IGNITABILITY OF MATERIALS IN TRANSITIONAL HEATING REGIMES

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Abstract

Piloted ignition behavior of materials, particularly wood products, during transitions between heating regimes is measured and modeled in a cone calorimetry (ISO 5660) heating environment. These include (1) effect of material thickness, density, moisture content, and paint coating variations on thermal response characteristics, (2) effect of fire retardant treatment concentration on smoldering and flashing prior to flaming ignition, and (3) effect of cone irradiance on inducing convective heat loss of the material. Thermophysical properties of volumetric heat capacity or thermal conductivity as functions of temperature and moisture content are obtained from available independent sources. Values of ignition temperature or adjustments to thermal conductivity are derived from a least-squares fit of cone irradiance as a nonlinear function of time to ignition. Independent measures of ignition temperature and thermal conductivity for redwood are in very close agreement with derived values. For 16 additional materials, which span a wide range of flammabilities, the reasonable values for material properties of heat capacity, thermal conductivity, surface emissivity, and ignition temperature are provided for use in mathematical fire models, such as the Fire Dynamic Simulator from NIST-BFRL.

BACKGROUND

Atreya (1998) provided the fundamental understanding of fire ignition, particularly for wood-type materials. He derived that the optimum location of the pilot is the eventual location of the steady diffusion flame. Furthermore, a critical value of fuel flow rate overcomes flashing (thermal quenching of the premixed flame propagating from the ignition source) in transitioning to the sustainable diffusion flame. He also derived that for a given set of kinetic parameters (for gaseous and solid phases), the surface temperature and the critical fuel mass flux at ignition are essentially independent of the external flux. If negligible thermal decomposition occurs prior to ignition, then one can assume that (i) surface temperature incorporates most of the effects of decomposition kinetics and may be assumed constant at ignition and (ii) an inert solid solution may be used for determining the ignition delay, as long as surface heat loses are correctly accounted. However, difficulties with this view of "wood" ignition can be shown by observations of smoldering occurring several seconds prior to ignition on certain woods at typical external flux (Bilbao and others 2001). Furthermore, it appears that in gypsum board with a thin paper facing, the volatiles are depleted and/or diluted by moisture from gypsum dehydration during low-level fluxes (Janssens 1991). Indeed, Dietenberger (1996) warned of these difficulties in his studies of redwood ignition in the LIFT apparatus (ASTM 1321) and the cone calorimeter (ISO 1993). He further found significant differences between the two apparatus in time to ignition data as function of heat fluxes, which he attributed to significant differences in convective cooling of the samples from the "chimney" airflow induced by the radiant heating elements.

Wesson and others (1971) examined piloted ignition effects on various lumbers of different oven-dried densities and thickness when exposed to two types of radiant heat source. Their choice of tungsten lamp and hexane flame as the two radiant heat sources had a significant effect on absorptance values for wood. Average absorptance of oven-dried wood is roughly 0.81, 0.76, 0.48, and 0.4, respectively, for hot plate, hexane flame, tungsten lamp, and solar radiation as heat sources. We note that typical radiant energy from the electric heating coils of the cone calorimeter has dominating wavelengths greater than those of either of Wesson's heat sources, in a region where spectral absorptance has small variations for various wood species (Wesson and others 1971). Therefore, we use a portable instrument that has a calibrated hot blackbody plate in which to measure emissivity ε_m (also equal to long-wavelength average absorptance) of the materials to be exposed to the cone heating

coils. The correlation for time to ignition reported by Wesson and others (1971) is applicable only to imposed heat fluxes significantly greater than the critical flux, because they did not explicitly consider radiation/convective heat losses or even variations in the ignition temperature.

In this study we applied two documented methods-those of Janssens (1991) and Dietenberger (1996)-for using time to ignition measurements for deriving the thermal inertia $k\rho c$, thermal diffusivity $k/\rho c$, and ignition temperature T_{ig}. These two methods were chosen because the ignition formula was designed to agree with theoretical heat conduction analysis as well as being convenient to use in a spreadsheet application. Janssens's method can be briefly summarized as follows: It was supposed that materials behaved as semi-infinite solid. Boundary condition of the exposed surface at the ignition time for gray-body materials was expressed by

$$\varepsilon_m \dot{q}''_{cr} = h_c(T_{ig} - T_a) + \varepsilon_m \sigma (T_{ig}^4 - T_a^4) \equiv h_{ig}(T_{ig} - T_a) \tag{1}$$

Time to ignition was correlated with irradiance by

$$\dot{q}''_e = \dot{q}''_{cr}\left\{1 + 0.73\left[\frac{k\rho c}{h_{ig}^2 t_{ig}}\right]^{0.547}\right\} \tag{2}$$

