

Ignitability Analysis of Siding Materials Using Modified Protocol for Lift Apparatus*

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This paper reports on the ignitability of common siding materials that could be exposed to wildland fires. When exposed to brands or fires, structures will experience piloted ignition, which is requisite for sustained ignition involving burn-through and surface flame spread in various directions. In this study, the Lateral Ignition and Flame Spread Test (LIFT) apparatus (ASTM E1321 and E1317) was used to test various siding materials (plywoods, softwoods, and vinyl), some of which were painted, humidified, or sawed. A recently developed protocol provided useful, accurate values of the following thermophysical properties: surface emissivity, surface ignition temperature, thermal conductivity, and thermal diffusivity. Full consistency was achieved with independent literature values of these properties and can be used directly in the database of fire growth models.

INTRODUCTION

The LIFT apparatus has a gas-fired radiant panel for heating a 150 mm by 150 mm specimen and a gas pilot for ignition. Thus, the time to ignition will decrease with an increase in surface heat flux as centered on the specimen. There have been various approaches trying to apply LIFT data to the problem of exposure to time-varying irradiances, as in wildland fires and fire growth in buildings.¹⁻⁴

One simple approach implemented in the first version of the Structural Ignition Assessment Model¹ (SIAM) is a two-step process. The first step is to use Janssens's² method of fitting a straight line to the plot of time to ignition raised to the -0.547 power as a function of irradiance in the thermally thick heating regime. The critical irradiance is then evaluated by setting time to ignition to infinity. A siding receiving radiance from, say, a tree or bush burning near the siding that is less than this critical level will not ignite. In the second step, SIAM uses a rearrangement of Janssens's correlation to state that the product of excess surface heat flux above critical raised to the $(1/0.547)$ power with time to ignition is an ignition constant. To take into account heat fluxes varying over time, SIAM computes a mean value for the term: excess surface heat flux above critical raised to the $(1/0.547)$ 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^{3,4} determined that the convective heat transfer coefficient on the ignition specimen in the LIFT apparatus is much greater than expected on building structures. This has a significant effect on the critical irradiances and predicting time to ignition in the end-use of the siding material. At lengthy exposure times, the material transitions into a thermally thin response, thereby invalidating use of Janssens's correlation. Also, cool-down periods inbet-

ween burning peaks of a wildland fire scenario are not properly simulated. Another approach⁵ 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, a rigorous approach is needed and applicable to use with SIAM on a personal computer. The idea is to use advanced approximate solutions of a one-dimensional thermal diffusion equation that allows for time- and apparatus-dependent boundary conditions. To use this rigorous approach, the basic material properties, such as material thickness, emissivity, thermal diffusivity, thermal conductivity, and surface temperature at ignition, are needed. Recently developed protocols^{3,4} that improve upon ASTM E 1321 were designed to obtain these basic properties. The purpose of the study reported here was to extend these protocols to common siding materials that may also be stained, painted, dried, or sawed.

If charring and/or wood treatment prevents burn-through and continuous flame spread for the given heat flux from a burning brand or vegetation, then volatile emissions from the specimen will cease and the ignition becomes unsustainable. McArthur and Lutton⁶ experimented with the effects of various ignition sources and the timber moisture content and ambient temperature on the ignitability of exterior building details. Their definition of ignitability was the extent of flame spread on building mock-ups, which we describe as sustained ignition. In agreement with their observations, Dietenberger³ analyzed a flame spread test (E 1321) on Douglas-fir plywood which indicated that flame spread becomes larger with (1) a decrease in ignition temperature and surface emissivity (which is associated with a decrease in moisture content in this paper), (2) an increase in ambient temperature, and (3) an increase in irradiance associated with larger ignition sources. These problems of sustained ignition, however, are beyond the scope of this paper.

In the following section the formula for piloted ignitability with LIFT apparatus is explained, paying particular attention to deriving basic properties using

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curve-fitting routines. Additional sections describe the materials and testing methods selected and the results from the seven siding materials considered in this study.

