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Experimental and Analytical Protocol for Ignitability of Common Materials

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In this study, a protocol was developed to increase accuracy, generality and efficiency when determining piloted ignition properties. A new procedure for calibrating the radiative and convective heat flux profiles on exposed specimens, such as Douglas-fir plywood, has been implemented for the lateral ignition and flame spread test (LIFT) apparatus. The boundary conditions needed for heat transfer analysis are made unambiguous by including a simple, direct measure of surface emissivity. A new aluminum foil shutter improves accuracy for measuring ignition time. A recently developed theory of ignitability provides a formula to account for the transition from thick to thin thermal behavior, allowing specimens of finite thicknesses and a full range of test irradiances.

INTRODUCTION

Initially, the intention of this study was to implement the ASTM E-1321[1] standard and follow its prescription to obtain material and flammability properties for wood products. However, after learning of proposed changes to the standard and our problems using the lateral ignition and flamespread test (LIFT) apparatus, we followed a more rigorous assessment and found several deficiencies that were remedied. Despite the progress made in understanding and measuring ignitability, inconsistencies remain between the various bench-scale fire tests and their suitability to derive thermophysical properties. Even with the Cone Calorimeter[2] (ASTM E-1354-92), variation in time to ignition is found near the critical irradiance (which also varies greatly[3]) when effects of geometry and ignition mode are investigated.[4] By extensive use of a Finite Difference Method (FDM) code and well-described material samples, Janssens[5] provides some insight into this problem.

For many common materials, there is a transition from thermally thick to thin behavior as the ignition time increases. If the material also has a broad range of surface temperature in which char develops, such as wood, the surface temperature at ignition may deviate significantly so that the critical heat flux is elusive to measure. In part because of these problems, Janssens suggests focusing on the thermally thick regime and using an accurate correlation formula derived by fitting to FDM solutions. He then prescribes a convenient procedure to obtain the critical heat flux value from fitting the formula to the ignitability data. In his work with wood products tested in the Cone Calorimeter, Janssens suggests nominal values of surface emissivity and convective heat transfer coefficient in analogy with the E-1321 protocol. In the study reported here, we examined these issues in greater depth, for the LIFT apparatus in particular, and found a more accurate approach for obtaining thermophysical properties.

The first section of this paper details new calibration, measurement. and correlation methods that are suggested as alternatives to that described in ASTM E-1321 and those in the literature. The second section provides an analysis of ignitability of Douglas-fir plywood.

NEW CALIBRATION, MEASUREMENT AND CORRELATION METHODS

Calibration of lateral heat flux profile

The LIFT apparatus uses a premixed gas panel burner oriented at 15 degrees laterally away from an 800 mm by 155 mm specimen holder (see Fig. 1). A heat flux gradient is created along the 800 mm length of the holder and results in a specific lateral surface temperature profile in the steady-state condition. The heat flux gradient to the specimen is specified in Table 1 of E-1321. Fluxes at 50 and 350 mm are to be set as accurately as possible. while flux at other positions are to be within 10%. At first, with our carefully calibrated water-cooled fluxmeters. we set the 50 mm location on the calibration board to be exposed continuously to 50.5 kWm^{-2} and positioned the specimen holder to try to get 23.9 kWm^{-2} at a 350 mm location. Because our high-pressure air supply for the gas panel was from a central building and not steady, it was difficuit to verify the two fluxes to closer than a few percentage points. Recording the ratio between the two fluxes did not improve accuracy, because, as discovered later, the flux profile was also affected by the flux levels of the gas panel burner and ambient conditions. The final approach was to slowly ramp the gas panel burner to maximum levels and ramp down to the very minimum levels in at least 10 min while recording the fluxmeter signals from the 50 and 350 mm locations and radiation pyrometer signals.

