ROOM/CORNER TESTS OF WALL LININGS WITH 100/300 kW BURNER

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ABSTRACT

Six room/comer tests of common wall linings were conducted with gypsum-lined ceiling exposed to propane burning at 100 kW for 10 min followed by 300 kW for 10 min. This test protocol is an option provided by ISO 9705. The flashover event occurred at 1,000 kW rate of heat release within several seconds of observing flames out the doorway. The time to flashover of the fire-retardant-treated polyurethane foam was 10.5 rein, which contrasts with no flashover for some melting materials exposed to propane burning at 40 and 160 kW. The time to flashover for all the wood materials tested ranged widely from 3 to 15 rein, with the longest times for fire-retardant-treated plywoods. This result provides effective indications of fire performance for common materials. A correlation between time to flashover with flame spread index from ASTM E84 along with thermophysical properties measured in the cone calorimeter is presented.

INTRODUCTION

A number of countries are looking at ISO methods as a possible replacement for obsolete reaction-to-fire tests. Recent work at the Forest Products Laboratory (FPL) related to this effort have concentrated on developing input data, validation data, and model algorithms for compartment fire models. Input data have included heat release data, [1-3] ignition data,[4] and better characterization of the burner.[5] Previous data from room tests were based on the North America exposure program of 40 kW for 5 min and 160 kW for 10 min. [6-8] Activity on model algorithms has included evaluation of the Ohio State University model[9] and development of algorithms for ignition and flame spread. Recent joint work between the FPL and the American Forest & Paper Association (AF&PA) was reported by Janssens[10] in his dissertation on the fundamental thermophysical characteristics of wood and their role in enclosure fire growth.

The most scientifically advanced proposal for evaluating reaction to fire of materials was developed in the Nordic countries a few years ago. Referred to as the EUREFIC proposal, its classification system is based on performance (time to flashover) in the ISO 9705 room/corner test. ” This performance can be measured directly in the full-scale test. or it can be calculated with a simple computer model on the basis of small-scale measurements in the ISO 5660 test.[12] Work on the appropriate room bum test protocol and the relationship between full-scale tests and bench-scale tests such as the cone calorimeter were conducted in Finland,[13] Sweden,[14,15] Canada.[16] and elsewhere. However, this proposal needed modification mainly because the severity of the room test protocol resulted in the highest sensitivity for materials with low combustibility.

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[a] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

The ISO 9705 room/comer test consists of an enclosure 2.44 m wide, 3.66 m deep, and 2.44 m high, with a ventilation opening (doorway) 0.8 m wide and 2 m high in the front wall. Samples of the material to be tested are mounted on the walls and/or the ceiling. Nordic countries use materials installed on both wall and ceiling, whereas tests in North America use materials on walls only. A propane gas burner source is located in one rear corner in contact \\ith the rear wall and one side wall. Two principal programs for the burner are (a) 100 kW for 10 min followed by 300 kW for another 10 min (used in the Nordic countries) and (b) 40 kW for 5 min followed by 160 kW for 10 min (originated in North America). All combustion products emerging through the doorway are collected in a hood and are extracted via an exhaust duct. Heat and smoke release rate are measured continuously in the duct. The principal performance criterion is time to flashover.

This paper is a progress report on room/comer tests that are part of the "Room/Corner Test and Reaction to Fire of Wood and other Building Materials" project being conducted under the auspices of the U.S.–Slovak Science and Technology Program. The primary objective is to develop an alternative system to assess reaction to fire of materials. On the one hand, the severity of the 100/300-kW program with materials on both walls and cei I ing (as in the EUREFIC proposal) resulted in short and fairly close values in the times to flashover for building products with normal reaction to fire. On the other hand, a recent international round robin under the auspices of the American Society for Testing and Materials (ASTM) Institute for Standards Research (ISR) indicated that the 40/160-kW program with miterial on walls only is problematic for some melting products. That is, during the 40-kW exposure, the material in contact with the ignition source flame melts and shrinks away from it, so that an insufficient amount is left after the change to 160 k W to cause flashover. Limited test data and preliminary modeling results indicate that the aforementioned anomalies may be resolved by combining the two test protocols. The resulting protocol calls for the Nordic 100/300-kW burner program, but with test samples on walls only.