FORMULA FOR PILOTED IGNITION IN THE LIFT APPARATUS

The correlations for the convective heat transfer coefficient and time-to-ignition as a function of other parameters shown in this section are reproduced from reference 4. Thus, only cursory explanations of the correlations are given here. Additional correlations introduced in this section are for thermal conductivity and heat capacitance for wood as functions of temperature, oven-dry density, and moisture content.⁶ Obtaining agreement with values of basic thermal properties from independent sources adds credence to the improved E 1321 protocol.

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 heat flux and the specimen's surface conductive flux were obtained. In addition to 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 the surface conductive heat flux is obtained from the product of material thermal conductivity and temperature gradient at the surface. To maximize the convective heat losses and obtain a fairly large temperature gradient in the material, insulative plugs were inserted in place of fluxmeters. These plugs were the same insulative material as the board holding the fluxmeters. The surface hemispherical emittance was measured with an emissometer. 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, I_{50} , which suggests that the gas panel burner induces airflow over the specimen; h_c also had a significant linear decrease with lateral distance from the hot end:

$$h_c = (0.0139 - 0.0138x)I_{50}^{1/4} \text{ kW m}^{-2} \times \text{K}^{-1} \quad (1)$$

that may be expected with a turbulent airflow between an angled wedge.

To correlate time-to-ignition with irradiance, most studies of ignitability consider either a thermally thick equation like Janssens's² correlation to derive thermal inertia, $pC_p\lambda$, and ignition temperature, or use a thermally thin solution to derive thermal thickness, $pC_p\delta$, and ignition temperature. With either of these extreme formulas, the thermal conductivity and diffusivity could not be determined separately, which are both needed to predict the thick to thin transitioning thermal behavior of

finitely thick wood products. To remedy this situation, an interpolation formula based on the extensive finite element model solutions was developed for finitely thick materials with convective cooling and radiative heating of the exposed side and insulated on unexposed side. This formula is

$$\frac{q_{ig}}{q_c} = T = \left(T_{thick}^5 + \frac{T_{thin}^5}{1 + 0.574Bi^{1.31}} \right)^{1/5} \quad (2)$$

where

$$T_{thick} = [1 + 0.73(Bi^2Fo)^{-0.547}]^{-1} \quad (3)$$

$$T_{thin} = 1 - \exp(-BiFo) \quad (4)$$

$$Fo = \alpha t_{ig}/\delta^2 \quad (5)$$

$$Bi = h_{ig}\delta/\lambda \quad (6)$$

$$h_{ig} = h_c + \varepsilon_s\sigma(T_{ig}^2 + T_\alpha^2)(T_{ig} + T_\alpha) \quad (7)$$

$$q_{ig} = h_{ig}(T_{ig} - T_\alpha)/\varepsilon_s \quad (8)$$

In examining Eqns (2) to (8) note that material thickness, d , should be measured in addition to the usual values of ε_s , h_c , I_{50} , t_{ig} , and T_α . Previous ignitability results⁴ with varying thicknesses of Douglas-fir plywood demonstrated the effectiveness of these equations. Three parameters remain to be determined: surface temperature at ignition, T_{ig} , thermal diffusivity, α , and thermal conductivity, λ .

In a 1964 study⁸ on the effect of moisture content on surface flammability of coated and uncoated cellulosic materials, the approach was to measure the surface temperature increase in response to irradiance for different moisture contents and to use the thermally thick solution to derive the dependence of thermal inertia on moisture content. For flammability, the flame spread index obtained with the radiant panel method was used to measure creeping flame spread and then correlated with thermal inertia. However, this thermal inertia was derived in the first series of tests in a temperature increase of only a few degrees Celsius. During piloted ignition and flame spreading, the surface temperature increase is typically about 300°C, and the wood dries out early in the heating phase. These changes in temperature and moisture content have a significant effect on the thermophysical properties, as shown by the following:^{2,7}

$$\lambda = [(0.1941 + 0.004064M)(\rho_{od} \times 10^{-3}) + 0.01864](T \times 10^{-3}/297) \text{ kW m}^{-1} \times \text{K}^{-1} \quad (9)$$

