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HRR UPGRADE TO MASS LOSS CALORIMETER AND MODIFIED SCHLYTER TEST FOR FR WOOD

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ABSTRACT

Enhanced Heat Release Rate (HRR) methodology has been extended to the Mass Loss Calorimeter (MLC) and the Modified Schlyter flame spread test to evaluate fire retardant effectiveness used on wood based materials. Modifications to MLC include installation of thermopile on the chimney walls to correct systematic errors to the sensible HRR calculations to account for radiant energy losses to the chimney walls. Additionally, pure ethylene glycol for low flame radiant losses and the PMMA for high flame radiant losses supplanted the use of methane for calibrating the sensible HRR. The FPL 3 MW HRR hood facility, updated with fast and accurate O₂, CO₂, and CO gas analyzers, was shown to provide accuracy within 0.5 kW as determined with the pure ethylene glycol burned in the MLC under the HRR hood. Thus the performance measure in the modified Schlyter fire test has been objectively determined with the HRR measure of upward fire growth, rather than based on the manually observed maximum flame height. Using the MLC for initial Fire Retardant (FR) screening and the modified Schlyter flame spread test for emulating severe fires should provide a low cost approach to evaluating fire retardant effectiveness.

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INTRODUCTION

It is common to use fire retardant treatment (FRT) of wood for various interior applications of structures, and also increasingly being used for exterior applications as the wildland urban interface (WUI) fire threats become more prominent. Because the fire retardants have the effect of reducing fire growth, various flammability tests have been developed to rate fire performance of treated wood products. Small specimen such as used in the Limiting Oxygen Index (LOI), and other such tests can have inherent wood inhomogeneity that causes inconsistencies in test results. Larger specimens that can accommodate inhomogeneity will tend to provide more consistent test results.

The cone calorimeter test (ASTM 1354), with the 100 mm by 100 mm sample area exposed to imposed heat flux and spark ignition, was shown at FPL with its measurements of time to ignition, heat release rates, mass loss rates, and smoke and combustion gas production to provide fire performance assessment and fire properties that is indicative of their material fire performance in full-scale fires.^{1,2,3} However, the Mass Loss Calorimeter (ASTM E2102-11, Standard test method for measurement of mass loss and ignitability for screening purposes using a conical radiant heater), is a low-cost version of the cone calorimeter in which the heat release rate (HRR) is determined by a less accurate heat release rate via the thermopile method instead of the oxygen consumption method. In both methods, a conical electric heater provides a constant heat flux onto the 100 mm by 100 mm test specimen and after piloted ignition by the spark igniter the mass loss and heat release rate are

recorded. Wood products of up to 50 mm thick can be used although a thickness of 19 mm is the usual thickness. Constant heat flux as high as 100 kW/m^2 can be used, although 50 kW/m^2 is the usual value corresponding to impinging flames. By relocating the MLC to under the updated FPL's 3 MW HRR hood, the measures of combustion emissions, smoke production, and oxygen consumption HRR provide equivalent results as the cone calorimeter for various materials. The MLC 2004 model from Fire Testing Technology, Limited (Figure 1) was installed and tested and further improvements are reported in this paper.

Figure 1

Mass Loss Calorimeter modified to include thermopile on chimney walls to compensate for radiant energy errors of the in-flow thermopile.



Another bench-scale fire test used at FPL to rate treated wood products is the modified Schlyter flame spread test ⁴. It is an older nonstandard test apparatus that is a Forest Products Laboratory (FPL) modification of a test developed in Europe and was used in various studies over the years. The apparatus has two vertical parallel sheets of 302 mm (11-7/8 in.) wide by 787 mm (31 in.) high test specimen placed opposite to each other with a small burner (normally at 7 kW of natural gas) placed between them (Figure 2). The burner is ignited and is normally burned for 3 minutes before being shut off, and then the specimen is allowed to continue to burn. The main test performance is the flame height over time, which requires visual observation of flame height. This test has certain advantages for the WUI fire studies, which are that (1) the external heat source to the specimen is a small burner representing small secondary (i.e. debris) ignition sources, (2) the vertical parallel specimens simulates the re-radiation and upward flame spread in large structures, and (3) open construction allows an external air flow to be applied as a test modification. Using HRR as a function of time as a

flammability measure offers improvements over flame height which is affected by lateral flame spread, propagation of burnouts, and variability of visual observations.

Figure 2

Modified Schlyter flame spread test located directly under FPL's 3 MW HRR hood



In this study we demonstrate the utility of the improved methods by testing Oriented Strand Board (OSB), Southern Pine (SP) plywood, and redwood in the order of decreasing flammability (according to ASTM E84 Steiner tunnel test) in comparison to the better performances of FRT Southern Pine plywood. These materials were used in previous Room Corner fire tests (ISO 9705)³, which provide additional comparisons for these wood products. Tests were also conducted on creosote treated lumber.