The location of the pyrometer is specified in 6.3.1 of ASTM E-1321. and the pyrometer is used to indirectly measure pane1 burner irradiance. We used a RADIAMATIC pyrometer, which required converting voltage signals and ambient temperatures to a radiant source

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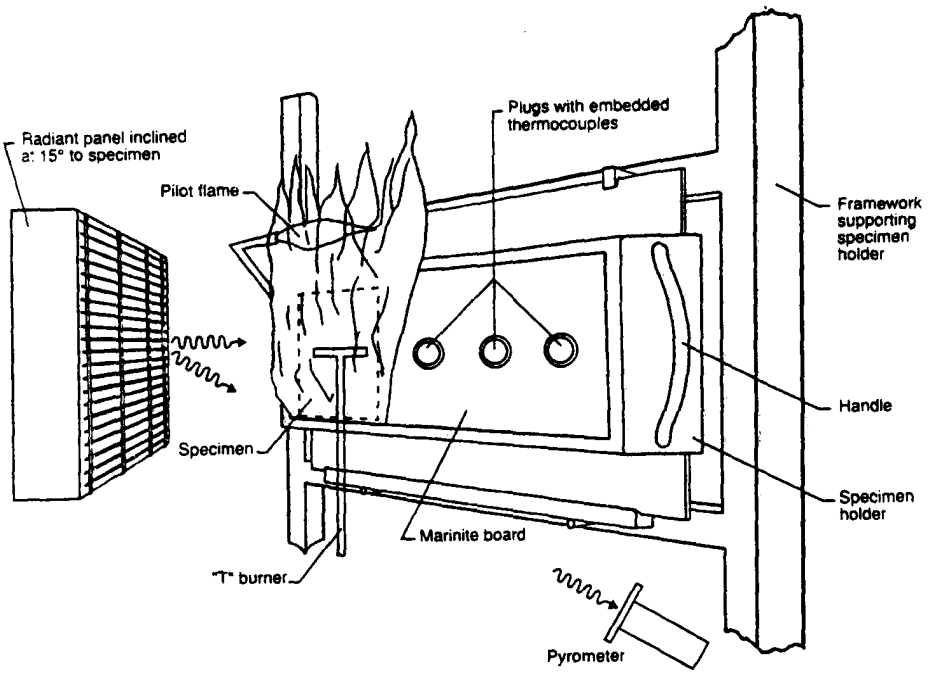

Figure 1. Scheme of LIFT apparatus for ignitability testing.

temperature using a table supplied by the manufacturer. Figure 2 shows the results of measured total heat fluxes at the 50 and 350 mm locations compared to the pyrometer irradiance converted from radiant source temperature using data-acquisition software. At first, we obtained data at the low flux levels (between 2 and 70 kWm^{-2}), which are represented by the solid and dashed straight lines in Fig. 2. A few days later, we obtained the data shown in Fig. 2 to examine the high flux levels (up to 120 kWm^{-2}). Deviations shown by open circle data above the solid line between total fluxes of 70 and 120kWm^{-2}seem to be the result of direct flame impingement on the specimen from the panel burner.

The agreement between the flux profile resulting in Fig. 2 and the E-1321 flux profile is shown in Fig. 3 plotted as relative deviation from FPL values, using 50.5 kWm^{-2} at a 50 mm location as the baseline. Note that all fluxes are normalized to unity at 50 mm. The solid line shows within $\pm$ 10% agreement with E-1321 for all measuring locations and within $\pm$ 1.5% agreement at the 350 mm location. Because the fluxmeters

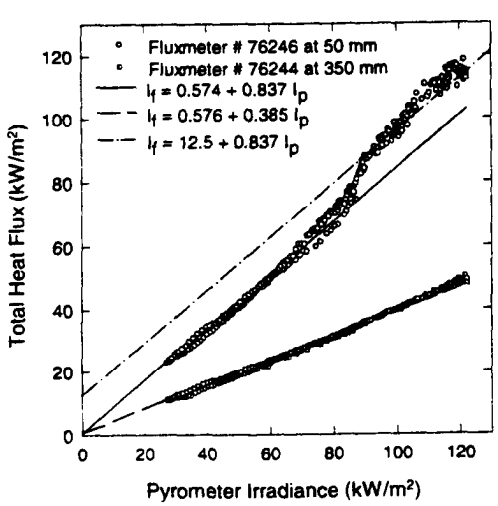

Figure 2. Comparison of total heat fluxes to pyrometer irradiance using data acquisition software (calibrated 10/5/93).