$$C_p = 1.25(1 + 0.025M)(T/297) \text{ kJ kg}^{-1} \times \text{K}^{-1} \quad (10)$$

$$\rho = \rho_{od}(1 + 0.01M) \text{ kg m}^{-3} \quad (11)$$

Janssens² used a finite difference method (FDM) to examine this effect of temperature dependency on the surface temperature prediction with correlations similar to Eqns (9) to (11) using different kinds of boundary conditions. He then showed that when using constant thermophysical parameters as evaluated at an average temperature between the initial and final values there was little loss in accuracy in predicting surface temperature. One factor that was not examined in detail with FDM by Janssens was the process of wood drying out while being heated to ignition. That is, there is a moisture profile in the heating portion of the wood, such that we propose an

effective moisture content for Eqns (9) to (11). Because thermal diffusivity is Eqn (9) divided by the product of Eqns (10) and (11), Eqns (9) to (11) were incorporated with the first eight equations in a commercial curve-fitting software to fit irradiance as a function of time-to-ignition and derived values of ignition temperature and effective moisture content, M (%), as fitting constants. The temperature used in Eqns (9) to (11) was the mean of initial and ignition temperature. Then, Eqns (9) to (11) were used to calculate the effective thermal conductivity and diffusivity. For the composite wood siding, it was suggested⁷ to apply a correction factor to the thermal conductivity Eqn (9). In the case of the vinyl siding material, Eqns (9) to (11) are deleted and the thermal conductivity and diffusivity are determined directly and compared for consistency with literature values.

METHODS AND MATERIALS

Materials acquired were (nominal 1-inch by 8-inch) tongue and groove boards of 19 mm by 184 mm No. 3 grade northern white-cedar, 19 mm by 178-mm No. 2 grade ponderosa pine 'car siding' with decorative ridges, and 19 mm by 191 mm clear grade redwood; 286 mm (nominal 12-inch-) wide hardboard siding boards coated with a primer; 1.22 m by 2.44 m (4 by 8 feet) sheets of 13 mm (nominal $\frac{1}{2}$ inch) thick, Douglas-fir plywood with natural rustic texture, and 14 mm (nominal $\frac{5}{8}$ inch) thick Douglas-fir plywood with a relatively smooth finish. Both of the 5-ply plywoods had 12.7 mm ($\frac{1}{2}$ -inch) wide vertical grooves every 203 mm (8 inches) and interior plies of true fir, spruce, and Douglas-fir. Ignition samples (155 mm by 155 mm) were cut from the flat portions of a siding structure (decorative ridges were included with pine siding). The last item acquired was a D5 WHT Forest ridge vinyl siding (double width of 127 mm (5 inch) each) in which a flat square portion of

the siding was cut out and backed by a Blue tongue and groove Dow Styrofoam[®] board for insertion into the LIFT specimen holder. Backing by the polystyrene foam are often used in home constructions, whereas vinyl siding is used commercially with gypsum board or a fibrous cellulosic material backing instead of the foam. For all materials, surface emissivity and thickness were measured; for selected materials, moisture content and density were measured or estimated. Table 1 lists the three solid wood, three wood composite and vinyl siding materials, and a summary of their condition prior to testing. These are typical exterior siding materials used on residences and office buildings, including those located in the wild-land/urban interfaces.

A test of a conditioned material consisted of varying the step-function irradiance and measuring the time to piloted ignition of several identically prepared samples. For ignition times less than 30 seconds, a flip-out aluminum sheet was used as a thermal shutter to shield the specimen while sliding the holder into position to initiate the test. This increases measurement accuracy because the slide time with the specimen holder is about 2 or 3 seconds. Data obtained were initially plotted as time to ignition, t_{ig} , raised to the -0.547 power as a function of irradiance following Janssens's² recommendation. These plots were useful in determining the adequate number of data points, detecting spurious data, and obtaining estimates of the critical fluxes.