The critical irradiance level $\dot{q}''_{cr}$ was found as the intercept of the line (fitted to the plot of $(t_{ig})^{-0.547}$ versus q_e) with the abscissa. Ignition temperature T_{ig} was calculated from Equation (1) using the Newtonian iteration method, and subsequently h_{ig} was calculated from Equation (1). The $k\rho c$ parameter was found by inserting the slope of the experimental line into Equation (2). For ignition temperature calculation, the convective heat transfer coefficient h_c is needed. Dietenberger (1996) measured the convective heat transfer coefficient in the cone calorimeter in horizontal orientation as a function of external heat flux, expressed as

$$h_{c,cone} = 0.01433 + 1.33x10^{-4}\dot{q}''_e \tag{3}$$

However, this now introduces nonlinearity into Equation (2), causing us to use a different numerical procedure, a nonlinear regression routine like those available in spreadsheets. Janssens's method has the advantage that neither ignition temperature nor thermal inertia must be known, and both of these parameters can be obtained only from the ignition time measurements. However, thermal inertia and surface temperature at ignition obtained by Janssens's method are sensitive to small changes of the slope of time to ignition versus irradiance.

Dietenberger (1996) developed an accurate interpolation formula for finitely thick materials of thickness d_m with irradiation heating coupled with convective/radiation cooling on the exposed side and insulation on the unexposed side. The exposed side then reaches the surface ignition temperature. The interpolation formula fitted to finite element solutions of transient heat conduction as function of Biot and Fourier numbers is

$$\dot{q}''_e = \dot{q}''_{cr}\left\{1 + (F_{thick}^n + F_{thin}^n)^{(-1/n)}\right\} \tag{4}$$

where

$$n = (2.68 + 0.4Bi) / (1 + Bi) \tag{5}$$

$$F_{thick} = \sqrt{\frac{4}{\pi} Bi^2 Fo} \tag{6}$$

$$F_{thin} = \exp\left(\frac{BiFo}{1+0.254Bi}\right) - 1 \tag{7}$$

$$Bi = h_{ig}\delta_m / k \tag{8}$$

$$Fo = (k/\rho c)t_{ig} / \delta_m{}^2 \tag{9}$$

Indeed, Equations (4) to (9) can be used to show that the Janssens correlation (Eq. (2)) is sufficiently accurate only for $0.1 \le q_{cr} / q_e \le 0.9$ and $F_0 \le 0.1$ This limitation is satisfied for the test materials listed in Table 1, except for the thin hardboard and fire-retardant-treated (FRT) polyurethane foam (in its fully melted/collapse condition prior to ignition) and at irradiances less than or equal to 25 kW/m^2 for others, as we will show later. Because Janssens's correlation is quite commonly used and both Equations (2) and (4) have irradiance as dependent variable and time to ignition as independent variable, it seemed more appropriate to plot q_e versus $(t_{ig})^{-0.547}$ versus, as shown in Figures 1 to 9. We note that material parameters of density, thickness, moisture content, and surface emissivity are easily measured just prior to testing (see Table 1). In some cases, the remaining material parameters of thermal conductivity, heat capacity, and surface ignition temperature are available as independent measurements and can be used to predict ignitability data using Equations (4) to (9) (or Eq. (2) if satisfying the limitations), as we will show for redwood lumber. To make best use of the Equation (4) correlation, we note that thermal conductivity, heat capacity, and density are known well for solid woods as (TenWolde and others 1988, Janssens 1991, Parker 1988)

$$k_w = [(0.1941 + 0.004064\,M)(r_{od}\,x10^{-3}) + 0.01864]\,(T \times 10^{-3}/297) \quad kWm^{-1}\,K^{-1}$$

$$c_w = 1.25\,(1 + 0.025\,M)(T/297) \quad kJ\,kg^{-1}K^{-1}$$

$$\rho_w = \rho_{od}\,(1 + 0.01\,M) \quad kg\,m^{-3}$$

The thermal conductivity formula is correlated for solid wood in the direction perpendicular to the grain. It will vary with wood grain orientation or if the wood is modified (as in composites), but it should remain intact with variation in density, moisture content, and temperature. On the other hand the heat capacity of wood is not dependent on grain orientation and is conveniently measured in a testing apparatus. Equations (10) to (12) can be used for evaluating ignitability of solid wood provided that moisture content is evaluated at its initial value and temperature is evaluated at an average between room temperature and ignition temperature (Dietenberger 1996, Janssens 1991). That is, we make the substitution in our SigmaPlot or Excel spreadsheet nonlinear least-square solvers in conjunction with the previous equations as

$$k = r_w k_w(M_o, (T_a + T_{ig})/2), \quad c = c_w(M_o, (T_a + T_{ig})/2), \quad \text{and} \quad \rho = \rho_w(M_o).$$

So instead of deriving ignition temperature and thermal inertia by Janssens's correlation, we derive ignition temperature and thermal conductivity ratio r_w by Dietenberger's correlation. We note that with these recent developments, our earlier derived thermophysical properties should be ignored (Grexa and others 1996).

