IGNITABILITY ANALYSIS USING THE CONE CALORIMETER AND LIFT APPARATUS

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ABSTRACT

The irradiance plotted as function of time to ignition for wood materials tested in the Cone Calorimeter (ASTM E1354) differs signiticantly from that tested in the Lateral Ignition and Flame spread Test (LIFT) apparatus (ASTM E1321). This difference in piloted ignitabilty is primarily due to the difference in forced convective cooling of the specimen tested in both apparatus. By calibrating for the convective heat transfer coefficient and using appropriate heat conduction analysis of the test data for both apparatus, similar values were derived for the following thermo-physical properties: surface emissivity, surface ignition temperature, thermal conductivity, and thermal diffusivity. This paper reports on results with tongue & groove boards of clear grade redwood.

INTRODUCTION

Piloted ignitability of wood materials can be determined in various fire testing apparatus. The resulting test data, however, are usually difficult to interpret for deriving fundamental thermo-physical properties or even for direct application to a tire scenario. This problem needs to be addressed because the values for surface emissivity, surface ignition temperature, thermal conductivity, and thermal diffusivity are essential as inputs to fire growth models designed to predict a general fire scenario. Such a model has usefulness in performance-based building codes. The cone calorimeter and LIFT apparatus are particularly useful for our work because they have very different heating and piloted ignition environments leading to different results on ignitability. The LIFT apparatus has a gas-fired radiant panel in an open-air environment for heating a 150- by 150-mm vertical specimen and uses acetylene gas pilot for ignition. During a test the technician slides the specimen holder carefully into position and then rapidly retracts an aluminum cover (thermal shutter) from the specimen. The cone calorimeter, on the other hand, has a truncated conical electric heater in a protective, enclosed, and controlled airflow environment for heating a 100- by 100-mm horizontal specimen. The spark igniter is automatically moved to above the specimen in a fraction of a second as the water-cooled thermal shutter retracts. There have been various approaches to applying these data to the problem of exposure to time-varying irradiances, as in wildland fires and fire growth in buildings (Tran, et a1.,1992; Janssens, l991; Dietenberger,1995a,1995b). In either apparatus, the flame spreads rapidly over the specimen at ignition and time to ignition decreases with an increase in surface irradiance on the specimen.

One simple approach taken in the first version of Structural Ignition Assessment Model (SIAM) (Tran, et al., 1992) is a two-step process. The first step is to use Janssens' (1991) method of fitting a straight line to the plot of time to ignition raised to the -0.547th power as a function of irradiance in the thermally thick heating regime. At very long time to ignition, the intercept on the horizontal axis is the critical irradiance. A siding receiving radiance from, for example, a tree or bush burning near the siding that is less than this critical level will not ignite. In the second step, Janssens' correlation is rearranged to state that the product of excess surface heat flux above critical raised to the (1/0.547)th power with time to ignition is an ignition constant. To allow for heat fluxes varying over time, SIAM computes a mean value for the term: excess surface heat flux above critical raised to the (1/0.547)th power over all time steps up to current time. If the product of this averaged term and current time exceeds the ignition constant, ignition is indicated. This two-step process is called the flux-time-product method.

The flux-time-product method is restricted to selected scenarios for various reasons. Recent papers (Dietenberger, 1994, 1995a, 1995b) determined that the convective heat transfer coefficient on the ignition specimen in the LIFT apparatus is much greater than expected on building structures. In this paper, we show that a similar conclusion applies to the cone calorimeter. This greatly affects the critical irradiances and the prediction of time to ignition in the end-use of the specimen. At lengthy exposure times, the material response is thermally thin, invalidating use of Janssens' correlation. Also, cool-down periods between burning peaks of a wildland fire scenario are not properly simulated. Another approach (Martin, 1983) used a linear ramping of the irradiance source and a correlation for time to ignition more complex than that of Janssens.

