction and chemistry of reaction. For cellulosic materials. the rate of pyrolysis follows an Arrhenius behavior, as documented by Parker (1988). An increase of 10°C doubles the reaction rate. Wood contains carbohydrate and lignin fractions that have different calorific values and pyrolysis temperatures. The lignin fraction has significantly higher heat of combustion and pyrolyzes at higher temperatures than the carbohydrate fractions, as documented by Browne (1963). Thus, we would expect both rate of reaction and heat of combustion of the volatiles to increase at higher temperatures.

Heat of Combustion

The average heat of combustion over the entire run was calculated for both the oxygen and thermopile methods by dividing total heat release by total ovendry mass loss. The ovendry mass loss is calculated using total mass loss minus calculated water content in the original specimen. The average heat of combustion data are given in Table 3. Since heat of combustion of wood depends on the fraction of wood that pyrolyzes, it varies during the course of burning. As shown by Parker (1988) using a pyrolysis-catalytic combustion device (PYROCAT) and Janssens (1988) using a Cone Calorimeter, heat of combustion of representative wood (Douglas-fir and white pine) is fairly steady at slightly above 13 MJ/kg and rises with the second peak in the HRR curve to 31 MJ/kg (heat of combustion of carbonaceous char). In our experiments, the tests were terminated after the rate of heat release had passed the second peak. Thus, average heat of combustion must be higher than the initial 13-MJ/kg value. The average heat of combustion using the oxygen method was consistently higher than 13 MJ/kg, except for FRT plywood. The low heat of combustion with the thermopile method again indicates that the method did not account for all the heat release.

Average heat of combustion of DF plywood was 13.9, 15.0, and 15.2 MJ/kg with the OSU/O_2 compared to 13.5, 14.0, and 14.35 MJ/kg in the Cone Calorimeter for the three increasing flux levels, respectively. Although the calculated heats of combustion are fairly close and the difference is within the uncertainty of difference in termination times, the data with the OSU apparatus is consistently higher than that of the Cone Calorimeter. This supports the hypothesis that temperature is higher in the OSU sample, leading to more pyrolysis of the components having higher heat of combustion.

Heat Release Rate and Heating Flux

The average rates of heat release over the first 3 min and 5 min for the six materials are plotted against the average flux over the same periods in Figures 11 and 12. Data for DF plywood with the Cone Calorimeter are also shown for comparison. HRR is almost a linear function of heating flux in the range of fluxes used. Janssens (1988) found the same trend using a Cone Calorimeter. Average HRR of DF plywood was significantly lower with the Cone Calorimeter. A correction of HRR with the OSU apparatus based on flux alone is not adequate to account for the difference between the two apparatuses. The difference between the OSU/O_2 method and the Cone Calorimeter is between 20% and 30%. An interesting note is that the

Table 2.--Repeatability with particleboard, 35 kW/m^2 nominal heat flux, standard ignition

Replicate	Flux (kW/m^2)		Time average heat release rate (kW/m^2)						Average extinction area (m^2/kg)
			Thermopile			Oxygen			
	Baseline	Average	1 min	3 min	5 min	1 min	3 min	5 min	
1	38.6	41.2	39	117	115	24	125	127	66.8
2	38.5	40.4	40	106	109	24	116	123	57.2
3	34.5	38.8	33	123	129	22	117	123	70.7
4	38.4	41.1	41	119	120	31	126	127	86.8
5	37.2	40.9	36	107	111	28	121	126	88.9
6	36.3	40.5	36	109	109	27	125	126	89.6
Average	37.25	40.5	37.0	113	115	26	122	125	77.7
Standard deviation	1.62	0.88	3.0	7.0	7.8	3.3	4.4	1.9	13.6
Coefficient of variation (%)	4.4	2.2	8.1	6.2	6.7	12.6	3.6	1.5	17.6

Table 3.--Average heat of combustion

Material	Heat of combustion (MJ/kg)					
	Nominal 25 kW/m^2		Nominal 35 kW/m^2		Nominal 45 kW/m^2	
	Oxygen	Thermal	Oxygen	Thermal	Oxygen	Thermal
Redwood	14.3	12.7	14.9	13.8	15.5	14.0
Fire-retardant-treated plywood	6.9	5.6	9.5	7.5	9.5	8.3
Douglas-fir plywood	13.9	11.1	15.0	11.9	15.2	13.3
Southern yellow pine plywood	15.1	12.1	15.2	11.9	15.0	12.7
Particleboard	13.0	10.1	14.1	11.9	14.1	11.6
Oriented strandboard	13.8	10.9	14.5	12.1	14.6	12.2

thermopile method, although underaccounting for the heat release in the OSU apparatus by 20 to 30%, gives roughly the same average HRR as the Cone Calorimeter.