Secondary objectives are to relate the room test results to data from the cone calorimeter and to results from fire growth models. The cone calorimeter is the currently accepted method for obtaining rate of heat release of materials, which is the critical material property that drives fire growth. Fire growth models allow the experimental results to be extrapolated to other fire scenarios and to other reactions to fire tests, such as ASTM E84 used in North America for building codes.

The first part of this paper describes the room/corner tests for six selected materials with fire performance characteristics spanning a relatively wide range. The second part describes the correlation of time to flashover with cone calorimeter data and with flame spread index (FSI) of ASTM E84 using a rudimentary flame spread model.

REACTION TO FIRE INDICATIONS OF TEST MATERIALS

The room fire tests followed the procedures specified in ISO 9705, except that only the walls were covered with the test materials. The ISO 9705 burner was used in the corner with the exposure program of 100 kW for 10 rein, followed by 300 kW for 10 min. In previous tests at FPL,[7,8] we used the large burner specified in a proposed ASTM standard and a burner program of 40 kW for 5 min followed by 160 kW for 5 min. For the earlier tests, a mass flow controller was used to regulate the propane flow to the burner. For the present tests, a second mass flow controller was installed, with propane gas flowing from a second tank in order to conduct tests at the 300-k W propane burner output. Both electronic mass flow controllers were calibrated to be in close agreement **(3%** difference) with decreasing mass of the propane tanks and with a laminar flow device installed in the gas line between the mass flow controllers and the burner. Great emphasis was given to reach close agreement (5% difference) for rate of heat release (RHR) calculated from the measurements of oxygen consumption with that calculated from the propane mass flowrate. Additional signal conditioning and an averaging technique wm applied to measurements of temperature, differential pressure. oxygen. carbon dioxide, and carbon monoxide in the exhaust duct to reduce bias and noise in the calculation of RHR from oxygen consumption. We used a laser smoke system similar to the cone calorimeter (ASTM E 1354) instead of the white light system. The procedures in ISO 9705 include measurements with thermocouples and fluxmeters at various places. In addition to these data, we obtained differential pressures around the room opening for use in model validation as explained by Tran and Janssens.[7]

As a primary indication of reaction to fire, the time to flashover can be measured by different criteria. Its timing at flames exiting the doorway is unambiguous, but it is subject to human error. Thus objective criteria have been proposed in the literature; for example, >600°C top of doorway temperature, >20 k W/m^2 floor flux, [17] and >1,000 kW RHR.[18] There is the question of whether just one or all criteria must be satisfied to define a flashover condition. Even if the thermocouples and fluxmeters are properly calibrated and positioned, they seem most subject to false or sporadic indications of flashover because of their sensitivity to thermal radiation from the hot soot layers in flames and the upper gas layer. Thus in recent years, the RHR has gained in importance as an objective criterion, particularly if it has a good potential of correlation with cone calorimeter data. However, the actual critical level of RHR for flashover may depend on the ignition and/or material lining protocol. For example, in our previous room bum tests with ceramic fiber linings,[7] floor fluxes exceeding 20 kW/m^2 corresponded to an RHR of about 500 kW for the ASTM burner against the center of the wall and to an RHR of about 700 kW for the ASTM burner against the room corner. In addition, some materials give rise to a double peak feature in RHR as a function of time.

Test Materials

Test materials and their characteristics and thermophysical properties are listed in Table 1. The properties were derived by cone calorimetry (see companion paper in this Proceedings by Grexa, Janssens and White). The cone calorimeter data for test 52 may need revision for testing on Douglas Fir ply as the exposed surface rather than pine ply facing. The thermal diffusivity values in the last column are values for similar materials obtained from the literature, taking into account density, moisture content, and temperature as appropriate.

Materials remaining from the ASTM/ISO round robin test series were used for tests 50, 53, 54, and 55. The materials for tests 51 and 52 were obtained from Forintek Canada, which is conducting similar tests at the National Research Council of Canada facilities in Ottawa.