RESULTS AND DISCUSSION

The appropriate plotting of the ignitability data with respect to Eqns (1) to (11) is the log-log plot of irradiance as a function of time to ignition, shown in Figs 1 to 6 for each siding material. The thermophysical constants corresponding to the fitted curves in each figure are given in Table 2. The time to ignition for a given material and

Table 1. Measured or estimated material characteristics

Material	Condition	ϵ_s (-)	δ mm	ρ_{od} (kg m^{-3})	M (%)
Cedar	Oven-dried ^a	0.79	18.5	310 ^b	2.0 ^c
Cedar	50%RH/thin	0.82	7.7	310 ^b	10.0
Redwood	Oven-dried ^a	0.77	19.1	410 ^b	2.0 ^c
Redwood	30%RH	0.82	19.2	410 ^b	6.0 ^c
Redwood	50%RH	0.86	17.0	410 ^b	7.4
Pine	Oven-dried ^a	0.72	18.5	420 ^b	2.0 ^c
Pine	30%RH	0.83	18.5	420 ^b	6.0 ^c
Pine	50%RH	0.82	17.9	420 ^b	9.3
Rustic plywood	50%RH	0.90	14.4	500 ^b	10.6
Painted plywood	50%RH	0.83	12.8	500 ^b	9.5
Hardboard	Oven-dried ^a	0.76	10.0	730	N/A
Hardboard	30%RH	0.84	9.8	730	5.0 ^c
Hardboard	50%RH/thin	0.85	6.4	730	7.9 ^c
Vinyl + polystyrene foam	N/A	0.89	0.93	1889 ^d	N/A

^a24 h in oven at 105°C; RH is relative humidity.

^bDensity values from reference 7 (10% variability within species from reference 9).

^cEquilibrium moisture content values estimated from reference 9.

^dDensity value from ASTM-D-3679-89.

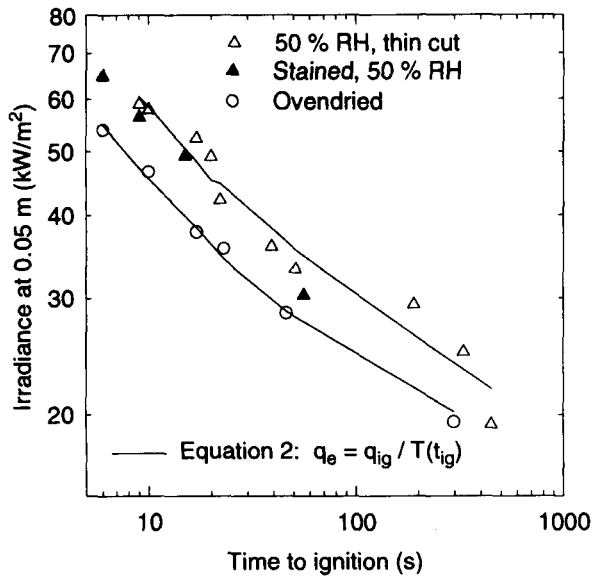


Figure 1. Piloted ignition data for cedar siding.

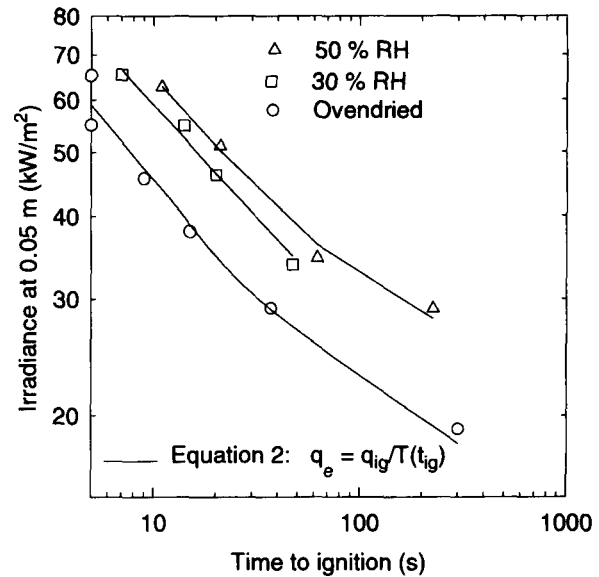


Figure 3. Piloted ignition data for redwood siding.