IMPROVED SENSIBLE HRR MEASUREMENTS IN MASS LOSS CALORIMETER

The tests were carried out according to the ASTM E2102-11 test method with modifications to HRR calculation. Samples were exposed in the horizontal orientation to the irradiance 50 kW/m^2 upon opening the thermal shutter and using an electric spark for piloted ignition. Ignitability was determined by observing the time for sustained ignition of the specimen with 4 seconds criteria for sustained ignition. The MLC was confirmed to have significant systematic HRR errors using the ASTM thermopile method, due to thermal radiation heat losses varying between materials with differing soot production. An improved HRR calculation was developed by constructing another thermopile on the fume stack itself, digitally deconvolving the signal of fume stack thermal response to radiant and convective energy absorption, and combining the resulting processed signal with the ASTM thermopile signal into a composite value with a linear correlation with measurable HRR of reference materials. This has successfully determined the HRR profile of PMMA, ethylene glycol, methane, OSB, SP plywood, redwood, and FRT SP plywood exposed to 50 kW/m^2 heat flux using a

single set of calibration constants. Their profile was additionally confirmed with enhanced gas analysis with FPL's HRR burn hood having dynamic range from 0.5 kW to 3 MW.

The MLC came with a manual methane flow meter that was used to follow the ASTM E2102 method for the linear correlation of the methane flow rate with the stack thermopile temperature. The imposed radiant heat flux was set at 50 kW/m². We found the linear correlation to be confirmed, but with considerable inaccuracy due to human errors, as shown in Figure 3 in the methane manual flow region. To improve upon this inaccuracy the pure ethylene glycol burned cleanly in a special holder for liquid fuels. The linear correlation of the HRR derived from the mass loss rate of the glycol times its heat of combustion with the stack thermopile was once again confirmed, and shown in Figure 3 to a much higher accuracy than that of manual methane approach. However, the high sooty PMMA burning in the MLC showed a 25% reduction in the thermopile prediction of the HRR in comparison to mass loss rate times the PMMA heat of combustion. In Figure 3 this was verified in two different tests of the black PMMA reference standard.

To compensate for this error in HRR predictions, a new thermopile was constructed as flattened thermocouples placed between thin ceramic washers and screwed into the chimney wall, as shown in Figure 1. The slow, but very smooth response, of the thermopile to the step changes in the methane heat release rates is shown in Figure 4 as the dashed curve. Using the notion that the chimney wall is thermally thin, the time constant, τ , for the corresponding exponential time response of the thermopile signal is approximated by the products of values for the steel density, steel heat capacity, and chimney wall thickness, and as divided by the value of the overall heat transfer coefficient to the chimney inner and outer surfaces (see Equation 40 of Reference 3). The overall heat transfer coefficient has both convective and radiant components that are strong functions of the stack thermopile temperature. That is, a higher stack temperature means a higher value of the heat transfer coefficient. Therefore, we opted to use a digital exponential deconvolution⁵ of the chimney wall thermopile signal to match the response of the stack thermopile with the formula (derivable from time derivative of Equation 40 in Reference 3),

$$T_c = T_w + \tau \dot{T}_w = T_w + \left(45 + \frac{14000}{T_p}\right) \dot{T}_w \quad [1]$$

to obtain the compensation temperature, T_c , of equivalently a very thin wall. The wall temperature rate, $\dot{T}_w$, was determined using the well-known Savitzky- Golay (SG) smoothing filter function for the first derivative of the measured wall temperature, T_w , and the data was shifted by minus 26 seconds. The resulting deconvolved signal was further increased in its magnitude by 1.83 (along with the empirical constants of Equation 1 obtained with the Excel solver) in Figure 4 as the fitting of dotted curve to the solid curve of the stack thermopile signal, T_p . Suspecting the deconvolved chimney thermopile signal is more sensitive to radiant energy losses, the linear correlation of HRR with solely the compensation temperature, T_c , was done in a similar manner to that in Figure 3 in fitting with the methane and glycol data. This time the sensible HRR prediction for PMMA was about 20% too high. The final HRR correlation using the Excel solver, as shown in Figure 5, was then obtained as a bilinear correlation with the two thermopile signals as,