MATERIALS/PROCEDURE

All room-burn materials from our ISO 9705 tests, except gypsum board and FRT polyurethane foam, were wood products (Table 1). Four materials (2, 5, 6, and 7) were left over from the ASTM Institute for Standards Research round robin (Beitel 1994). Two materials (3 and 4) were obtained from Forintek Canada Corp. Seven materials (8 to 14) are from a wood industry material bank (MB) for fire research. The materials tested in the cone calorimeter were conditioned at 55 % RH and 23 °C.

However, additional special conditions were applied to redwood lumber to investigate the full predictive features of Equation (4).

Table 1 Characteristics of the tested materials

Material	Test no.	Thickness (mm)	Density (kg/m^3)	Moisture content (%)	Material emissivity
Gypsum board, Type X	1,7,15	16.5	662	—	0.9
FRT Douglas-fir plywood	2	11.8	563	9.48	0.9
Oak veneer plywood	3	13	479	6.85	0.9
FRT plywood (Forintek)	4	11.5	599	11.17	0.9
Douglas-fir plywood (ASTM)	5	11.5	537	9.88	0.85
FRT polyurethane foam	6	23	29	0.0	0.68
FRT Southern Pine plywood	8	11	606	8.38	0.9
Douglas-fir plywood (MB)	9	12	549	6.74	0.89
Southern Pine plywood	10	11	605	7.45	0.88
Particleboard	11	13	794	6.69	0.88
Oriented strandboard	12	11	643	5.88	0.88
Hardboard	13	6	1,026	5.21	0.88
Redwood lumber	14	19	421	7.05	0.86
White spruce lumber	16	17	479	7.68	0.82
Southern Pine boards	17	18	537	7.82	0.88
Waferboard	18	13	631	5.14	0.88

Cone calorimeter tests were conducted according to the procedure prescribed by ISO 5660. The samples were 100 by 100 mm, with the actual thickness. The retainer frame was used to minimize edge effects. The sample was located on a thick low-density ceramic fiber blanket, backed by a calcium silicate board, and tested in the horizontal orientation. In FPL's cone calorimeter the materials were also located directly on type X gypsum boards (material backing in room tests) and cement board (material backing in ASTM E84 tests). The irradiances used were 25, 30, 35, 40, 50, and 65 kW/m^2. For some materials, additional tests were conducted at lower irradiance levels and smaller heat flux increments. The tests were terminated when the average value of mass loss rate over a period of 1 min dropped below 150 $g/s\text{-}m^2$, effectively removing afterglow measurements.

IGNITABILITY ANALYSIS TO DERIVE THERMOPHYSICAL PROPERTIES

Solid Wood and OSB

Correlations of irradiance versus time to ignition are shown in Figures 1 to 3 for redwood and OSB, based on both Janssens's and Dietenberger's methods. Of the solid woods, redwood was the first to be evaluated because of the availability of measured surface temperature at ignition (thin thermocouple pressed into wood surface crevice created by a razor blade). Janssens (1991) reported measured ignition temperatures of 358°C, 369°C, and 394°C for thick redwood. In recent tests at FPL, average ignition temperatures of 353°C, 364°C, and 367°C for material thicknesses of 19, 1.8, and 0.9 mm, respectively, were measured. From Janssens's correlation we derived an ignition temperature of 380°C; from Dietenberger's correlation (Eqs. (4) to (12)) we derived an improved 365°C (638 K) for ignition temperature and $r_w = 1$ for thermal conductivity ratio using the SigmaPlot spreadsheet nonlinear least-squares function fitting (Fig. 2). We note that it is much easier in the spreadsheets to fit irradiance as a function of time to ignition rather than time to ignition as a function of irradiance. Figure 1 shows the prediction of Dietenberger's correlation, as time to ignition varies with irradiance, material thickness, moisture content, and paint coating, all the while using the thermophysical properties corresponding to $r_w = 1$ and $T_{ig} = 638$ K. Very recently we found that changing wood grain orientation also changes ignition temperature, as well as obviously affecting thermal conductivity and surface emissivity. One also notes the important role of surface emissivity measurements, as these

change with material thickness, moisture content, or paint coating. All these factors are inclusive within Dietenberger's correlation curves as shown in Figure 1 and which demonstrate the limitations of a simpler correlation as used in Figure 2.