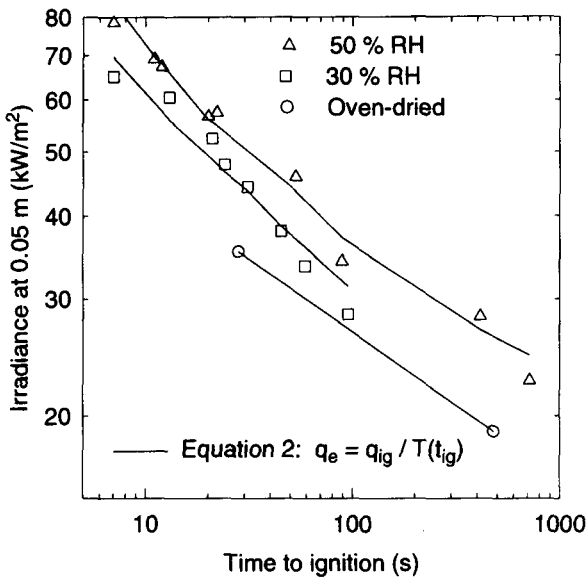


Figure 2. Piloted ignition data for pine siding.

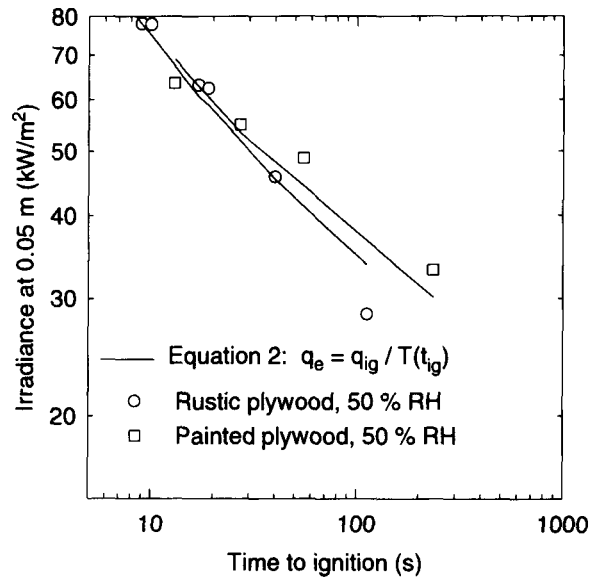


Figure 4. Piloted ignition data for plywood siding.

fixed irradiance generally increases with moisture content and oven-dried density. However, it is not clear if and how various thermophysical properties affect the ignition data. Cursory examination of Tables 1 and 2 indicates 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. Surface emissivity and ignition temperature appears to vary little with species (at least for softwoods). Figure 1 shows that staining has a negligible effect on ignitability.

According to Eqn (2) 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 Figs 1 to 6 because minimum irradiances were not searched experimentally. However, in previous results with Douglas-fir plywood,³ the critical irradiance for piloted ignition on the LIFT apparatus

was determined to be 17 kW m^{-2} which is in close agreement with the experimental minimum value. The equivalent critical flux for measurements made using the cone calorimeter (assuming $h_c = 0.0135 \text{ kW m}^{-2} \text{ K}^{-1}$) was calculated from Eqns (7) and (8) as 12 kW m^{-2} . This difference of 5 kW m^{-2} is significant. Thus, it is necessary to determine h_c for a given fire scenario and calculate the critical irradiance for that scenario. 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.

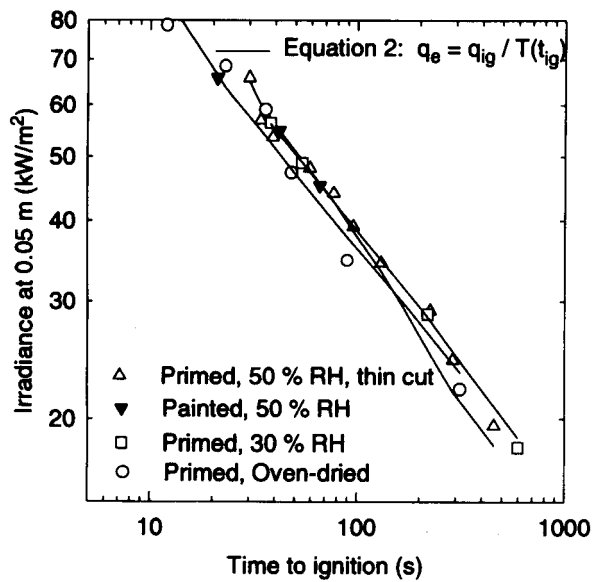


Figure 5. Piloted ignition data for hardboard siding.