To avoid developing several correlations for different scenarios, we followed a rigorous approach using at least approximate solutions of a one-dimensional thermal diffusion equation that allows for time- and apparatus-dependent boundary conditions. This rigorous approach required the use of basic material properties, such as material thickness, emissivity, thermal diffusivity, thermal conductivity, and surface temperature at ignition. The purpose of the study reported here is to show the validity of this approach for interpreting ignitability data from various apparatus. Results from tests with the two apparatus on redwood specimens are given. Various heat transfer terms are analyzed to show the main difference between the two apparatus is in the convective heat transfer coefficient. Finally, the solution to the thermal diffusion equation is shown in three forms: finite element method, thermal wave/collocation method, and correlation for constant irradiance on finitely thick materials. The consistency in the derived thermo-physical properties is also shown.

TEST RESULTS

Table 1 lists test conditions and measured material properties for redwood samples. The appropriate plotting of the ignitability data for comparing with predictions is the log-log plot of irradiance as a function of time to ignition, as shown in Figure 1. Time to ignition for fixed irradiance generally increases with moisture content. The cone calorimeter data, however, has significantly lower times to ignition than the corresponding LIFT data (compare the two 50% relative humidity (RH) curves in Figure 1). To explain this behavior, the heat transfer terms used in prediction of ignitability are examined in the next section.

Table 1. Measured or estimated material characteristics.

Material/Test	Condition[a]	ϵ_s (-)	δ (mm)	$\rho_{o.d.}$ (kg/m^3)[b]	M (%)[c]
Redwood/CONE	50%RH	0.87	17.2	410	9.2
Redwood/LIFT	Ovendried	0.77	19.1	410	2.0
Redwood/LIFT	30%RH	0.82	19.2	410	6.0
Redwood/LIFT	50%RH	0.86	17.0	410	9.2

[a] Ovendried pertains to 24 h in oven at 105 °C; RH is relative humidity.
[b] Density values from TenWolde et al. (1988) and 10% variability within species from the Wood Handbook (Forest Products Laboratory, 1987).
[c] Equilibrium moisture content values estimated from Wood Handbook.

CALIBRATION OF CONVECTIVE HEAT TRANSFER COEFFICIENTS

A typical ignitability analysis involves a simplified heat conduction analysis that uses an equation containing variables with dependency on the apparatus only, on the material only, or for both conditions. Any variable dependent on the apparatus should be measured and calibrated. Any material variable should be measured if possible; otherwise, it becomes a parameter to fit the equation to the ignitability data. For finitely thick materials, the significant dimensionless terms for transient heat conduction analysis are Fourier and Biot numbers defined by

$$Fo = \alpha t_{ig}/\delta^2 \qquad (1)$$

$$Bi = h_{ig}\delta/\lambda \qquad (2)$$

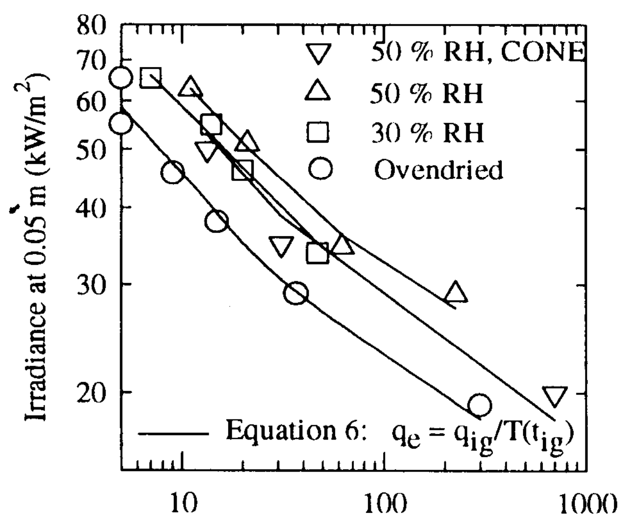

Figure 1. Piloled ignition data for Redwood siding

where

$$h_{ig} = h_c + \epsilon_s \sigma (T_{ig}^2 + T_a^2)(T_{ig} + T_a) \qquad (3)$$

The remaining variables are defined in the list of nomenclature at the end of this paper. Examination of these variables suggests that the convective coefficient and the air temperature are the only variables as a function of the apparatus, while other variables are primarily material parameters. The surface temperature at ignition may under special conditions vary with the apparatus and is not well known, so it is a parameter to fit the data. In a previous paper (Dietenberger, 1995b) we found the convective coefficient for the LIFT apparatus correlates solely with the panel radiant flux and lateral distance along the specimen from the hot end. Similar calibration technique was found also applicable to the cone calorimeter.