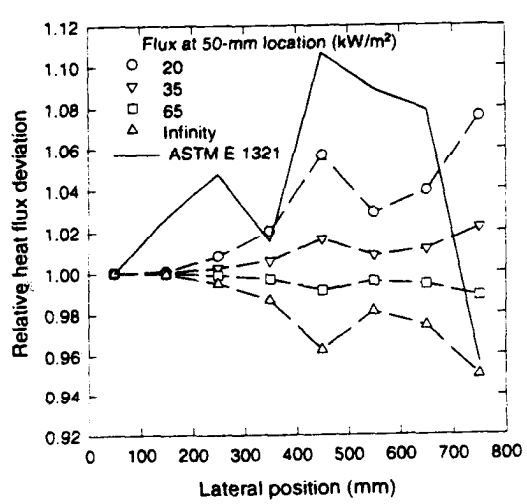

Figure 3. Systematic relative deviation from FPL's LIFT total heat flux profile using 50.5 $kW\,m^{-2}$ at a 50 mm location as the reference level (calibrated 9/16/93).

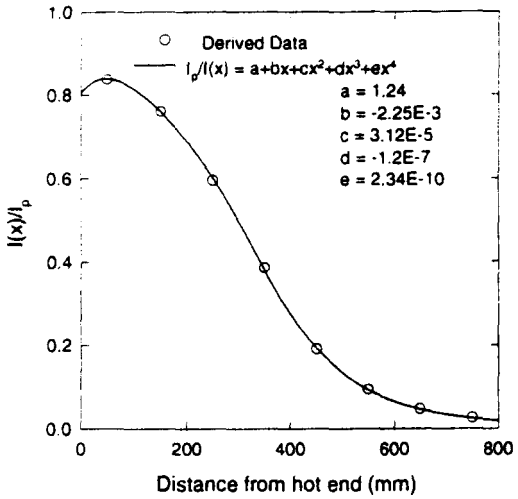

Figure 4. Derived irradiance profile ($I(x)$), on FPL LIFT apparatus relative to the pyrometer irradiance (I_p).

were water cooled, the total measured heat flux comprised some convective and reradiative heat transfer, in addition to the panel irradiance. Because of the presence of this convective and reradiative heat flux, there was a bias of as much as 13% at the 750 mm location as Fig. 3 showed with dashed lines. As further evidence of a convective and reradiative heat flux bias we used the flux ramping procedure on a cold, winter day and obtained data that nonlinearly deviated 10% to 15% below the solid and dashed lines in Fig. 2. If the intent is to obtain the irradiance profile on the specimen, then the pyrometer should be used as the reference level and the slopes of the straight lines (represented in Fig. 2) are ratios of surface irradiance to pyrometer irradiance. This result is shown in Fig. 4, with a corresponding rational functional fit to the data. This profile was used in calibrating other parameters, such as the convective heat transfer coefficient discussed in the next section.

CALIBRATION OF CONVECTIVE HEAT TRANSFER COEFFICIENT

The air flowing over the specimen is probably induced by the panel burner, although additional buoyancy induced by the heated specimen surface is likely. The temperature difference between air flowing over the specimen and the water-cooled fluxmeter is small, which means it would be difficult to evaluate convective heat transfer with the fluxmeters installed. Instead of fluxmeters, insulating plugs were installed with thermocouples inserted at various depths. With the plugs exposed to panel burner irradiance, their surface temperature will rise to an equilibrium level, represented by the heat balance equation:

$$h_c(T_s - T_a) = \varepsilon_s[I(x) - \sigma(T_s^4 - T_a^4)] - \lambda_s\frac{\partial T_s}{\partial y} \quad (1)$$

Net radiative heat flux minus surface conductive heat flux are on the right side of Eqn (1), and convective heat loss is on the left side of Eqn (1). If the surface temperature were the same as the ambient, the surface conductive heat flux would be proportional to the irradiance, $I(x)$. This is where the water-cooled fluxmeter can be advantageously used. Note that the surface emissivity of the fluxmeter should not degrade if it is to remain accurate. However, the entrained airflow is heated slightly by the radiant gas panel, so that the air temperature is slightly greater than ambient. The best approach to derive the convective heat transfer coefficient, h_c, depends on several considerations. The first is to use insulating material (Calcium Silicate (Marinite)) board with well-known values of λ_s) in the plugs to minimize conductive heat flux and maximize convective heat loss. The plugs were the same material as the board of the calibration holder; therefore, we measured surface hemispherical blackbody emittance, ε_s, by using a D&S Emissometer Model AE to get the value 0.9. Next, a small thermocouple close to the surface was inserted sideways into the plug to a spot in the center and about 1-3 mm deep. Two additional thermocouples were inserted to greater depths in the plug. Their depth positions were accurately measured with an electronic digital caliper. Because three thermocouples were used, an interpolation function fitted to temperature as function of depth was used to derive values for T_s and $\partial T_s/\partial y$. Long before temperatures reached steady-state during exposure to selected irradiances, the material conductive heat flux became small compared with other terms, and the derived convective heat transfer coefficient became constant.