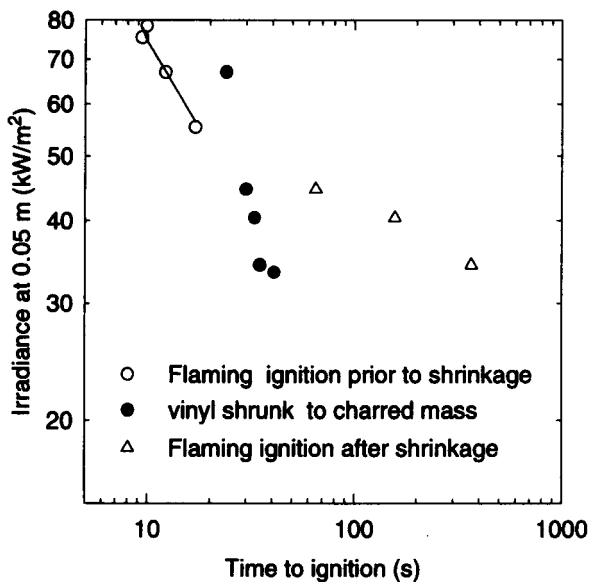


Figure 6. Piloted ignition data for vinyl siding.

Effects of the different thermophysical properties are similar for the various wood sidings and provide consistent results. For example, the moisture content of cedar, redwood, and pine was measured to be 10%, 7.4%, and 9.3%, respectively, after they were conditioned at 50% RH, 23°C. Theoretical equilibrium moisture content of wood⁹ at these conditions is 9.2%. These are in good agreement with derived moisture content levels of 9.9%, 9.4%, and 9.2%, respectively, for the same three wood species. Similar agreement is noted for the conditioning at 30% RH, 26°C, in which equilibrium moisture content⁹ is 6%. Thus, it is feasible to simplify the least-squares fitting procedure in which the effective moisture content is taken equal to the measured value and only solve for the ignition temperature as an unknown parameter.

Although the derived ignition temperatures are in the range recommended for piloted ignition (300-350°C) and

increase with moisture content, their comparison with direct observations of surface temperatures is problematic because of the systematic measurement errors involved.² Placing a thermocouple on the surface is subject to error, because the wood surface already starts to pyrolyze and heat-up by oxidative catalysis at 473 K (200°C) and the thermocouple bead is exposed to radiation. The ignition at 473 K that has been commonly measured for wood is actually temperature of a hot forced airflow in a furnace, in which small wood pieces are slowly heating by oxidative catalysis to reach the critical surface temperature for piloted ignition. However, it is known that significant amounts of released volatiles begin at about 553 K (280°C) and a minimum concentration of it 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 values for effective thermal conductivity increases with moisture content and diffusivity decreases slightly with moisture content according to Eqns (9) to (11).

The results on composite sidings (Figs 4 and 5) follow the pattern of time-to-ignition that decreases with irradiance and increases with moisture content and dry density. In fitting data in Fig. 4 for the plywoods, the most consistent result was achieved by assuming a solid wood density (that of Douglas-fir), using the measured value of moisture content into Eqns (9) to (11), and deriving the ignition temperature from the least-squares fit. The results in Table 2 show that the ignition temperatures of plywood are similar to solid woods for the same exposure conditions.