The convective heat transfer coefficient was calibrated for the LIFT apparatus in the following manner. Because the values for convective heat flux were needed in an intermediate step, accurate values for the difference of net radiative and specimen surface conductive fluxes were obtained. Besides the panel irradiance profile already calibrated, the surface emissivity and temperature needed to be measured to derive the net radiative surface heat flux. The value for conductive surface fluxes is obtained from the product of material thermal conductivity and temperature gradient at the surface. To maximize the convective heat losses and obtain a large temperature gradient in the material, insulative plugs were inserted in place of flux meters. These plugs were the same insulative material as the board holding the flux meters. The value for surface hemispherical emittance was measured with an emmissometer. Three thermocouples were inserted at fixed depths within the plugs, and an interpolation function was used to derive the surface temperature and its gradient. Long before the 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, h_c (convective heat flux divided by the surface temperature rise), became constant. Data correlated best with one-fourth power of the panel irradiance, q_e , which suggests the gas panel burner causes airflow over the specimen; h_c also had a significant linear decrease with lateral distance from the hot end,

$$h_{c,LIFT} = (0.0139-0.0138x)\, q_e^{1/4} \quad kWm^{-2}K^{-1} \tag{4}$$

that may be expected with a turbulent airflow between an angled wedge. For the cone calorimeter, a strip of insulative bar slab was used for inserting fine thermocouples into thin holes on the side at three different depths. Three strips were clamped together to form a 100- by 100-mm "specimen" to put under the cone heater. The thermal shutter provided a step increase in irradiance. Figure 2 shows the thermocouple data obtained for exposure to 50 kW/m^2 at the dead-center of the specimen. After obtaining the convective coefficient using the method used for the LIFT, we verified its value by predicting the temperature profiles from the solution of the thermal diffusion equation by the thermal wave/collocation method. This is shown as solid curves in Figure 2. The same calibration procedure was done at other irradiances (20 to 65 kW/m^2) and at positions 20 and 40 mm from dead-center.

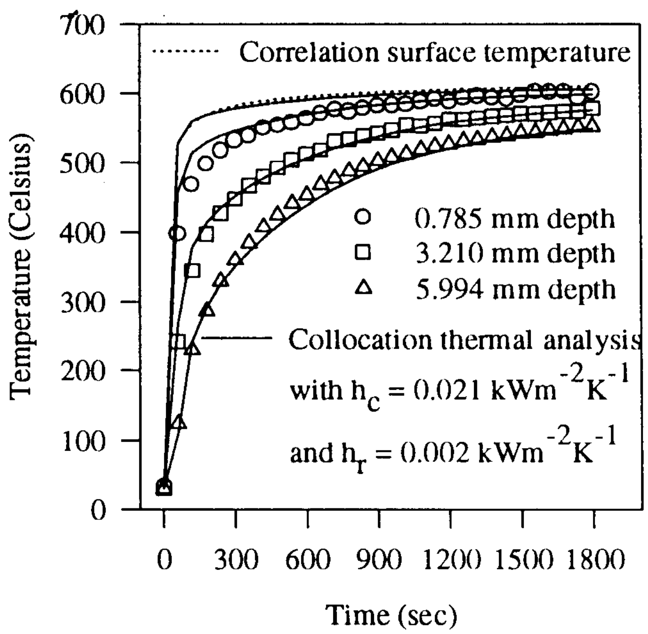

Figure 2. Colibration of sample convective coefficient with cone flux of 50 kW/m^2 at dead center

The resulting correlation of the convective coefficient for the cone calorimeter is

$$h_{c,CONE} = 0.01433 + 1.33 \times 10^{-4} q_e \quad kWm^{-2}K^{-1} \tag{5}$$

If specimen-centered averages over the irradiance range of 20 to 65 kW/m^2 are desired, then the LIFT and CONE values are 0.034 and 0.02 $kWm^{-2}K^{-1}$ respectively. Contrast this with a typical turbulent wall convective coefficient of $\leq$.01 $kWm^{-2}K^{-1}$. These differences will have an effect on critical heat fluxes and thermo-physical properties as shown in the following section.