Calibration of Ignition Burner

Our calculations of RHR from consumption of propane gas and from depletion of ambient oxygen were based on formulas in Annex F of ISO 9705; they agreed to within 5% during

Table 1. Characteristics and thermophysical properties of test materials

Test[a]	Density (kg/m^3)	Thickness (mm)	Peak RHR (kW/m^2)	$\Delta H/L$	T_{ig} (K)	$\lambda\rho C$ (kW/m^{2}K)^2 s	$\lambda/\rho C$ (mm^2/s)
50	558	11.8	113	1.57	635	0.45	0.16
51	479	13.0	294	2.79	553	0.47	0.16
52	599	11.5	71	0.66	676	0.45	0.16
53	541	11.5	222	2.71	628	0.24	0.16
54	29	23.0	71	1.49	545	0.042	0.25
55	1,511	16.5	97	1.26	614	0.46	0.13

[a](50) fire-retardant-treated (FRT) Douglas Fir plywood (ASTM); (51) oak veneer plywood (Forintek); (52) FRT plywood (Forintek); (53) Douglas Fir plywood (ASTM); (54) FRT polyurethane foam (ASTM); (55) gypsum, 16-mm-thick type X (ASTM).

steady-state burning of the ignition burner. However, the two calculations sharply disagreed during step changes in propane mass flow rates, even when the ignition burner was located under the exhaust hood. This is the reason for the ISO recommendation to place the burner at the comer of a noncombustible room and to use the oxygen depletion method to calibrate the contribution by the burner during an actual room burn. This approach would require reproducibility in the burner profile during the test. Since the mass flow controllers provide rapid and precise control of propane mass flow rate during step changes, their signals are utilized to define the bum rate profile during an actual test.

The source of disagreement between the two. methods of computing RHR during step changes are the time constant and time shifting of the gas sampling system. When span calibration gases were used in step concentration changes of oxygen, carbon dioxide, and carbon monoxide, the besmearing of their measurement signals to true signals (deconvolution)--assuming an exponential system response function—resulted in a time constant of 10 s. While the ignition burner was operative, changes in the pressure of the bidirectional probe caused by step changes in exhaust venting or changes in the exhaust duct temperatures caused by step changes in propane flow rates corresponded to changes in the gas sampling signals to define time shifting of the gas sampling system. This resulted in a gas-sampling time shift of 60 s for test 52 and a time shift of 51 s for the other tests. Since the data from measurements of gas concentrations during a calibration bum were noisy, a deconvolution of these data resulted in noises that overwhelmed the true measurement.

The alternate approach is to convolute or smooth the data from the mass flow controllers, bidirectional pressure probe, and duct temperatures with a time constant τ of 10 s, shift the gas analysis data by the time lag in the gas lines, and then utilize processed data for computation of the RHR. This process is explained in more detail as follows. The convolution of the true signal S, with an exponential system response S_r is

$$S_r(t) = \int_0^t \frac{1}{\tau} \exp\left(\frac{-(t-\varepsilon)}{\tau} \right) S_t(\varepsilon)\, d\varepsilon \qquad [1]$$

If the true signal occurs in step changes as in

$$S_t(t) = \sum \left[S_t(t_{i+1}) - S_t(t_i) \right] H(t - t_i) \qquad [2]$$

where is H(t) is the Heaviside function, then the exact solution for the convoluted signal is

$$S_r(t_n) = S_t(t_n) - \sum_{i=-\infty}^{n} \left[S_t(t_i) - S_t(t_{i-1}) \right] \exp\left(\frac{-(t_n - t_{i-1})}{\tau} \right) \qquad [3]$$