Taking into account the noise level in Figure 2, both SDVU and FPL cone calorimeters are essentially in agreement on their measurement of time to ignition. The combined data sets are complementary in that there are more tests overall with the SDVU cone calorimeter, while more test data at extreme fluxes of 20 and 65 kWm^2 were obtained with the FPL cone calorimeter (as is also true for the other specimens). Also the FPL data include varying the specimen backing from insulation, to gypsum board, to cement board. It is evident that within the noise level, varying the backing has no effect on time to ignition, as we would expect if the material's ignition time is less than the arrival time of the irradiantly induced thermal wave to the material's back end. This is the fundamental reason for the Janssens correlation being limited to Fourier numbers less than 0.1. If we had used Equations (10) to (12) in Janssens's correlation in its valid regime, an ignition temperature agreeing with Dietenberger's correlation would be obtained. Work is underway to independently measure the thermal conductivity of the redwood sample (and of other specimens) as a check on Equation (10). Similar correlation was found for white spruce lumber and Southern Pine board (data not shown). The OSB (Figure 3) was included in this series of materials because it too was found to be consistent with the use of Equations (10) to (12) and r_w = 1. The derived thermophysical constants are provided in Table 2.

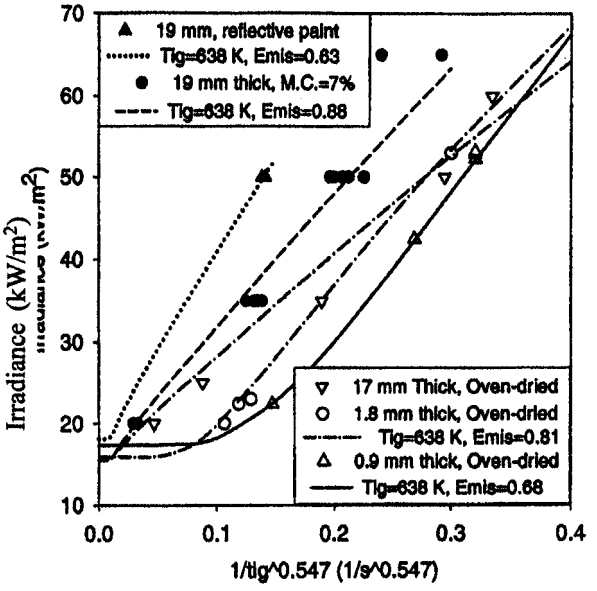

Figure 1. Prediction of redwood piloted ignition with varying irradiance, thickness, moisture content, and surface emissivity using Dietenberger's correlation

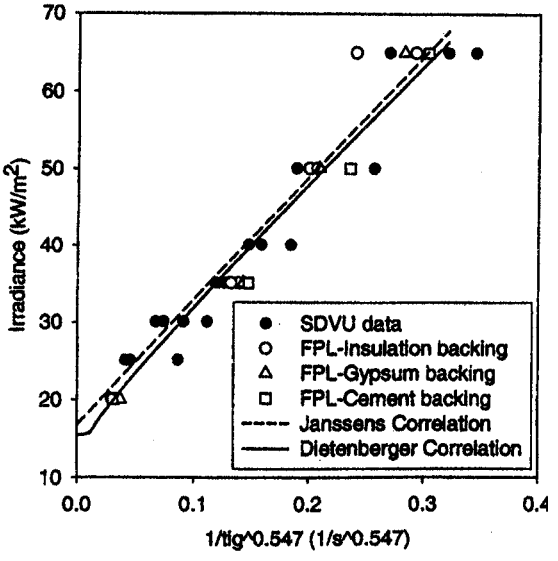

Figure 2. Correlation to piloted ignition data of redwood (ISO 14)

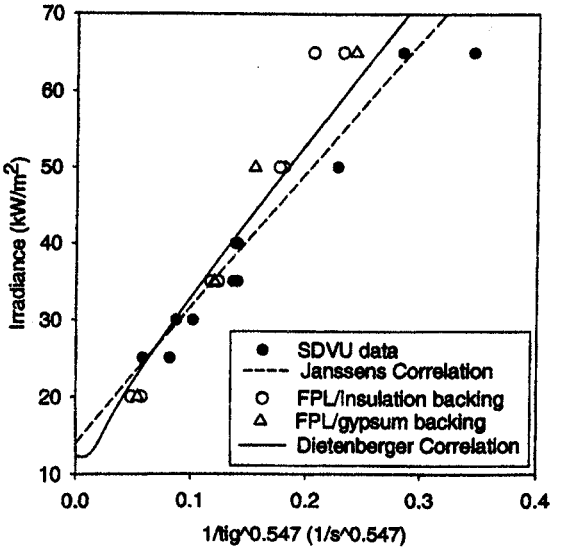

Figure 2. Correlation to piloted ignition data of oriented strand board (OSB) (ISO 12)