$$HRR = 4.468(T_p + 3.5T_c) - 15.75 \quad [2]$$

Figure 3

HRR correlation via stack thermopile correlation shows ~25% error for PMMA fuel

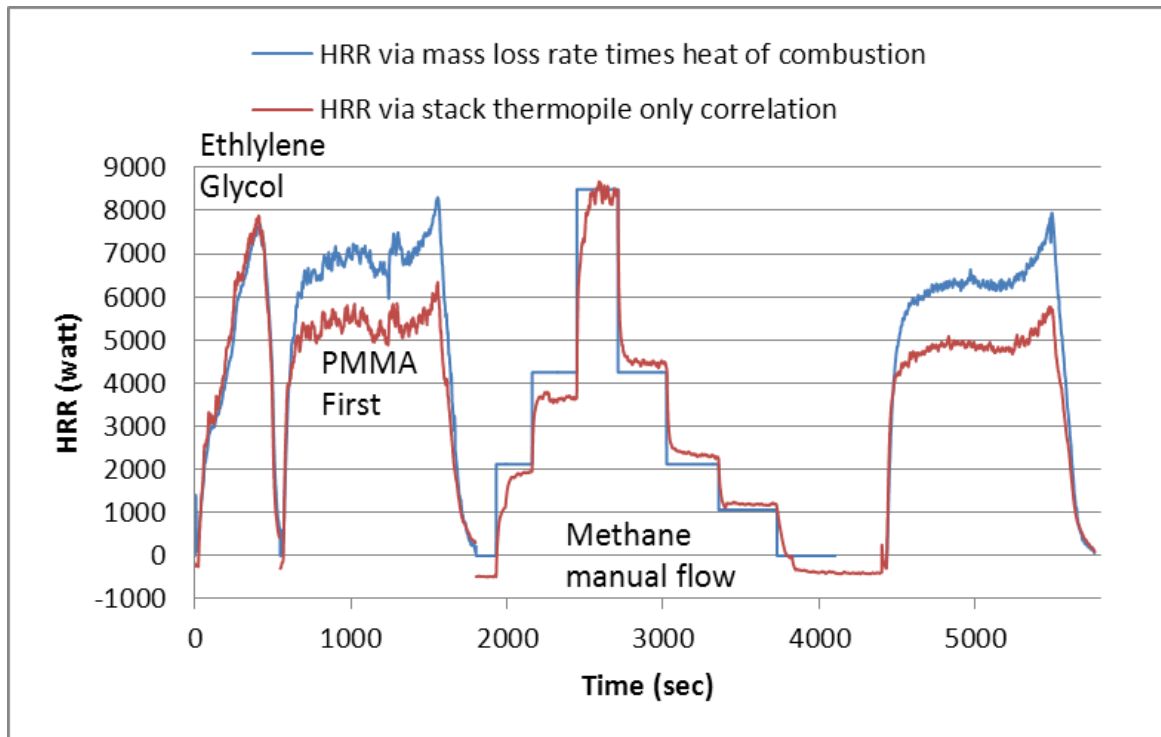


Figure 4

Deconvolution of chimney thermopile temperature profile to match the stack thermopile temperature profile

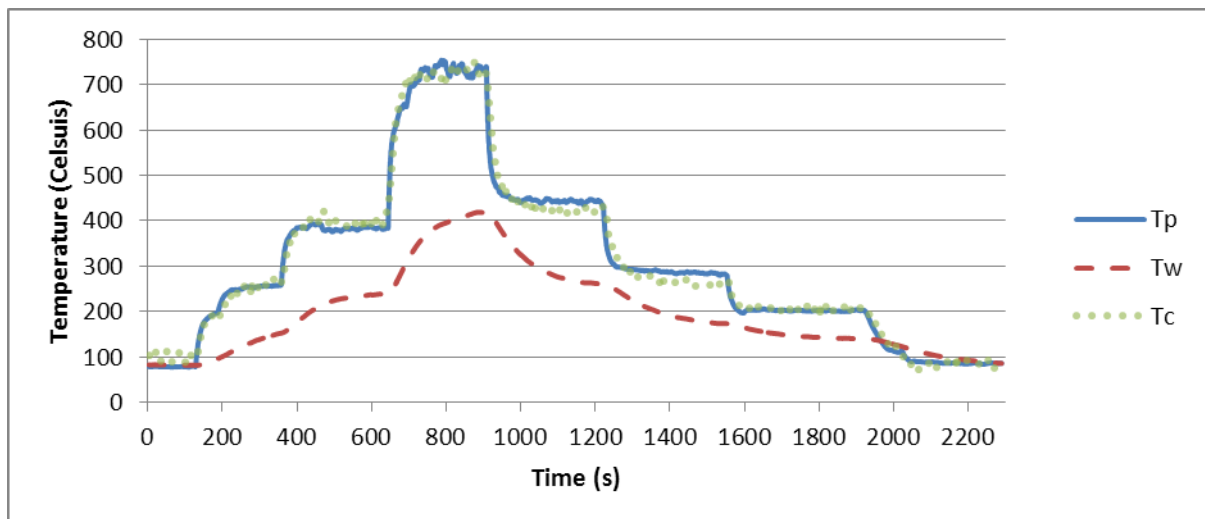
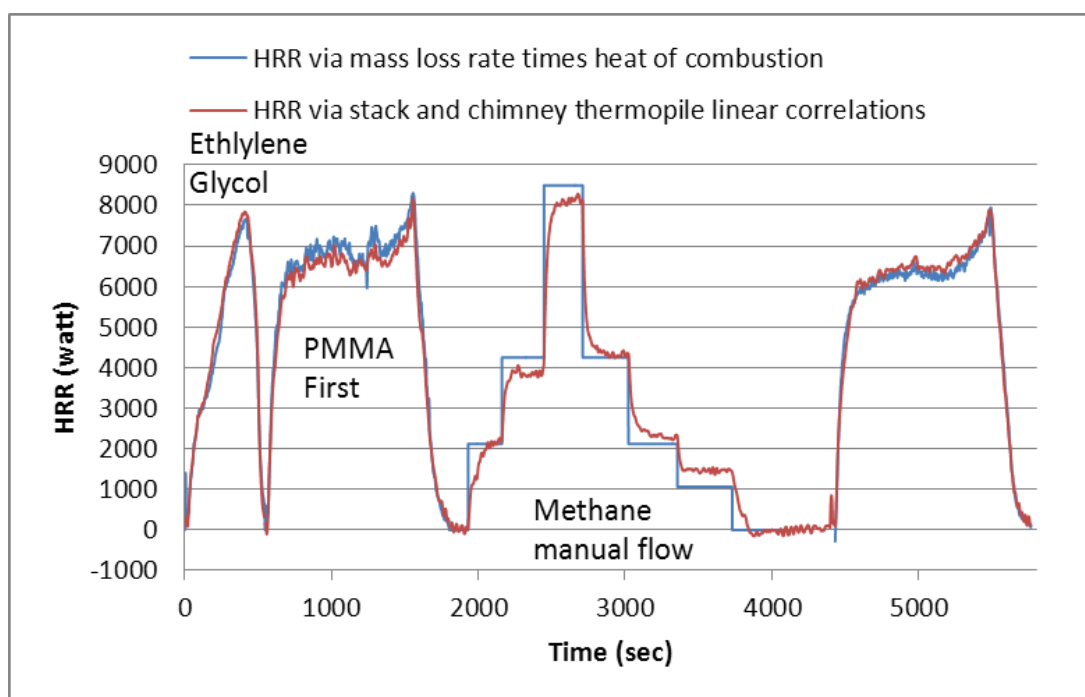