The E-1321 recommendation of 0.015 kW Km $^{-2}$ for h_c was also obtained using Eqn (l), but assumptions about the various terms were quite different. Surface emissivity was assumed by E-1321 to be unity. An FDM analysis and a surface thermocouple were used to derive the surface conductive heat flux. Note that a surface thermocouple requires corrections due to exposure to irradiance and finite contact with the surface. The burner irradiance was equated to that measured with a water-cooled fluxmeter. Even then, the measurements seemed limited to locations within 250-600 mm and at a flux of 50.5 k W m $^{-2}$ at the 50 mm location. There was a need to consider the full lateral length of the specimen holder, the full range of panel burner irradiance, and the full range of methane flow in calibration 'T' burner. Figure 5 shows the results of using the improved method of deriving h_c and measurements for the 50, 350 and 650 mm locations, for panel irradiances at 50 mm of about 21, 37.51, and 71 kW m $^{-2}$. with and wit bout our methane calibration burner flaming. The values of h_c derived were much greater than can be expected from the airflow induced by the heated specimen[5]. In Figure 5, data correlate best with one-fourth power of the panel irradiance, which seems consistent with the idea that the gas panel burner induces airflow over the specimen. If the airflow is 'forced' over the specimen. the convective heat transfer coefficient would not be a strong function of specimen temperature; h_c also had a significant linear decrease with the lateral distance from the hot end.

$$h_c = (13.9 - 0.0138x)(I_{50})^{1.4} \times 10^{-3}\ \mathrm{kW\,Km^{-2}} \quad (2)$$

as can be expected with a turbulent airflow between an angled wedge. The methane T burner covered the lateral positions from 100 to 300 mm so that it would not be

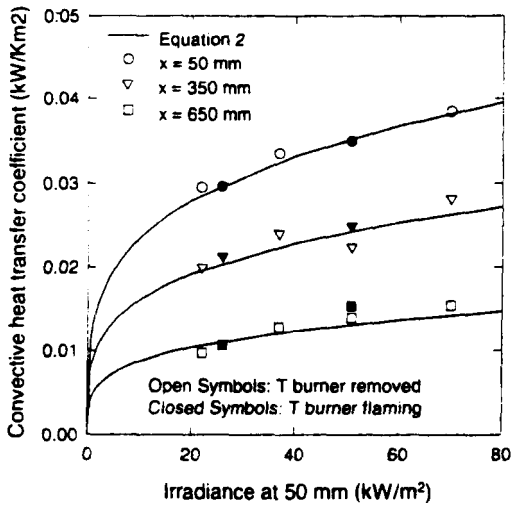

Figure 5. *Correlation of convective heat transfer coefficient for the specimen holder on FPL's LIFT apparatus.*

directly over an instrumented plug (see Fig. 1). The objective was to see if controlled flaming from the specimen iocation had an effect on h_c derived at instrumented plug locations. Figure 5 shows that 'specimen' flaming had a negligible effect on h_c. This systematic study of the convective heat transfer coefficient suggested that the value recommended by E-1321 does not apply to our LIFT apparatus and must be replaced by a procedure to calibrate the convective heat transfer coefficient, as discussed in this paper.

Improved measurement of time to ignition

Some investigators have suggested using irradiances between several percentages above a critical level and up to 60 kW m^{-2} and treating the material as thermally thick. However, if we have a correlation function of ignitability that accurately accounts for the transition behavior from thermally thick to thin, the time to piloted ignition should cover the full range of irradiances available in an apparatus. One problem is when high irradiances are reached (>55-60 k W m^{-2}), many materials ignite within a few seconds. Sliding of the specimen holder in the LIFT also takes 2-3s. To improve accuracy of time to ignition, we constructed a flip-out aluminum sheet located over the specimen. After sliding the holder into place, the string attached to the flip-out sheet was immediately pulled to start the test. Starting at the highest practical irradiance of 70 kW m^{-2} for the LIFT, we used the flip-out procedure. As we decreased the iradiance level, the time to ignition increased. When the time to ignition became greater than 30s, the flip-out procedure was not necessary.