Table 2 Derived thermophysical parameters of ignitability

Material	Test no.	$k\rho c$ (MJ) [kJ²/m⁴K²s]	T_{ig} (MJ) [K]	$r_w = k/k_w$	T_{ig} (MD) [K]	$k/\rho c$ (m²/s) ×10⁷	$k\rho c$ (MD) [kJ²/m⁴K²s]
Gypsum board, Type X	1, 7, 15	0.519	603	N/A	608.5	3.74	0.451
FRT Douglas-fir plywood	2	0.515	623	0.86	646.8	1.37	0.261
Oak veneer plywood	3	1.103	577	1.11	563	1.77	0.413
FRT plywood (Forintek)	4	0.412	649	0.86	650	1.31	0.346
Douglas-fir plywood (ASTM)	5	0.282	608	0.863	604.6	1.37	0.221
FRT polyurethane foam***	6	0.033	545	N/A	689	4.91	0.0284
FRT Southem Pine plywood	8	1.209	615	1.43	672	2.26	0.547
Douglas-fir plywood (MB)	9	0.231	634	0.86	619	1.38	0.233
Southern Pine plywood	10	0.256	640	0.86	620	1.38	0.29
Particleboard	11	1.195	524	1.72	563	2.72	0.763
Oriented strandboard	12	0.244	621	0.985	599	1.54	0.342
Hardboard	13	0.4	624	0.604	593	0.904	0.504
Redwood lumber	14	0.165	653	1.0	638	1.67	0.173
White spruce lumber	16	0.286	615	1.0	621	1.67	0.201
Southern Pine boards	17	0.328	627	1.0	644	1.63	0.26
Waferboard	18	0.793	509	1.62	563	2.69	0.442

* MJ-T_{ig} and $k\rho c$ derived by Janssens's procedure.

** MD-T_{ig}, $k\rho c$, and $k/\rho c$ derived by Dietenberger's procedure.

*** Thickness prior to ignition is the melted/shrink thickness.

UNTREATED PLYWOOD AND WAFER BOARD

The next group of materials is the most easily ignitable of wood products because of their low ignition temperatures or low thermal inertia. The most thoroughly tested plywood is Douglas-fir plywood used in the ASTM round robin and corresponds to room test #5 of our ISO 9705 series of room tests. Figure 4 shows a high correlation coefficied for both Janssens's and Dietenberger's correlations ($r^2 > 0.97$). It is noted that at the irradiance of 15 kW/m², the Dietenberger correlation captures the long ignition time of around 1,000 s, corresponding to the Fourier number of unity, which is clearly a thermally thin behavior. Even at irradiance of 25 kW/m², the corresponding ignition time and its Fourier number are 135 s and 0.13, respectively, indicating that the transition to thermally thin behavior is underway. The derived thermal conductivity was found to be 86.3 % of that of the solid wood (listed as the ratio, $r_w = k/k_w$, in Table 2), in agreement with TenWolde and others (1988) for plywood. The corresponding derived ignition temperature was a reasonable value of 332 "C. The next material evaluated, another untreated Douglas-fir plywood, had a higher noise level than that in the previous plywood data. Indeed, these noise levels give rise to high tradeoffs between thermal conductivity and ignition temperature in optimally fitting the data. By setting the thermal conductivity to 86% of that of solid wood in the nonlinear regression solver, the ignition temperature is derived to be a reasonable 346 °C. Oak veneer plywood and wafer board result in derived ignition temperatures of 204 °C and 236 °C using the Janssens correlation. These unreasonably low values of ignition temperature are unavoidable with the Janssens correlation. If we were to set the ignition temperatures to a reasonable lower limiting value of 290°C, then the Dietenberger correlation fitted to the data results in reasonable derived values of thermal inertia and thermal diffusivity as given in Table 2 for these materials. The resulting Dietenberger's correlation appears to fit the data about as well as the Janssens correlation (not shown) and yet provide a more reasonable critical irradiance of 10 kW/m².

TYPE X GYPSUM BOARD AND FIRE-RETARDANT-TREATED PLYWOOD

One of the presuppositions in both procedures is that the materials are inert prior to ignition. This means that chemical degradation or dehydration of material is considered negligible prior to ignition. This is a reasonable assumption for untreated wood products. However, chemically treated wood products or Type X gypsum board behave in a significantly different way.

The correlation of ignition time versus irradiance for gypsum board is shown in Figure 5. For gypsum board the experimentally observed minimum irradiance level, below which no sustained burning occurred, was approximately 20 kW/m^2. The critical irradiance levels derived were 12.5 and 12.9 kW/m^2, respectively, for Janssens's and Dietenberger's correlations. Janssens (1991) and Dietenberger (1996) explained the difference between the minimum and critical irradiance for this type of material. At low irradiance levels, fuel volatiles are exhausted or quite diluted with water vapor from dehydration, which keeps the fuel mixture outside the flammability region in the gas phase, even at high temperatures adjacent to the spark plug. At higher irradiance levels, the minimum mass flu of volatiles to create a flammable mixture is generated before fuel exhaustion or extreme inert dilution (Dietenberger 2002). However, there were no problems in determining the ignition times at irradiances above 20 kW/m^2, and the data showed good linearity in Figure 5. Although ignition temperatures of 330°C and 335.5°C, respectively, for Janssens's and Dietenberger's correlations are reasonable, obtaining independent measurements for thermal diffisivity, thermal inertia, or even ignition temperature will be useful, given the high amount of dehydration occurring in the gypsum substance.