The materials rank from the lowest to highest HRR as follows: FRT plywood, redwood, DF plywood, SYP plywood, particleboard, and OSB. The separation between the materials is better with the 5-min average HRR. The order of HRR values agrees well with the order of FSIs (ASTM E 84) of the materials and with the relative performance in the room burn tests. Simplistic and approximate correlations can be made between HRR with flame spread index and room test results. This confirms again that HRR is very important in a developing fire. However, other factors, such as ignition and flame spread rate, also control the rate of fire growth. Because of the complexity of scaling from bench-scale to full-scale fire, the physics required are best handled by a higher level of correlation, namely modeling. At the moment. the modeling effort is beyond the scope of this paper and will be dealt with in more detail in a separate paper.

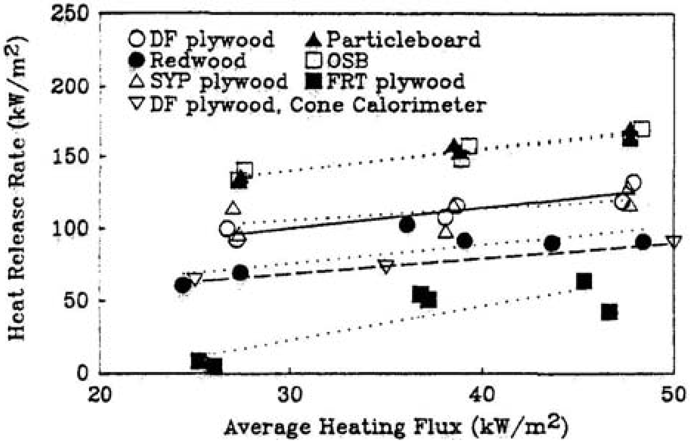

Figure 11. Mean heat release rate over 3 min for oxygen consumption method in remote ignition mode.

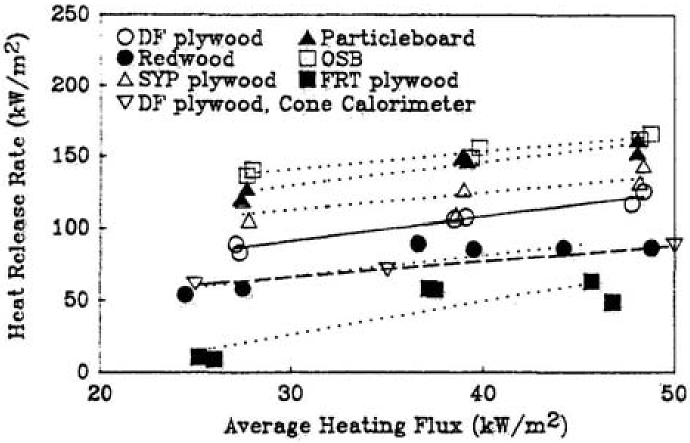

Figure 12. Mean heat release rate over 5 min for oxygen consumption method in remote ignition mode.

CONCLUSIONS

Modifications to the OSU apparatus were made to improve its accuracy and to provide data that would not otherwise be obtained in the standard operating mode. The major modifications were the addition of the oxygen consumption method and the auxiliary heat flux meter to monitor heating flux. Ignition data were obtained with the pilot flame above the specimen. Good agreement was found with ignition data from the Cone Calorimeter and the LIFT apparatus.

The standard thermopile method underaccounts for the heat release. Because of problems associated with the standard thermopile method, the oxygen consumption method is more advantageous and should be considered as a better sensing method. The probe design and position used in this work were found to be satisfactory without extensive modification of the existing apparatus.

With the auxiliary heat flux meter, we could monitor the heating flux to the sample indirectly. The deviation in heating flux to the sample was significant and should be taken into account in the analysis. Heat release rate is a function of heating flux and can be erroneous if baseline flux is assumed. In addition, the drift in baseline flux is significant from test to test. Because it is impractical to control the heating flux in this apparatus, we recommend that heating flux be monitored so proper correction can be made. Using a smaller sample size and holder can reduce the reradiation problem. However, heat release rate is increased due to increased edge effect.

Comparison of the modified OSU apparatus and Cone Calorimeter results was encouraging although more work must be done to explain the differences. There was good agreement in the first and second peaks of heat release. Heat release rate during the intermediate phase is higher in the OSU apparatus. The difference is most likely due to the environment the sample is in. Heat transfer through the sides of the holders in the two apparatuses is in opposite directions. The effect is the difference in temperature, which controls rate of pyrolysis and the chemistry of combustion. The higher rate of heat release and heat of combustion in the OSU apparatus support that hypothesis. The heat release rate of a truly one-dimensional system should be somewhere between the rates of the two apparatuses.

Because the boundary conditions around the sample holder can significantly affect the results of HRR tests, special attention must be paid to this critical area to obtain meaningful results.

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