ANALYSIS OF DOUGLAS-FIR PLYWOOD IGNITABILITY

On testing days, we rechecked all calibrations to be sure equipment was operational and within nominal range. The time to ignition of several Douglas-fir plywood specimens with varying thicknesses (6–15 mm) was measured over the full range of the gas panel irradiances up to 70 kW m^{-2}. The plywood was conditioned at around 25% humidity at 26°C for several days. The corresponding equilibrium moisture content for generic wood is around 5.3%. With our emissometer. the surface emittance was measured to an average value of 0.86.

Testing results are shown in Fig. 6, using the vertical and horizontal scale recommended by Janssens[5]. If the wood is thermally thick. the correlation for the time to ignition to the – 0.547 power compared to irradiance should be a straight line (Fig. 6). The open-circle data (e.g. 14.9 mm-thick plywood) seem adequately straight. Janssens' correlation is summarized by the following equations:

$$(t_{ig})^{-0.547} = a + bq_e \tag{3}$$

$$q_{ig} = \frac{-a}{b} = \frac{h_{ig}}{\varepsilon_s}(T_{ig} - T_a) \tag{4}$$

$$h_{ig} = h_c + \frac{\varepsilon_s \sigma (T_{ig}^4 - T_a^4)}{T_{ig} - T_a} \tag{5}$$

$$\rho C_p \lambda = h_{ig}^2 \left(\frac{-1}{0.73a}\right)^{(1/0.547)} \tag{6}$$

The straight line in Fig. 6 is represented by Eqn (3). and the critical heat flux is given by Eqn (4) at 17.8 kW m^{-2}. This seems greater than had been reported using other ignitability apparatuses. If we also assumed that h_c = 0.015 kW Km^{-2} and ε_s = 0.88, as recommended by Janssens, then Eqns (4) and (5) can be used to derive the values h_{ig} = 0.0416 kW Km^{-2} and T_{ig} = 676 K. This surface temperature at ignition seems much too high considering that the pyrolysis of wood with flammable volatiles is known to become significant in the range from 555 to 605 K. The thermal inertia, $\rho C_p \lambda$, from Eqn (6) is derived to be 0.14 (kJ Km^{-2})^{2}s^{-1}. This value is 27% less than the corresponding dry Douglas-fir wood properties[6] evaluated at an averaged temperature, $(T_{ig} + T_a)/2$. However,

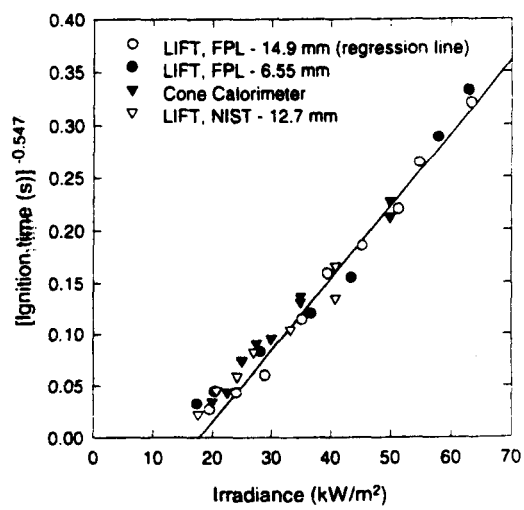

Figure 6. Piloted ignition data for Douglas-fite plywood of varying thicknesses.

if we set the surface emissivity to 0.86 and use Eqn (2) for the convective heat transfer coefficient, then with Eqns (4) and (5) we obtain the values h_{ig} = 0.048 kW Km^{-2} and T_{ig} = 627 K. This surface temperature has now decreased by 59°C and is in closer agreement with combustible pyrolysis temperatures of the wood. The thermal inertia is this time 0.19 (kJ Km^{-2})^{2}s^{-1} which is 10% greater than the corresponding dry Douglas-fir wood properties at an averaged temperature. Moisture content in the wood generally increases thermal conductivity and heat capacitance slightly more than that of dry wood. However, wood dehydration is completed locally below 200°C, which implies that overall thermal properties should be close to dry wood when heated to pyrolysis temperatures. In any case. the inferred thermal properties become much more reasonable because of increased accuracy for the irradiance and surface emissivity values. and in particular, the convective heat transfer coefficient.