Three FRT wood-based materials were tested both in the cone calorimeter and room/corner test: FRT Douglas-fir plywood, FRT plywood from FORINTEK, and FRT Southern Pine plywood. Due to non-uniformity of the treatment and variance in the uptake, different kinds of burning behaviors were observed. In some cases the specimen was ignited, but the flame extinguished shortly after the spark igniter was removed. The flame did not always cover the whole surface of the specimen, mainly under lower irradiance levels. In some cases the heat release rate (HRR) had similar shape as that for untreated wood materials. In other cases only a single peak was observed. The variance of the specimen mass of the impregnated plywood materials was much higher than that for the untreated plywood materials. This also suggests that the tested FRT materials were less homogenous than the untreated wood materials.

In spite of the these problems, efforts were made to obtain representative ignition parameters from the cone calorimeter measurements. A major problem with evaluating experimental ignition data for treated wood products was the uncertainty of time to sustained ignition. Visually determined ignition times showed significant scatter. The largest problems of this kind were observed with the FRT Douglas-fir plywood. To overcome the visually observed errors of ignition, the criterion of heat release rate was chosen for this material and for FORINTEK FRT plywood. After some trial and error, HRR = 30 kW/m^2 was chosen as a suitable limit. With a lower value, some specimens extinguished their flames shortly after HRR had reached the threshold. This is consistent with Atreya's (1998) calculated value of critical fuel flux of 1.5 g/sm^2 needed to achieve sustained ignition for generic untreated wood at the ignition temperature of 650 K. This is assuming the initial ablated surface layer of generic untreated wood has a net heat of combustion around 20 kJ/g, resulting in a HRR of 30 kW/m^2 needed for sustained ignition of an arbitrary wood product. For the FRT Southern Pine plywood, the ignition times were possible to observe visually also.

In examining derived properties in Table 2, the higher values for time to ignition of FRT Douglas-fir plywood are primarily due to the higher ignition temperatures compared to the untreated Douglas-fir plywood. However, the FRT Southern Pine plywood has the highest values for time to ignition of all the materials due to its high values of both thermal inertia and ignition temperature (Figure 6). Results of Janssens's correlations for these materials instead primarily derived thermal inertias much higher than that of untreated plywood (Table 2). Since the one of the main processes of fire retardant treatments is to decrease tar production and increase dehydration of the wood substance, the heat of combustion of wood volatiles is significantly reduced for treated wood products. So to achieve the sufficient ignition criterion of HRR = 30 kW/m^2 requires a corresponding increase in critical volatile

mass flow rate achievable only with a higher surface temperature at ignition for treated materials, as Table 2 (and Figure 6) implies.

THICKNESS EFFECTS ON WOOD COMPOSITES

In this section we highlight the effects of material thickness on the derivation of ignition properties. The two thinnest materials, Southern Pine plywood at 11 mm and hardboard at 7 mm, have a considerable range of irradiances that should not be considered thermally thick. In the case of Southern Pine plywood (Figure 7), the irradiances of 30 and 20 kW/m^2 have derived Fourier numbers of about 0.1 and 0.6, respectively, at their times of ignition. Whereas, for the hardboard (Figure 8), irradiances of 40 and 20 kW/m^2 have derived Fourier numbers of about 0.1 and 0.65, respectively, at their times of ignition. Recall that the Janssens correlation is technically limited to Fourier numbers less than 0.1 but begins to show large errors at Fo > 1/3. We note that thermal diffisivity is a required parameter of Fourier number, which was used to indicate values of time to ignition for valid use with thermally thick heat conduction solutions. Mere examination of the data presented in Figures 7 and 8 show the linear trend through the noisy data, giving one a false notion that all the data fit within the realm of thermally thick behavior. We note also that the Fourier numbers in the transitional regime between 0.1 and 1.0 would not allow the use of thermally thin heat conduction solution to correlate time to ignition. This essentially leaves us with the Dietenberger correlation valid with any Fourier or Biot numbers, which is plotted in Figures 7 and 8. Table 2 shows that reasonable ignition properties are derived for these wood composites.