The thermal analysis for hardboard siding, however, does require adjustment to the thermal conductivity Eqn (9) because of the random orientation of wood particles. Note that the thermal conductivity of wood along the grain is about 2.5 times that in the cross direction. In anticipation of this factor, moisture content was set to zero, measured density was 730 kg m⁻³, for the oven-dried hardboard, and the least-squares fitting arranged to derive ignition temperature and multiplication factor for Eqn (9). The corresponding curve fit is shown in Fig. 5 (open circle data). The factor was determined to be 1.84 and was also used for the other hardboards conditioned for moisture. The equilibrium moisture content of cardboard is assumed to be slightly less than that of wood, giving 5% and 8% for the conditions 30% and 50% RH, respectively, at around 26°C. Using these values, the curve fitting to the data in Fig. 5 resulted in ignition temperature of 578 and 581 K. These changes in the ignition temperature with moisture content are much smaller than that for solid wood and plywood and could be explained with retardation of moisture evaporation by the prime paint. Note in Fig. 5 that data with the 8% moisture content have ignition times equal or less than data with the 5% moisture. This seemingly contradictory result is explained by the 8% moisture content board

Table 2. Derived thermophysical constants for siding materials

Material/condition	q_{ig}^{-2} (kW m^{-2})	λ Factor	T_{ig} (K)	M (%)	$\lambda \times 10^{-3}$ ($\text{kW m}^{-1} \text{K}^{-1}$)	$\alpha \times 10^{-6}$ ($\text{m}^2 \text{s}^{-1}$)
Cedar/oven-dried	15.3	1.0	587	7.6	0.134	0.178
Cedar/50%RH/thin	20.1	1.0	635	9.9	0.144	0.172
Redwood/oven-dried	13.3	1.0	560	3.4	0.152	0.181
Redwood/30%RH	16.7	1.0	600	8.7	0.171	0.166
Redwood/50%RH	19.2	1.0	631	9.4	0.179	0.165
Pine/oven-dried	14.3	1.0	561	4.7	0.158	0.176
Pine/30%RH	18.8	1.0	621	5.6	0.169	0.174
Pine/50%RH	20.8	1.0	640	9.2	0.183	0.164
Rustic plywood/50%RH	18.8	1.0	634	10.6 ^a	0.217	0.157
Painted plywood/50%RH	19.5	1.0	629	9.5 ^a	0.211	0.159
Hardboard/oven-dried	14.7	1.84	572	0.0	0.237	0.176
Hardboard/30%RH	14.7	1.84	578	5.0 ^a	0.257	0.163
Hardboard/50%RH/thin	14.5	1.84	581	7.9 ^a	0.273	0.156
Vinyl + polystyrene foam	N/A	N/A	700	N/A	0.145	0.087

being cut thinner to 6.4 mm, while the 5% moisture content board thickness remains at 10 mm. Note how the fitted curve for the ‘thin’ hardboard is nonlinear, and the other two curves are somewhat linear. This demonstrates the effectiveness of the interpolation Eqn (2) in capturing the thermophysical properties. Data shown in Fig. 5 for the painted hardboard (latex paint topcoat), decreased slightly the time-to-ignition when compared to the primed samples. Also note that the critical irradiance given in Table 2 is constant for the three moisture levels and results from the unique pattern of surface emissivity and ignition temperature increasing with moisture content.

In the LIFT tests, the vinyl siding shows the characteristics that you would expect from a poly(vinyl chloride) compound (PVC) prepared from poly(vinyl chloride) homopolymer resin. In Fig. 6, the time to full shrinkage (melting was not observed) is plotted with time to ignition on the horizontal axis and irradiance on the vertical axis. The two data sets appear to cross at time, 30 seconds, and at irradiance, 45 kW m^{-2} . In Fig. 6, vinyl shrinkage is as low as 33 kW m^{-2} , which is the point where flaming ignition no longer occurs on the charred mass. Previous tests found that the PVC shrinks at an irradiance level as low as 17 kW m^{-2} . The open circle data in Fig. 6 represent piloted ignition on PVC prior to complete shrinkage. The solid line fitting the open circle data is Eqn (2) with the values for thermophysical properties from Table 2. From reference 10, the PVC flash-ignition temperature is 664 K and the self-ignition temperature is 727 K, which places our piloted ignition temperature, 700 K, about in the middle. Reference 10 gives the range for thermal conductivity as 0.126 to $0.293 \text{ W m}^{-1} \text{K}^{-1}$ whereas the derived value is $0.145 \text{ W m}^{-1} \text{K}^{-1}$ and near the lower end. Heat capacitance for PVC from reference 10 ranges from 0.84 to $1.17 \text{ kJ kg}^{-1} \text{K}^{-1}$. Using the formula, $C_p = \lambda / \alpha \rho$, and a typical density of $\rho = 1889 \text{ kg m}^{-3}$ (using ASTM-D-3679-89), the derived heat capacitance is $0.88 \text{ kJ kg}^{-1} \text{K}^{-1}$, which is also near the lower end. The open triangle data in Fig. 6 represent flaming ignition of the charred mass