For computational purposes this equation is converted to the recursive formula

$$S_r(t_n) = S_t(t_n) - \left[S_t(t_n) - S_r(t_{n-1}) \right] \exp\left(\frac{-(t_n - t_{n-1})}{\tau} \right) \qquad [4]$$

which mimics a first-order low-pass recursive filter. Thus, the noisy data from the bidirectional pressure probe are smoothed and step changes are made to be in phase with the data from measurements by using $\tau = 10$ s. We note that Equation [4] can be rearranged to solve for the true signal from the measurement signal (that is, deconvolution). but it is only effective for a smooth measurement signal, and a true signal that occurs in steps. In any case, Equation [4] was also applied to the mean of the duct temperatures and the RHR of the propane mass flow rate obtained from the two mass flow controllers. The good comparison with RHR from the oxygen consumption formula is shown in Figure 1 for the required calibration of the ignition burner in steps of 100 and 300 kW. The implication of this result is that for fire growth model validation purposes, the calculation of system convolution as represented by Equation [4] should be applied to model predictions to mimic the time constant of our gas sampling system. Note also that in Figure 1, we did not quite reach 300 kW during the calibration tests, but made the corresponding adjustments to the mass flow controller voltages for the room burn tests for better accuracy.

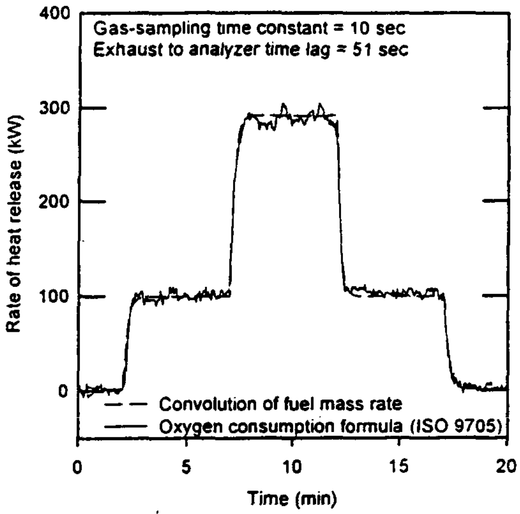

Figure 1. Calibration of ignition propane burner

Room Burn Tests

As a preliminary to tests 50 to 55, we performed a corner-room bum test with a gypsum board wall-lining to verify our ability to calculate RHR of the ignition burner. The agreement between the two different RHR calculations was better than **5’%0** at the 100-kW level afier reaching steady state. However, there were additional time lag aid slower response during step changes of RHR as a result of gas flow spreading on the ceiling of the room, exiting the doorway, and rising up the exhaust hood before mixing with the rapidly flowing ambient air. Thus, a preconvolution with a time constant of 20 s and a preshifiing of 3 s was applied to the comer ignition burn along with the convolution and shifting due to the gas sampling system to obtain agreement with RHR from the oxygen consumption method. If a fire growth model does not take into account this apparent diffusion of gaseous product concentrations, then preconvolution and preshifiing of model predictions can be similarly performed. In evaluating tests 50 to 55, the time constant and time shift remained the same for all tests.

Figures 2 to 7 show the results of RHR calculations for tests 50 to 55. Only test 55, with the gypsum wall lining, did not flash over and maintained an RHR below 400 kW for the duration of the test. The apparent 75-kW increase in RHR after pulling to higher exhaust flow near 1,200 s may be extraneous, and a repeat test is planned. The behavior of the ignition burning rate was clearly shown in the figures as a function of the propane mass flow rate, as explained in the previous section on RHR. The first five tests all indicated a peak in RHR upon step changes in the propane flow rate. The secondary rapid high rise in RHR occurred near the observed flame from doorway and would have resulted in a second high peak had we not extinguished the room fire after the flashover. For test 52, the FRT plywood (Forintek) showed a peculiar peak in RHR above 1000 kW at 800 s (Fig. 4) and apparently resulted in doorway temperatures above 600^{o}C, as evident by pulling to the highest exhaust flow. However, the other flashover criteria were not exceeded at the peak. The high exhaust flow after the peak could lead to greater errors in computation of RHR and may explain the observation of flame from the doorway at RHR above 1000 kW for test 52. In the other tests with flashover, flame from doorway was significantly below 1000 kW, although there was a small time lag from the doorway to the gas sampling probes. Thus, for future tests, we have modified our protocol to pull the vent to the highest flow rate after observing flame from the doorway and shutting off the ignition burner. The fan blower may be adjusted to a higher set point to prevent escape of smoke from the collecting hood.