DETERMINATION OF THERMO-PHYSICAL PROPERTIES

To predict the thick to thin transition thermal behavior, an interpolation formula was developed for finitely thick materials with convective cooling and radiation heating of the exposed side and insulation on the unexposed side. The material is assumed to ignite at a critical surface temperature on the exposed side. The interpolation formula fitted to the finite element solutions of transient heat conduction as a function of Biot and Fourier numbers (see Figure 3) is

$$\frac{q_e}{q_{ig}} = \frac{1}{T_s} = 1 + \frac{1}{(F_{thick}^n + F_{thin}^n)^{1/n}} \tag{6}$$

where

$$q_{ig} = h_{ig}\,(T_{ig} - T_a)/\varepsilon_s \tag{7}$$

$$n = (2.68 + 0.4Bi)/(1 + Bi) \tag{8}$$

$$F_{thick} = \left(\frac{4}{\pi} Bi^2 Fo\right)^{\frac{1}{2}} \tag{9}$$

$$F_{thin} = \exp\left(\frac{Bi\,Fo}{1 + 0.254Bi}\right) - 1 \tag{10}$$

Note that Equation 9 dominates the interpolation and approaches the theoretical formula at low Fourier numbers, while Equation 10 dominates the interpolation and approaches the theoretical formula at high Fourier numbers. The empirical Equation 8 provides an accurate transition between Equations 9 and 10 as function of Biot number. Equation 7 provides definition for critical irradiance. Although we formulated other interpolations as reported in previous papers (Dietenberger, 1994,1995a,1995b), Equations 6 to 10 were superior in representing the finite element solution at values of normalized surface temperature near 0 and 1. These equations are useful in commercial least-squares curve-fitting routines as was done for this paper. If the time-changing irradiances are interpreted as step-changing heat fluxes over short intervals, then the interpolation formula can be used in a supposition solution in the form of Duhamel's integral to solve for surface temperature as a function of time. It provides an effective replacement to the flux-time-product method. Another use for the interpolation formula is as comparison with transient heat conduction solutions for predicting surface temperature, as Figures 2 and 3 show (dotted lines are almost indistinguishable from solid lines).

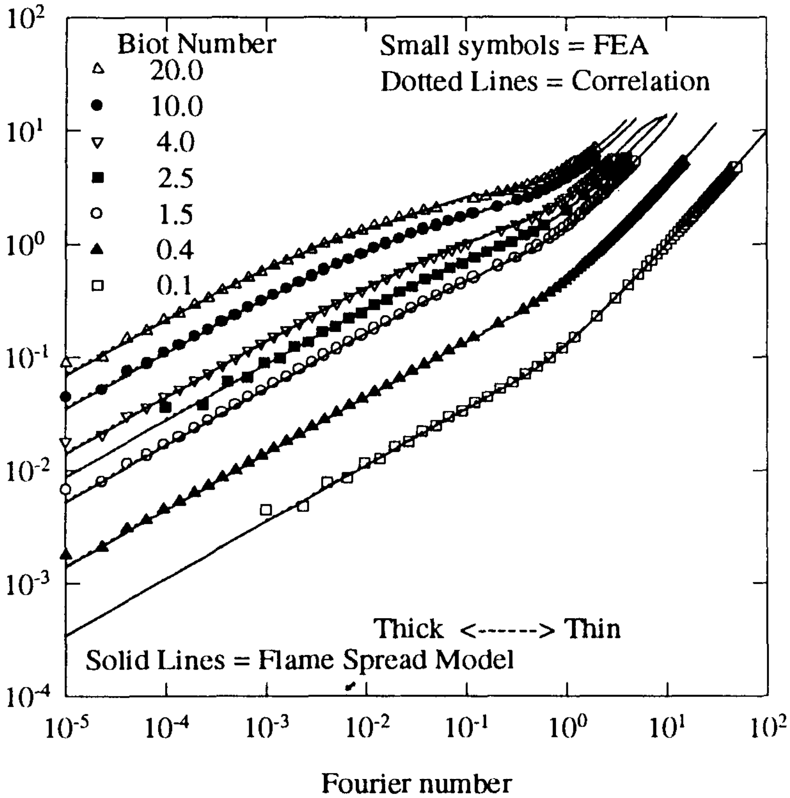

Figure 3. Comparison of normalized surface temperature predictions of three methods for response to constant irradiance.