Certain materials having high thermal inertia (particleboard) have ignition behavior that is best fitted with a full regime correlation. The particleboard data (Figure 9) show a highly linear trend, so that the Janssens correlation fits the data extremely well ($r^2 = 0.97$). However, the ignition temperature is 251 °C (Table 2), which seems unreasonably low. Dietenberger's correlation provides an equally good fit to the same data but with a more reasonable ignition temperature of 290°C and a more reasonable lower value for the thermal inertia (Table 2). The two samples, oak veneer plywood and wafer board, discussed earlier, are described similarly. Because of the high tradeoff possible between ignition temperature and thermal properties with Dietenberger's correlation, and because of unexpected problems with Janssens's correlation, it would be useful to obtain independent measurements of thermal conductivity and heat capacity for particleboard.

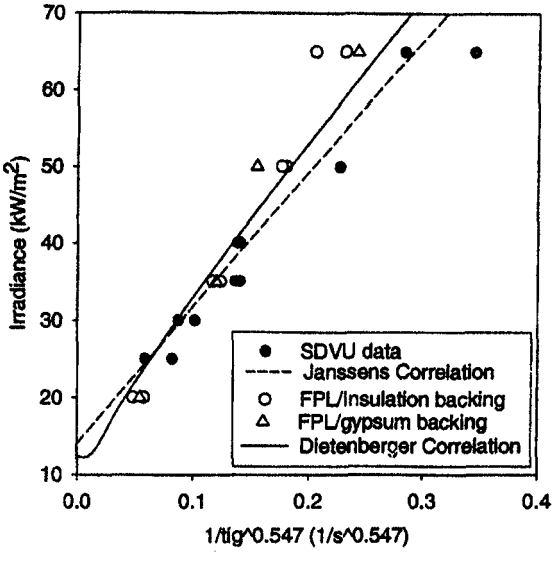

Figure 3. Correlation to piloted ignition data of Douglas-fir plywood (ASTM) (ISO 5)

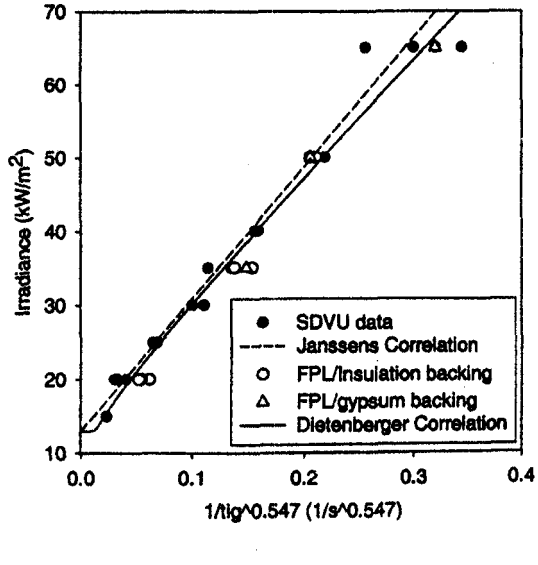

Figure 4. Correlation to piloted ignition data of Douglas-fir plywood (ASTM) (ISO 5)

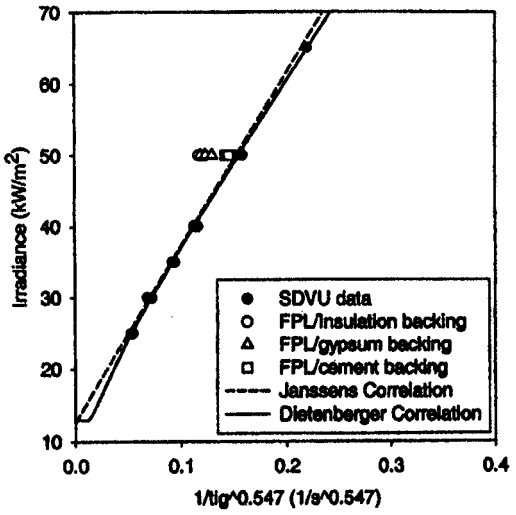

Figure 5. Correlation to piloted ignition data of Gypsum X (ISO 1)

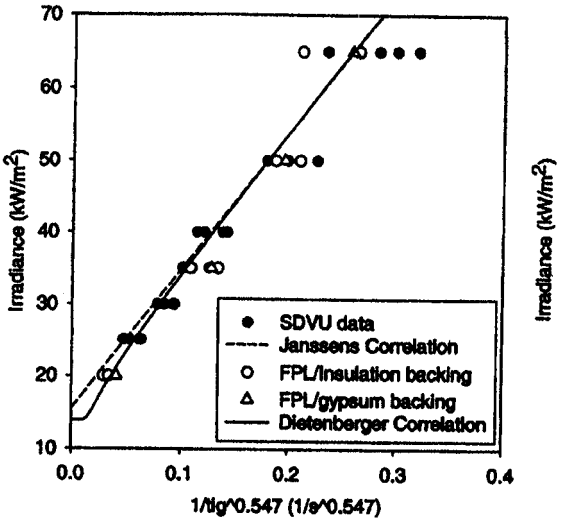

Figure 6. Correlation to piloted ignition data of Gypsum X (ISO 1)