The results suggest that 1,000 kW is an adequate objective criterion provided that it is in the **close** vicinity of observed flame from the doorway and thereby avoids confusion with the RHR peak that often occurs with step changes in the ignition burner. The actual times to flashover for the tests are listed in Table 2. The next best criterion is the exiting upper layer temperature of 600”C with a time lag of up to 45 s after observed flame out of doorway. The criterion of 20 kW/m^2 at the floor seems more uncertain, and in particular it failed in the case of test 53. The time to flashover of both non-FRT plywoods was less than 10 rein, during which 100 kW of ignition was being applied. All of the FRT materials tested had times to flashover between 10 and

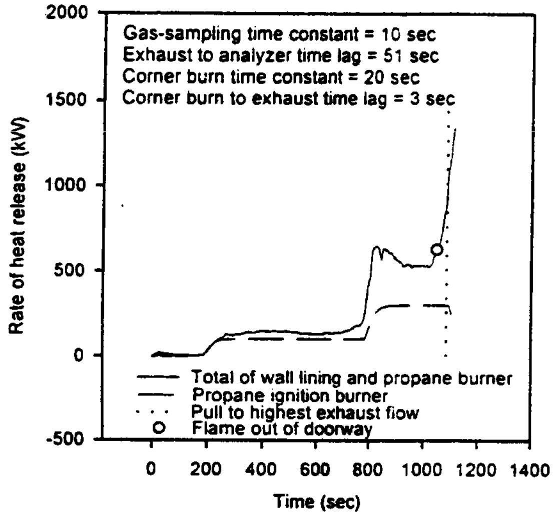

Figure 2. Test #50, FRT plywood, Round Robin

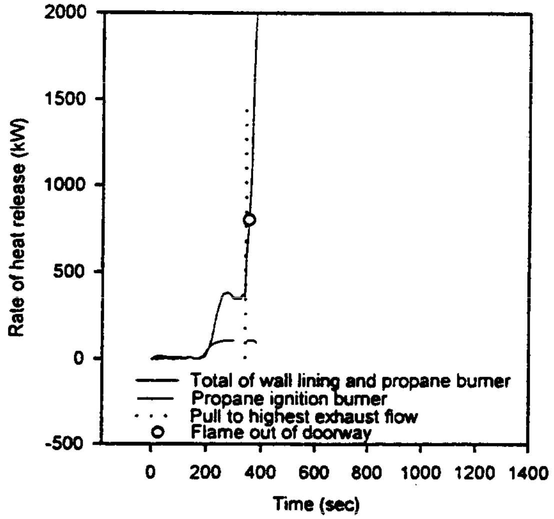

Figure 3. Test #51, Oak veneer plywood, Forintek

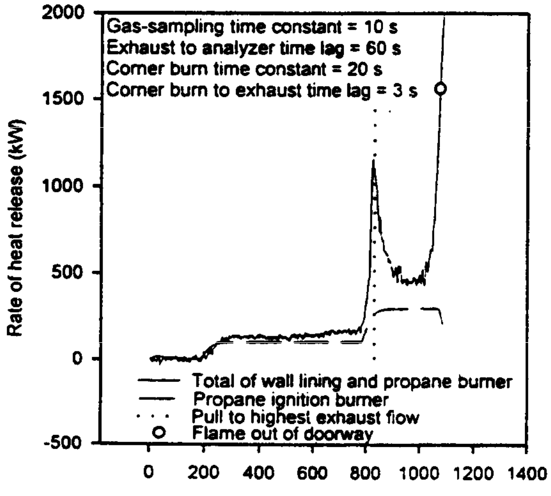

Figure 4.Test #52, FRT plywood, Forintek

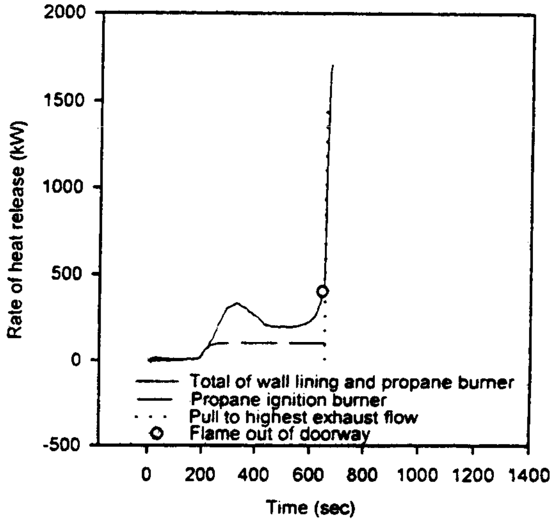

Figure 5. Test #53, Douglas fir plywood, Round Robin

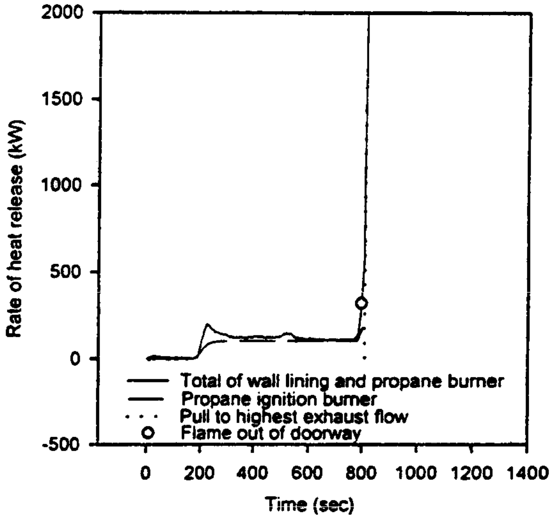

Figure 6. Test #54, FRT polyurethane foam, Round Robin

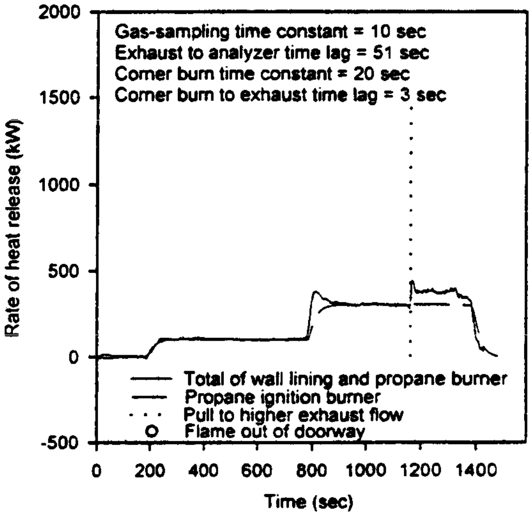

Figure 7. Test #55, Type X Gypsum board, Round Robin

Table 2. Times to flashover and ASTM E84 FSI of test materials

		Time to flashover (min)				
Test	Material	Flame from doorway	1000 kW	600°C	20 kW/m^2	FSI
50	FRT plywood ASTM	14:30	15:09	15:15	15:27	17
51	Oak veneer plywood	2:53	3:00	3:24	3:24	155 est
52	FRT plywood Forintek	14:55	14:42	14:36	14:42	—
53	Douglas Fir plywood ASTM	7:45	7:57	8:27	—	91.2