Figure 5

Final correlation of sensible HRR based on both stack and chimney thermopiles



COMPARISON OF FOUR ROUND ROBIN WOOD PRODUCTS VIA SENSIBLE HRR AND MLS

Four round robin wood products retrieved from the series of corner room tests⁵ represented a wide range of the flame spread index (FSI) and listed in Table 1. The Mass Loss Rate (MLR) was computed using the SG filter function for first derivatives instead of the formula suggested in ASTM E2102 as it gave a more responsiveness in showing the peaks, and yet gave a smoother result, as shown in Figure 6 for the four materials. The HRR profiles in Figure 7 mimic their counterparts in the MLR curves in Figure 6, indicating a relatively constant heat of combustion with time that is typical of wood. In Table 1 are listed the averaged heat of combustion for untreated wood of around the reasonable values of 12 MJ/kg, whereas for FRT SP plywood the averaged heat of combustion is a reasonable 7.2 MJ/kg, which are the values typically obtained also with the cone calorimeter. The result is that the improved sensible heat release method for the MLC can capture the very low HRR of FRT wood products, as well as the high HRR typical for plastics. It is noted that soot accumulation on the stack thermopile and on the inner walls of the chimney needs to be removed periodically to maintain HRR accuracy.

The OSB, as Class C on the basis of FSI (ASTM E84), is the most flammable, and seen as having the largest features in the Mass Loss Rate (MLR) as the red curve in Figure 6 and HRR also as the red curve in Figure 7. The similar flammable material, the Southern Pine Plywood, has a shorter ignition and burn time due to it being the thinnest material, which should be normalized for its comparison with other materials. The MLR of the FRT SP plywood (Class A FSI) is generally larger than the MLR of redwood (Class B FSI) in Figure 6, which is inconsistent with their flammability ranking. However, the HRR of the FRT SP plywood tends to be less than the HRR of the redwood in Figure 7, therefore preserving the ranking of their respective flammability. Table 1 has that the first peak HRR decreases with the lesser flammability of the material, as well as the term described as the material bulk heat release factor³, as given by the formula in the last column, also decreases with the lesser

flammability of the wood products. That is, OSB and SP plywood is more flammable than redwood, which is turn is more flammable than FRT SP plywood. This trend in flammability is verified by the HRR profiles in Figure 8.