The measurable quantities in Equations 1 to 10 are **d**, x, e_g, h_c, q_e t_{ig}, and T_a. Three parameters remain to be determined: Surface temperature at ignition, T_{ig} , thermal diffusivity, **a** , and thermal conductitity, **l** . During piloted ignition and flame spreading, the surface temperature is typically about 300 to 350 °C, and the wood dries out early in the heating phase. These changes in temperature and moisture content greatly affect the thermo-physical properties, as shown by the following (TenWolde et al., 1988; Janssens, 1991):

$$\lambda = [(0.1941 + 0.004064M)(\rho_{od} \times 10^{-3}) + 0.01864]\ (T \times 10^{-3} / 297) \quad kWm^{-1}K^{-1} \tag{11}$$

$$C_p = 1.25\,(1 + 0.025M)(T/297) \quad kJkg^{-1}K^{-1} \tag{12}$$

$$\rho = \rho_{od}\,(1 + 0.01M) \quad kgm^{-3} \tag{13}$$

Janssens (1991) used a finite difference method (FDM) to examine this effect of temperature dependency on the surface temperature prediction using different kinds of boundary conditions. He then showed that when using constant thermo-physical parameters as evaluated at an average temperature between the initial and final values, there was little loss in accuracy in predicting surface temperature. In a previous paper (Dietenberger,1994), we found that the initial moisture content is the best value to use in Equations 11 to 13, and that errors would be small if equilibrium moisture content is used (Table 1). The last variable to consider is the oven-dried density in Equation 11, which is measurable. This leaves the surface temperature at ignition as the sole fitting parameter in the least-squares curve fitting program.

Table 2 lists the results obtained and Figure 1 shows prediction of ignitability. Cursory examination of Tables 1 and 2 suggests that small increases of surface emissivity, ignition temperature, heat capacity, and thermal conductivity with moisture content all result in an increase of the time to ignition. According to Equation 6 and experimental results reported in the literature, irradiance will decrease to some minimum value as the time to ignition approaches infinity. This is not apparent in Figure 1 because minimum irradiances were not searched experimentally. However, in previous results with Douglas-fir plywood (Dietenberger, 1995a), the critical irradiance for piloted ignition on the LIFT apparatus was 17 kW/m^2, which is in close agreement with the experimental minimum value. In comparing the results for the cone calorimeter and the LIFT, the difference in critical irradiance is 4.5 kW/m^2 while the other thermo-physical property values agree. If these results are extrapolated to turbulent-free convection on a vertical wall, with a convective coefficient of 0.01 $kWm^{-2}K^{-1}$, the critical irradiance is lower than the cone calorimeter value by 3.8 kW/m^2 to a critical irradiance of 10.5 kW/m^2. Thus, it is necessary to determine h_c for a given fire scenario and calculate the critical irradiance for that scenario.

Table 2. Derived thermo-physical constants

Material/Condition	Test	q_{ig} (kW/m²)	T_{ig} (K)	$\lambda \times 10^{-3}$ (kW/m K)	$\alpha \times 10^{-6}$ (m²/s)
Redwood/50%RH	CONE	14.3	626	0.177	0.165
Redwood/Ovendried	LIFT	13.6	563	0.149	0.185
Redwood/30%RH	LIFT	17.3	606	0.165	0.173
Redwood/50%RH	LIFT	18.8	629	0.178	0.165

We note that for charring wood, cessation of volatiles emission can occur at some large heating time, unless material oxidative catalysis continues to overwhelm heat losses. Thus, the concept of critical irradiance corresponds to having an adequate supply of volatiles generated at a critical temperature. The minimum irradiance required for piloted ignition is greater than the critical value, if cessation of volatiles dominates, and is less than the critical value, if oxidative catalysis dominates. Therefore, it is not recommended to use the values of critical heat fluxes in Table 2. It is also known that significant amounts of released volatiles begin at 553 K (280 °C) and a minimum concentration of volatiles mixed with air is needed to achieve piloted ignition. Heated wood with moisture content will generate steam, diluting the volatiles, so that even higher surface temperatures are needed to increase the rate of released volatiles to the minimum level. Surface temperature at ignition remains a viable basic ignition parameter when it varies only with moisture content. Surface emissivity is also a basic ignition parameter that increases with moisture content, which is not surprising because the surface emissivity of liquid water is near unity. Lastly, the effective thermal conductivity increases with moisture content and diffusivity decreases slightly with moisture content according to Equations 11 to 13.