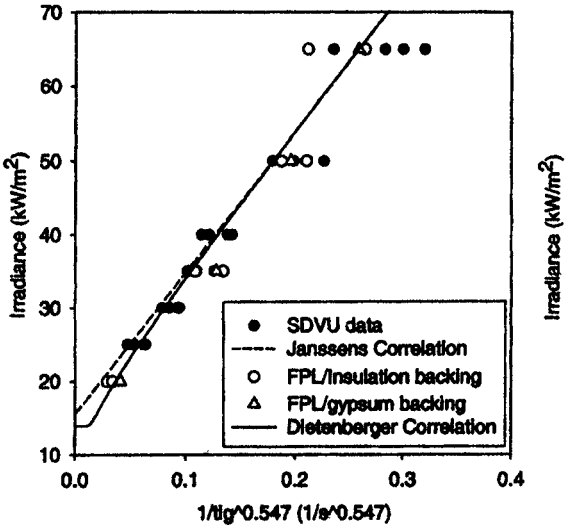

Figure 7. Correlation to piloted ignition data of Southern pine plywood (ISO 10)

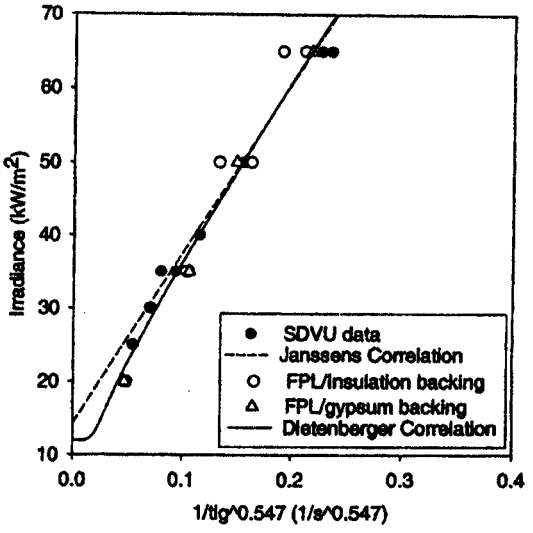

Figure 8. Correlation to piloted ignition data of Hardboard (ISO 13)

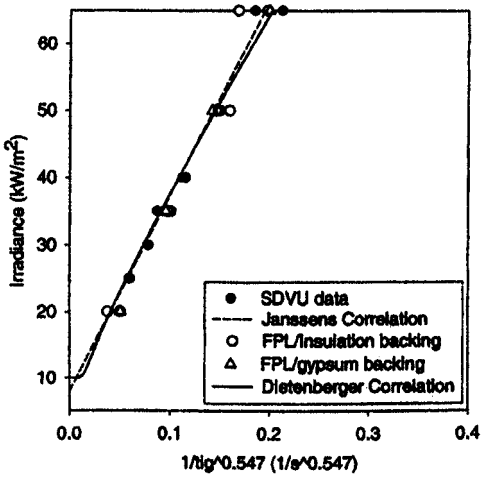

Figure 9. Correlation to piloted ignition data of Particleboard (ISO 11)

CONCLUSION

In examining various material heating variations specifically for redwood lumber, we demonstrate by using Dietenberger's correlation (Eq. (4) to (12)), that all points on the ignitability graph can be predicted by merely using thermophysical properties that are in close agreement with independent measurements. There is then no need to use "effective" thermal inertia or other properties typically required with simpler ignitability formulas. Therefore, with the other wood products, the ignitability data are used to derive values of (1) surface ignition temperatures and (2) r_w term that adjust the thermal conductivity expression. The result is a set of thermophysical parameters ideally suited for input to computer fire modeling, by allowing the flexibility of application to complexity in a thermal conduction model. That is, on the simplest level, a thermally thick heat conduction solution can be used with a very thick material using values of thermal inertia and ignition temperature labeled as Dietenberger's values from Table 2. At the next level of complexity, the thermal properties of "averaged" thermal diffisivity, thermal conductivity (derivable using the thermal inertia and thermal diffusivity), and ignition temperature from Table 2 can be used in an efficient finite difference model (FDM) of thermal conduction. At the highest level of complexity, Equations (10) to (12) (with the ratio, $r_w = k/k_w$, listed in Table 2) can be used directly in a mechanistic pyrolysis model in which kinetics of wood pyrolysis is calibrated to obtain ignition temperatures listed in Table 2. Although transitions in heating regimes occur quite often in standard testing, it is not commonly appreciated and may even be considered too difficult to tackle. Here we show an ignitability analysis that remains simple yet adaptable to complex ignition behavior.

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