1. Global data of modified MLC for four wood products of differing flammability

Material	Thicknes s (mm)	Mass Loss (%)	Tig (s)	1 st PHRR (kW/m ²)	THR (MJ/m ²)	Hc (MJ/kg)	(THR/Tig)* (12.5/Thick)
OSB	11.5	78	23	160	79	11.7	3.75
SP plywood	10.5	61	18	136	60	11.5	3.99
Redwood	19	76	26	104	95	12.6	2.41
FRT SP plywood	11.5	61	30	83	34	7.2	1.21

Tig = Time to Sustained Ignition, PHRR = Peak Heat Release Rate, THR = Total Heat Release, Hc = Heat of Combustion, (THR/Tig)(12.5/Thickness) = "Bulk Heat Release Factor"

Figure 6
Mass Loss Rates data for four wood products

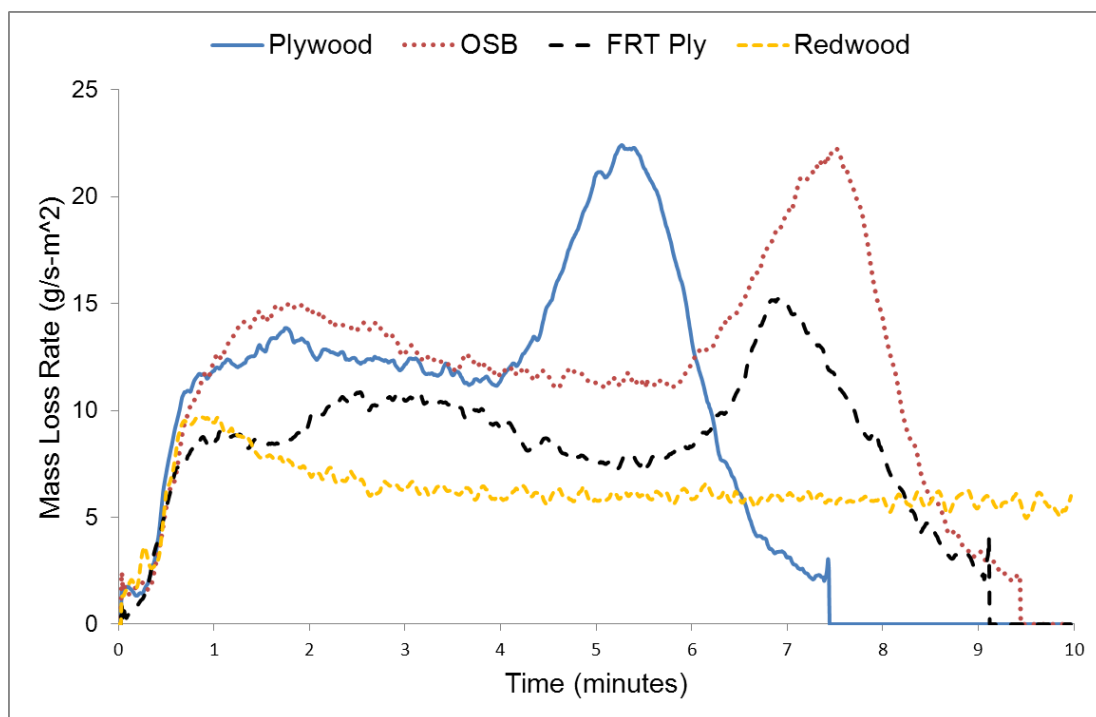
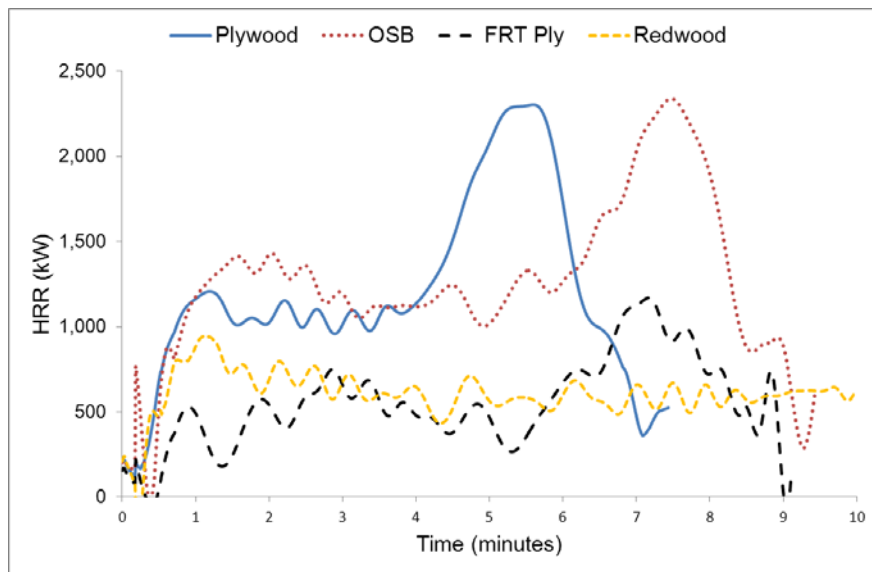
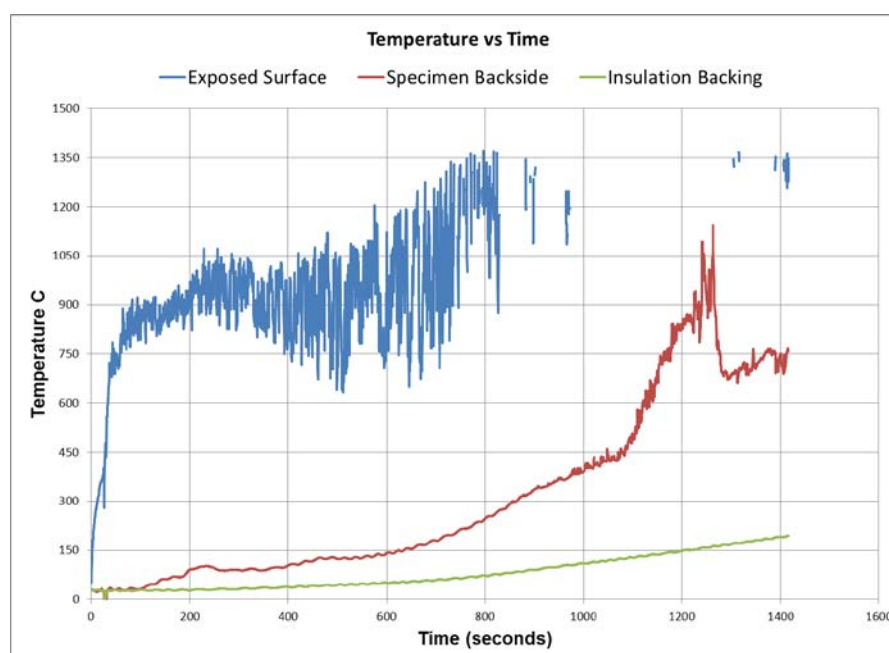