Returning to Fig. 6, we find additional difficulties when considering finite plywood thicknesses. For example, the criterion that separates thermally thick from thermally thin behavior require values of thermal diffusity, conductivity, and specimen thickness. Thus, it is not obvious where to draw a straight line through the data in Fig. 6, particularly for the smaller plywood thicknesses. In addition, there is an appearance of large scatter and a bias in the data near the critical flux. It was not until the thickest plywood was exposed to the full range of LIFT irradiances that a straight line tit could be established. To remedy this situation, we developed formulas to fit our extensive one-dimensional Finite Element Analysis (FEA) solutions (see Fig. 7) for finitely thick materials heated on exposed side and insulated on unexposed side. The result is the interpolation equation,

$$\frac{q_{ig}}{q_e} = \mathbf{T} = \left(\mathbf{T}_{\text{thick}}^5 + \frac{\mathbf{T}_{\text{thin}}^5}{1 + 0.574\, Bi^{1.31}}\right)^{1/5} \tag{7}$$

where

$$\mathbf{T}_{\text{thick}} = 1/[1 + 0.73(Bi^2 Fo)^{-0.547}] \tag{8}$$

$$\mathbf{T}_{\text{thin}} = 1 - \exp[-(BiFo)] \tag{9}$$

$$Fo = \alpha t_{ig}/\delta^2 \tag{10}$$

$$Bi = h_{ig}\delta/\lambda \tag{11}$$

and is shown in Fig. 7 as solid curves. Note that the Biot number was needed in Eqn (7) to improve the interpolation between thick and thin solutions. Equation (8) was first formulated by Janssens[5] for thermally thick materials, and we verified its accuracy with the FEA analysis. At the high Biot number of 20.0, Eqn (7) especially reduces to Eqn (3). This is effectively shown by the curve fit to open triangle points in Fig. 7.

Close examination of Eqns (4), (5), and (7) to (11) shows that material thickness, δ, should be measured along with ε_s, h_c, $I(x)$, t_{ig}, and T_a. There remains three unknown parameters: surface temperature T_{ig}, at ignition, thermal diffusivity, a, and bulk thermal conductivity, λ. Inserting these parameters, except $I(x)$, into Eqns (4), (5), and (7) to (11), a calculated value for the imposed irradiance, q_e, is obtained, which can then be compared directly with a pyrometer-derived value. This is shown in Fig. 8 for FPL LIFT data using Douglas-lit plywood. Values of fitting parameters are T_{ig} = 608 K, x = 1.48 × 10^{-7} m^{2}s^{-1} and λ = 0.164 W mK^{-1} (7.7% greater than that of averaged dry plywood properties[6]). The corresponding parameters are q_{ig} = 17.0 k W m^{-2}, h_{ig} = 0.047 kW Km^{-2}, and pC_p = 1,108 kJ K^{-3} (16% greater than that of averaged dry plywood properties[6]). In reference 6, plywood is described as having variability in thermal conductivity depending on how well the wood plys are glued together. A reduction of λ by 0.86 was cited to account for air spaces between the plys. Taking this factor into account, the derived values of λ and pC_p correspond to a moisture content of 4.5% at averaged temperatures.[6] The good agreement shown in Fig. 8 and the good agreement with independent correlation for wood panel thermal properties argues against a more advanced transient thermal analysis, at least for plywood. Indeed, any confusion in whether to use thermally

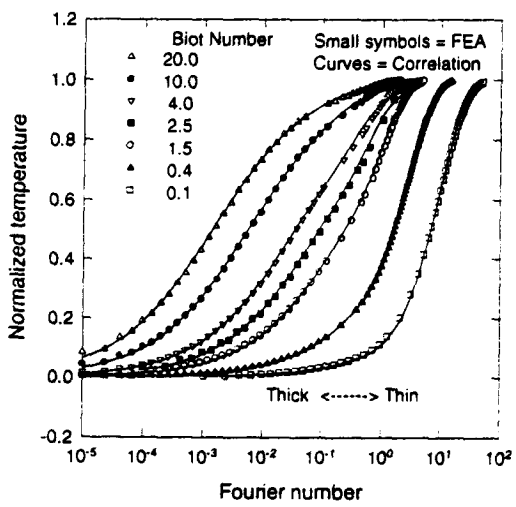

Figure 7. Correlation to FEA surface temperature solution as a function of Biot and Fourier numbers based on interpolation of thick and thin solutions.