after shrinkage. To incorporate these data into a SIAM analysis, a suggestion would be to use the ignition prediction for irradiances greater than 45 kW m^{-2} (which converts to equivalent irradiances in end-use of vinyl siding) and the shrinkage prediction at the lower irradiance levels.

CONCLUSIONS

Results of this research indicate that surface emissivity, material density, moisture content, and thickness of the specimen should be measured before testing. In addition, the irradiance profile and the convective heat transfer coefficient for a given apparatus should be carefully calibrated and correlated. During testing, a thermal shutter should be used at high levels of panel irradiance. A full range of achievable irradiance levels 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.

Results with various exterior sidings confirm expectations of the new protocol devised for ASTM-1321. Most sidings are quite thick and would require several thinly cut samples to properly derive values for the three basic thermophysical parameters. However, with the availability of correlation of thermal conductivity and capacitance from reference 6 as a function of oven-dry density, moisture content, and temperature it was found that (1) the easily measured values of density and moisture content of a wood composite could be directly used in the correlation, (2) an adjustment to thermal conductivity correlation by a factor of 1.84 is required for hardboards, (3) the effective temperature is evaluated as the mean of initial and ignition temperatures, (4) and the ignition temperature is derived from the least-squares fit of interpolation Eqn 2 to irradiance as a function of ignition time. The ignition temperatures derived for the exterior sidings were in reasonable range. It appears that

oven-dried samples have ignition temperatures in the range of 560 to 587 K, and increasing with moisture content. It is speculated that the steam dilution of volatiles is the cause of this trend.

In the case of vinyl siding, where few data are at the high levels of irradiance prior to shrinkage, it seemed reasonable to assume a value of 700 K to the piloted ignition temperature using the existing data on PVC. The least-squares procedure was arranged to derive values for thermal conductivity and diffusivity, and the results showed these values to be within the range expected for PVC materials. We found that shrunken vinyl siding will ignite at an irradiance as low as 33 kW m^{-2} . An equivalent value at least 5 kW m^{-2} less than this may be observed in the cone calorimeter because of differences in convective heat transfer and sample orientation.

An obvious benefit of the thermophysical properties presented in Table 2 is their direct inclusion into a database for fire growth models. Additional work is needed to obtain basic flame spread properties for siding materials as part of the improved protocol to ASTM E 1321.

NOMENCLATURE

C_p	heat capacitance ($\text{kJ kg}^{-1} \text{K}^{-1}$)
h_c	convective transfer coefficient ($\text{kW K}^{-1} \text{m}^{-2}$)
h_{ig}	linearized transfer coefficient ($\text{kW K}^{-1} \text{m}^{-2}$)
I_{50}	irradiance at 50 mm position (kW m^{-2})
M	moisture content (%)
t	time (seconds)
T	temperature (K)
T	normalized temperature
q	Surface heat flux (kW m^{-2}) (subscript ig is ignition)
x	lateral position from hot end (m)
α	thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)
δ	thickness (m)
λ	thermal conductivity ($\text{kW K}^{-1} \text{m}^{-1}$)
ϵ_s	surface emissivity
ρ	density (kg m^{-3}) (subscript od is oven-dried)
σ	Stefan-Boltzmann constant ($5.67\text{e-}11 \text{ kW K}^{-4} \text{ m}^{-2}$)

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