Figure 7
Sensible Compensated Heat Release Rates (HRR) for four wood products



Prior to placing the redwood specimen in the sample holder, three thermocouples were attached to it. The exposed surface thermocouple (36 gauge Type K wire) was inserted into a slanted surface crevice formed with a razor blade. Ignition of the redwood can be determined from this thermocouple sudden rise in value at 26 seconds in Figure 8. The second thermocouple was taped to the backside surface at the sample's middle, in such a way to prevent electrical contact with the aluminium wrapping. This thermocouple shows the transition from flaming to glowing when it reaches 450 Celsius. The third thermocouple was inserted behind the insulating layer behind the specimen, which verified the insulation performance. These thermocouple measurements can provide the researcher additional insights to material behaviour and can provide data for validating a wood pyrolysis model (Figure 8).

Figure 8
Thin thermocouples attached to the specimen at three different depths



IMPROVING HRR MEASUREMENTS VIA OXYGEN CONSUMPTION METHOD FOR THE HRR HOOD

The following upgrades to the HRR facility⁵ were made. Exhaust gas composition was determined using three gas analyzers from Sable Systems (www.sablesys.com) and a relative humidity sensor from U.P.S.I. (www.upsil.fr). Oxygen was measured using the PA-10, a paramagnetic analyzer capable of resolution to 0.0001 %O₂ and modified to provide even faster response by reducing internal volume of the filters. Exhaust gas to the sensor was dried using the Sable ND-2, a permeable-membrane dryer. Carbon dioxide was measured using the CA-10, a dual wavelength infra-red sensor capable of resolution to 1 ppm. The same technology was used in the CM-10A for carbon monoxide detection. Gas was delivered to the analyzers using two pumps. The first larger pump pulls exhaust quickly to the location of the Sable equipment through a pre-filter and water-bath controlled (50 °C) water-to-air heat exchanger to provide consistent incoming air conditions. Then a sub-sample pumps pulls exhaust smoothly through the dryer and analyzers.

The Sable components provide analog signals, including the barometric pressure. These signals along with the type K thermocouple readings at various locations in the specimen were captured by the data acquisition system (Measurement Computing USB-1616HS) at 4 Hz. Raw signals were then time-shifted based on time-of-flight to the sensor to have all changes correspond to the mass loss signal from the MLC placed under the HRR hood.