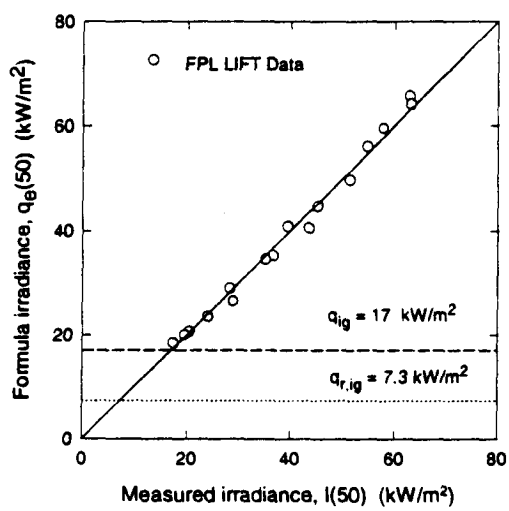

Figure 8. Piloted ignition data for conditioned Douglas-fir plywood replotted to interpolation correlation.

thick or thin equations has **now been** resolved with a single accurate formula applicable to a finitely thick material insulated on its back side.

For comparison with cone calorimeter, assume[5] $h_c = 0.015$ kW Km^{-2} along with $\varepsilon_s = 0.86$ and $T_{ig} = 608$, and evaluate Eqn (4) to obtain $q_{ig} = 12$k Wi^{n-2}. This is a significant reduction of 5 kW m^{-2} from that of the LIFT apparatus. Combine this with variability in q_{ig} as represented in Fig. 6 shows that critical flux is much less reliable than the ignition temperature as a basic parameter to use. It also shows the importance of reporting on the values of h_c and ε_s when reporting on T_{ig}.

CONCLUSIONS

The initial effort to implement the ASTM-E-1321 standard for ignitability has now been superseded with a new protocol described in this paper. After learning of proposed changes to the standard and our problems, we followed a more rigorous assessment and remedied several deficiencies. The more careful calibrations of the panel irradiance profile and the convective heat transfer coefficient should become part of the standard.

For studies of ignitability, it was also important to measure surface emissivity and thickness of the specimen before testing. During testing. a thermal shutter should be **used** at high panel irradiances. A full range of achievable irradiances for piloted ignition is recommended for ignitability testing, because the accurate formula for the finitely thick materials can be used to derive reasonable values for the surface temperature at ignition, thermal diffusivity, and thermal conductivity. However, we suggest preliminary plots similar to Fig. 6 to ensure that the material is thin enough or time to ignition is long enough to result in nonlinear deviations near the critical flux.

If we had used values of emissivity and convective heat transfer coefficients recommended in the standards and applied Janssens's correlation to our thickest plywood, the derived ignition temperature would have been 70°C greater than our value. and the derived thermophysical properties would have been about 27% less than the averaged dry wood values. However. with our procedure, a better statement can be made about the critical heat flux for a certain configuration and then extrapolate the results to other configurations. Indeed. the same techniques developed in this work can be applied to the Cone Calorimeter or similar apparatus for ignitability. The main differences among the apparatues are in air convection geometry and in specimen holder, and it is not surprising that reported critical heat fluxes for a given material vary considerably.

NOTATION

Bi	Biot number
C_p	specific heat capacitance (kJ kgK^{-1})
Fo	Fourier number
h	heat transfer coefficient (kW Km^{-2})
I	measured specimen irradiance (kW m^{-2})
q_e	specimen irradiance from formula (kW m^{-2})
q_{ig}	derived specimen irradiance at ignition (kW m^{-2})
t	time (s)
T	temperature (K)
$\mathbf{T}$	dimensionless temperature response
x	lateral distance from hot end (mm)
y	distance into specimen surface (mm)
α	Thermal diffusivity (m^2 s^{-1})
δ	material thickness (mm)
ε_s	surface hemispherical emmitance
λ	material thermal conductivity (kW mK^{-1})
ρ	material density (kg m^{-3})
σ	Stefan–Boltzmann constant (kW m^{-2} K^4)

NOTES

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