54	FRT polyurethane foam	10:30	10:30	10:36	10:24	23.9
55	Gypsum board	—	—	—	—	9.1

20 min, during which 300 kW of ignition was being applied. Finally, the limited combustibility gypsum board did not flash over. This appears to provide an effective discrimination of common materials for reaction to fire and provides a promising basis to compare with other reaction-to-fire tests and fire growth models.

CORRELATION OF ROOM/CORNER TEST RESULTS

As shown in Table 2, the ASTM E84 Flame Spread Index (FSI) decreased montonically with increasing time to flashover. This suggests a closer examination of the E84 test, which may reveal similarities with the room burn tests. Basically the E-84 test also uses an ignition burner (set at 79 kW), but the fire growth is wind-aided (at 1.2 m/s) along the ceiling of the 7.6-m-long tunnel. Further details and review of studies of the E84 test can be found in a paper by Janssens.[19] In this paper, we provide reliable data for FSI from ASTM round robin and thermophysical properties from cone calorimetry (see Table 1). In addition, Quintiere's flame spread model[19] for E84 test was modified to achieve better prediction. Without going into details, the intent of calculating FSI in the ASTM E84 test is that it is inversely proportional to time of arrival of flame at the position 7.6 m. For some materials, flame spread occurs very slowly or even erratically, which is accounted for by special calculation methods for obtaining FSI. An analogous flame spread index concept for the room burn is the inverse of the time to flashover (flame from doorway). A rudimentary quasi-steady equation for flame spread is given by