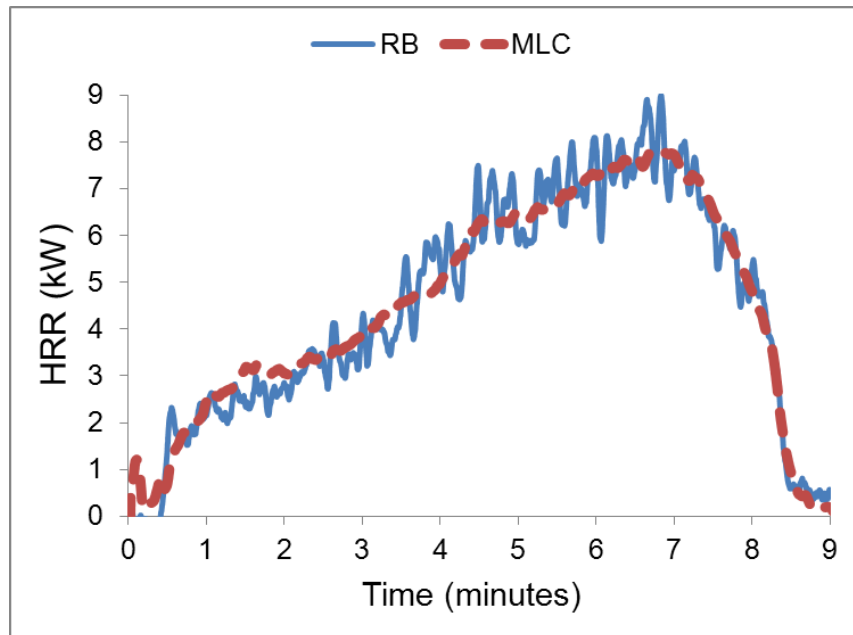
Exhaust flow rate calculations were based on ISO 9705 formula using pressure drop across the bidirectional probe, temperature of the exhaust, and various gas concentrations. Further fine tuning of the exhaust flow rate is based on matching the computed mass flow rates of depleted oxygen, carbon dioxide, and water with that determined from nearly complete combustion of pure ethylene glycol, whose fuel mass flow is measured with the weigh scale in the MLC placed under the HRR hood.

No fine tuning of zero and span parameters for oxygen, carbon dioxide, and carbon monoxide gas analysis were needed, whereas the relative humidity sensor required minor calibration adjustments. To match up their response times from 10% to 90% levels during step changes, small digital filtering was applied to sensor data for carbon dioxide, carbon monoxide, and water vapor, and a small digital deconvolution was applied to the oxygen sensor data. Since the molar fractions of O₂, CO₂, CO, and H₂O are now available and synchronized, we followed the ASTM E1354 Annex procedure, as extended to the HRR hood, for calculating the mass flow rates, respectively, of the same molecules. The soot mass flow rate is merely calculated as the smoke production rate (product of volumetric rate and extinction coefficient) divided by the specific extinction area, 8.3 m²/g, for the black smoke. Indeed, carbon solid and carbon monoxide fuel has further deviations, such that the heat release due to incomplete combustion (producing C and CO from oxidizing the organic carbon) has the formula⁶,

$$HRR = 13.23\Delta\dot{m}_{O_2} - 2.54\dot{m}_{CO} + 2.48\dot{m}_s \quad [3]$$

The improved results are shown in Figure 9 for the burning of ethylene glycol in which the HRR via oxygen consumption (solid curve) is within 0.22% error overall with the HRR from the mass loss rate of glycol as measured in the MLC times its heat of combustion (dashed curve).

Figure 9
Validating Oxygen Consumption method for low HRR measurements



RANKING OF ROUND-ROBIN WOOD PRODUCTS VIA HRR OF MODIFIED SCHLYTER TESTS

As discussed in the introduction, the fire growth performance with the modified Schlyter flame spread test of various wood-based materials is better established on the basis of HRR criteria, rather than on the manually determined flame height criteria. The first tests were done on materials likely to give extreme results. The creosote treated lumber appears to give the most acceleration of HRR after ignition (Figure 10), and will burn at as high as 80 kW, which gave such high flame height that it could not be accurately observed. At the other extreme, using the pilot burner at the level of 7 kW, the FRT SP plywood appeared to experience damped fire growth, going no higher than 15 kW. Upon removal of pilot burner at 6 minutes, the FRT SP plywood fire was self-extinguished quickly. Thus the usual exposure time of pilot burner at 3 minutes may very well be suitable.

Figure 10
HRR of treated wood in the modified Schlyter flame spread test.

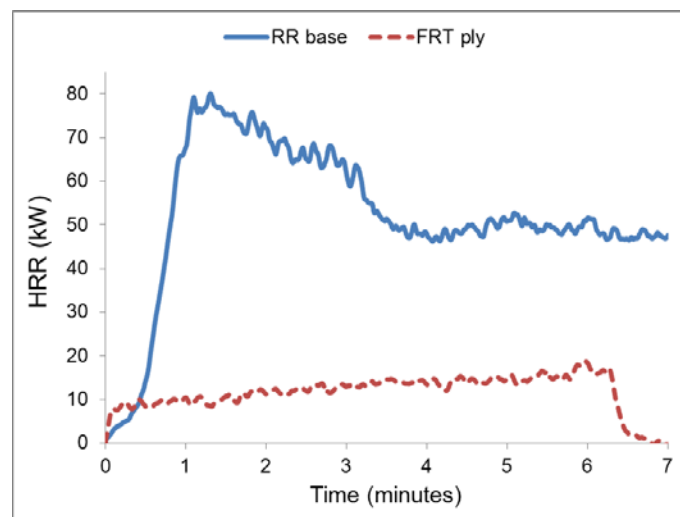


Figure 11
HRR of untreated wood products in the modified Schlyter test.