CONCLUSIONS

Results showed basic agreement in the derived values of ignition temperatures, thermal diffusivities, and thermal conductivities between LIFT and cone calorimeter ignitability tests. Critical irradiance, however, is not a viable ignition parameter because of large differences in convective cooling of the specimen in different testing apparatus. Material surface emissivity, material density, moisture content, and thickness of the specimen should be measured before testing for use in thermal conduction analysis. In addition, the irradiance profile and the convective heat transfer coefficient for a given apparatus should be carefully calibrated and correlated. A full range of achievable irradiances for piloted ignition is recommended for ignitability testing, because our empirical formula for the finitely thick materials can be used to derive reasonable values for ignition temperature, thermal diffusivity, and thermal conductivity. A future paper will describe similar results on additional wood-based materials.

NOMENCLATURE

C_p	Heat capacitance (kJ $kg^{-1}K^{-1}$)
h_c	Convective transfer coefficient (kW $m^{-2}K^{-1}$)
h_{ig}	Linearized transfer coefficient (kW $m^{-2}K^{-1}$)
q_e	Irradiance at 50 mm position (kW/m^2)
M	Moisture content (%)
t	Time (seconds)
T	Temperature (K) (Normalized form in Equation 6)
q	Surface heat flux (kW/m^2) (Subscript ig is ignition)
x	Lateral position from hot end (m)
α	Thermal diffusivity (m^2/s)
δ	Thickness (m)
λ	Thermal conductivity (kW $m^{-1}K^{-1}$)
ε_s	Surface emissivity
ρ	Density (kg/m^3) (Subscript o.d. is ovendried)
σ	Stefan-Boltzmann constant (5.67e- 11 kW $m^{-2}K^{-4}$)

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REFERENCES

Dietenberger, M.A., 1994, Ignitability Analysis of Siding Materials Using Modified Protocol for LIFT Apparatus, Fire & Materials 3rd Int. Conf. Oct., 1994, Crystal City, VA, USA, Interscience Communications Limited, London, pp. 259-268.

Dietenberger, M., 1995a, Protocol for Ignitability, Lateral Flame Spread and Heat Release Rate Using LIFT Apparatus, Fire and Polymers II - Materials and Tests for Hazard Prevention, Proceedings of the American Chemical Society, Division of Polymeric Materials: Science and Engineering, American Chemical Society, Washington DC, 1995, ACS symposium series 599, Chapter 29, pp. 435-449.

Dietenberger, M., 1995b, Experimental and Analytical Protocol for Ignitability of Common Materials, Fire & Materials Journal, Vol. 19, pp.89-94.

Forest Products Laboratory, 1987, Wood Handbook: Wood as an Engineering Material, Agric. Handb. 72, Washington DC.: U.S. Department of Agriculture, 466 p..

Janssens, M., 1991, Fundamental Thermo-physical Characteristics of Wood and their Role in Enclosure Fire Growth. Ph.D. Thesis, University of Gent, Belgium, November 1991.

Martin, S.B., 1983, Predictions of Ignition Thresholds During Ramp Heating, Behavior of Polymeric Materials in Fire, E.L.Schaffer, ed., ASTM-STP-816, pp. 13-20.

TenWolde, A., McNatt, J. and Krahn, L., 1988, Thermal Properties of Wood and Wood Panel Products for Use in Buildings, DOE/USDA-21697/1 or ORNL/Sub/87-21697/1.

Tran, H., Cohen, J., and Chase, R., 1992, Modeling Ignition of Structures in Wildland/Urban Interface Fires, Fire and Materials 1st Int. Conf.,Sept.1992,Washington DC,USA, Interscience Communications Limited, London, pp.253-262.

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