$$\frac{dA_p}{dt} = \frac{\beta A_p}{\gamma} \tag{5}$$

β is a dimensionless parameter that relates the size of pyrolysis zone to the characteristic size of a heating zone that corresponds to a surface temperature rise from ambient to ignition. The heating zone in the tunnel test corresponds to flame in assisting flow and results in Equation [6][19]

$$\beta = 0.00188(\dot{q}'')^{1.25} \tag{6}$$

whereas the heating zone for a room has a dependency on development of room thermal radiation and is assumed to be proportional to Equation [6]. A more advanced model (see companion paper by Janssens et al.) would calculate values for surface temperatures preheated by thermal radiation and use localized flame-spread-rate formulations to account for heating from preheated surface condition to ignition. Thermal time response term, γ, results from theoretical analysis of the flame spread rate with one expression for thermally thick material and a different expression for thermally thin material as follows:

$$\gamma_{\text{thick}} = \lambda\rho c\left(\frac{T_{\text{ig}} - T_{\text{s}}}{\dot{q}_{\text{f}}''}\right)^2 \qquad [7]$$

$$\gamma_{\text{thin}} = \frac{\rho c\delta(T_{\text{ig}} - T_{\text{s}})}{\dot{q}_{\text{f}}''} = \delta\sqrt{\gamma_{\text{thick}}/\alpha} \qquad [8]$$

Net heat flux from flame at pyrolysis front, $\dot{q}_{\text{f}}''$, is related to heat release flux, $\dot{q}''$, in the equation

$$\dot{q}_{\text{f}}'' = \dot{q}''\frac{\Delta H}{L} \qquad [9]$$

The heat release flux is assumed to be the peak value measured in the cone calorimeter with the external radiant flux set at 50 kW/m^2. Thermal properties and ignition temperature are determined from the ignitability analysis using several materials, as shown in Table 1. Integrating Equation [5] over the flame spread distance of 7.6 m in the tunnel results in the proportionality relationship

$$\text{FSI} \propto \beta/\gamma \qquad [10]$$

Results are shown in Figure 8. Best results were achieved using the thermally thin response term, Equation [8]. A thermally thin response for our test materials is expected because a test typically takes a few minutes to complete. The closed circles are perhaps the most reliable data in that identical materials were used in round robin tests for FSI, for our room burns, and for O. Grexa's cone calorimeter data. The actual correlation is the following formula (using data from Table 1 and with $r^2 = 0.99$):

$$\text{FSI} = -11.5 + 3660\left[0.00188(\dot{q}'')^{2.25}\Big/\left(\delta\sqrt{\frac{\lambda\rho c}{\alpha}}\,\frac{L(T_{\text{ig}} - T_{\text{s}})}{\Delta H}\right)\right] \qquad [11]$$

The data indicated by open symbols in Figure 8 are less reliable because some thermal properties were derived using ASTM E1321 methods or the FSI was estimated using similar materials. The