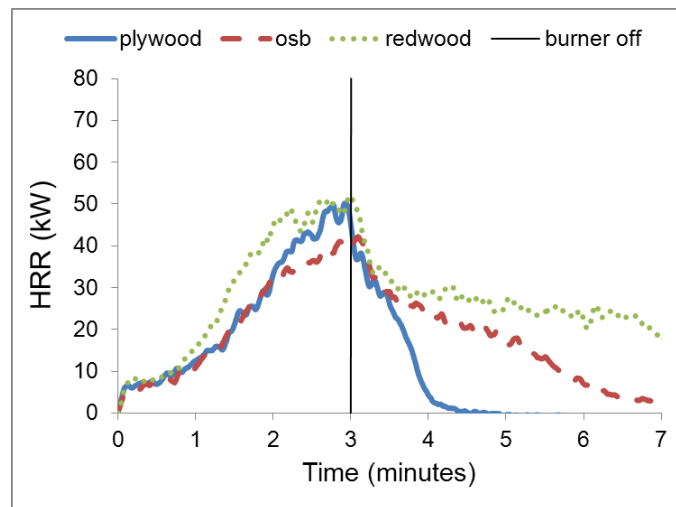
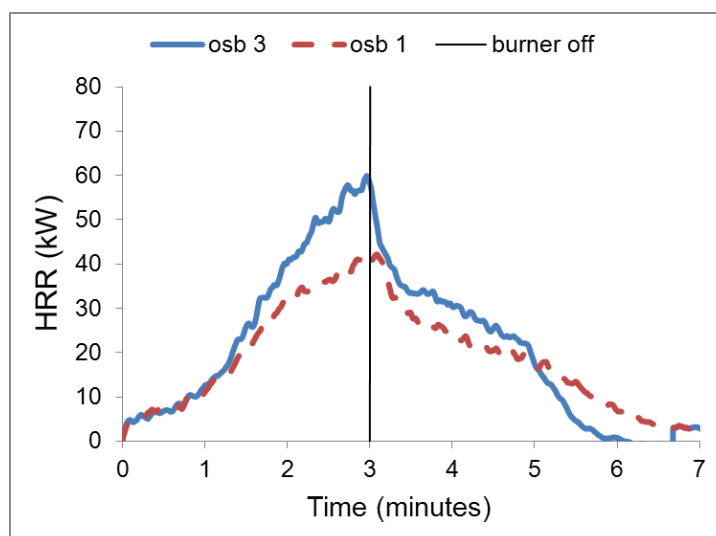


Figure 11 shows the intermediate fire performance of various untreated wood. The graphs show a slight accelerative HRR profile during most of the 3 minute pilot burner exposure. The apparent dampening of their HRR at around 2 minutes is the result of lateral flame spreading that covers the full width of the boards by 3 minutes. The HRR goes only as high as 50 kW, which gives a measurable visual flame height. Upon turning the pilot burner off, all wood products were decreasing in HRR values, each to its own rate of decrease. It is interesting that the redwood shown by the dotted curve has slightly higher HRR than that of OSB and plywood, which is inconsistent with their flammability ranking via FSI. However, test replications of these samples under strict conditioning should be done for verification. The visual flame heights during this stage of extinguishment showed inconsistent results. These untreated woods will eventually self-extinguish unless there is a gust of air, or an ignition source is reapplied. However, the FRT SP plywood will be difficult to reignite given the char layer developed, and the quite low heat of combustion for any further volatile emissions.

Figure 12
Modified Schlyter test of OSB replicates.



To address partially the testing replication situation, Figure 12 shows that for two different OSB samples, the upward flame spread is essentially the same between them for almost 2 minutes, but will diverge during the lateral flame spreading between 2 and 3 minutes. Indeed, the OSB test shown by the solid curve has HRR higher than the Redwood's in Figure 11. This should be investigated further with more replications of various samples, to determine if the burner head is adequate, or if the problem is due to material inhomogeneity specifically of the OSB board.

CONCLUSION

It is evident from test results of wood with MLC that the sensible heat release rates measurement are important for ranking of wood materials, and also for establishing wood fire properties for use in fire growth models. However, this required improving the HRR measure via use of a thermopile on the chimney wall to successfully compensate for radiant heat losses. Calibration of the HRR based on the thermopiles with the heat release rates of ethylene glycol and PMMA was an improvement over the manual methane calibration. This calibration provided for reasonable values for the heat of combustion of both untreated and treated wood. The HRR of ethylene glycol and PMMA in the MLC were also used to verify the HRR hood's oxygen consumption method for the low levels of HRR as low as 0.5 kW. This improvement in accuracy for the HRR hood provided a new HRR criterion to be developed for the modified Schlyter flame spread test that supplant the flame height criterion,. Furthermore, the modified Schlyter flame spread test has a unique self-extinguishment feature in the test, in which after the burner is shut off, the HRR gradually decreases for the untreated wood materials, and suddenly extinguished in the case of FRT SP plywood. We have developed a data acquisition system for implementing ASTM E2102 for the MLC containing our improvements in a MS Excel, with macros.

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