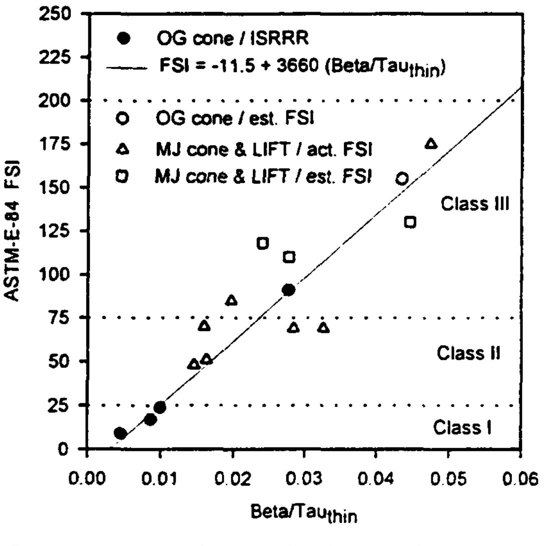

Figure 8. Data of E84-FSI plotted with B/T

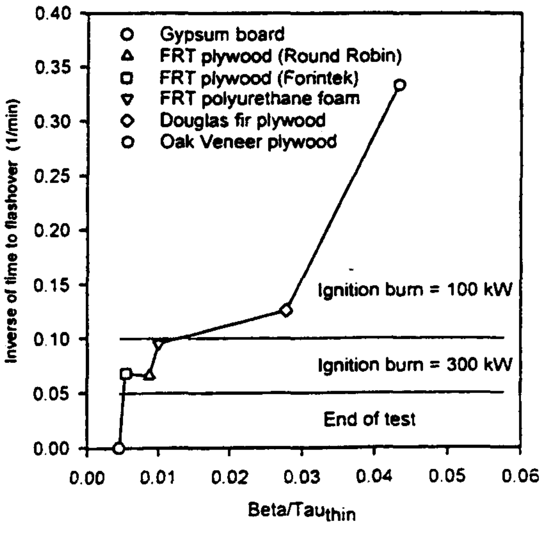

Figure 9. Relation between time to flashover and flame spread terms

similarity for room bum through the use of the flame growth Equation [5] is shown in Figure 9 as inverse of time to flashover plotted as a function of Equation [6] over Equation [8]. The apparent discontinuity at time of flashover at 10 min could be interpreted as the increase needed in the size of fire (increasing the coefficient in Equation [6]) to increase flame spread sufficiently to flashover before material burnout occurs. As a note, the data indicated by the open square is considered tentative because new calorimeter data will be obtained for the FRT plywood (Forintek) on the same exposed side as that tested in the room burn. In comparing Figures 8 and 9, it is evident that for some Class I materials, which are treated with fire retardants, flashover took longer than 10 min and for Class III materials, flashover took less than 10 min. The gypsum board, a Class I material with the lowest FSI of 9, did not flash over. These results show the very effective discrimination of the fire performance of common materials with the "100/300-kW ignition-wall linings only" protocol. We are conducting more room tests to have more data to prescribe a correlation function.

CONCLUSION

By using wall linings with gypsum-lined ceiling exposed to propane burning at 100 kW for 10 min followed by 300 kW for 10 rein, the room/comer tests of common materials indicate an effective differentiation of fire performance. Time to flashover of untreated plywood was less than 10 min, whereas that of fire-retardent-treated materials was greater than 10 min. Of course, the gypsum board wall lining did not flash over. A rate *of* heat release (RHR) of 1000 kW is a suitable objective criterion provided that it occurs near the observed flame from doorway. We describe a successful use of a rudimentary flame spread model to explain and correlate the room/comer time to flashover and ASTM E84 flame spread index (FSI) with the cone calorimeter data. The key derived parameters for correlation were flame characteristic length and ignition characteristics of a growing fire, which is consistent with the literature. The result of plotting the inverse of time to flashover with the key parameters indicated a discontinuity at the time to flashover of 10 min. More room tests will be done to solidify these conclusions and provide more data for functional correlations.

NOMENCLATURE

A_p	Pyrolyzing rectangular area with one edge moving at a time (m^2)
c	Heat capacity of material (kJ kg^{-1} K^{-1})
ΔH	Heat of combustion at peak RHR (kJ kg^{-1})
L	Effective heat of pyrolysis at peak RHR (kJ kg^{-1})
$\dot{q}''$	Peak heat release flux for 50-kW/m^2 exposure (kW m^{-2})
$\dot{q}_f''$	Net heat flux from flame to pyrolysis area (kW m^{-2})
S	Experimental signal for data acquisition (V)
t	time (s)
T	Temperature (K)
α	Thermal diffusivity (m^2 s^{-1})
β	Ratio of characteristic flame size to pyrolysis size
γ	Thermal time response term (s)
δ	Material thickness being heated (m)
λ	Material thermal conductivity (kW m^{-1} K^{-1})
ρ	Material density (kg m^{-3})

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