FPInnovations

Project No. 301007969
Report 2013/14

Assessing the Flammability of Mass Timber Components: A Review

by

Jim Mehaffey, Ph.D.
CHM Fire Consultants Ltd.

and

Christian Dagenais, Eng., M.Sc.
Scientist – Serviceability and Fire Performance
FPInnovations

February 2014

Christian Dagenais
Project Leader

Mohammad Mohammad
Reviewer

Erol Karacabeyli
Department Manager

Abstract

In recent decades, the wood industry has developed a number of innovative mass timber products. Among others, structural composite lumber (SCL) products, such as parallel strand lumber (PSL), laminated strand lumber (LSL) and laminated veneer lumber (LVL), have been used in the construction of buildings of combustible construction in Canada for some time. SCL are proprietary products manufactured in accordance with ASTM D5456 Standard and evaluated for conformance by the Canadian Construction Materials Center (CCMC).

Division B of the National Building Code of Canada (NBCC), also called the "*acceptable solutions*", currently prescribes that mid- or high-rise buildings be of non-combustible construction. Although some combustible components are permitted in non-combustible construction, mass timber products are generally too thick to meet these provisions (i.e., limited to 25mm in thickness). In buildings of non-combustible construction, Division B of the NBCC sets prescriptive limits on the surface flammability (flame spread rating) of interior finish and also restricts its thickness to no more than 25 mm. Mass timber products can be shown to meet the flame spread ratings in most applications and in fact to exhibit significantly lower (better) flame-spread ratings than 19 mm traditional lumber products. However, mass timber products are too thick to meet the acceptable solutions of the NBCC. This effectively prevents the use of mass timber slabs as unprotected floors, walls or ceilings in buildings of non-combustible construction. As such, benefits could be obtained from developing "*alternative solutions*" to the NBCC acceptable solutions in order to permit the use of SCL for a building of any height for most occupancy classifications. However, such alternative solution requires better documentation of the fire performance of mass timber assemblies used as floors, walls and ceilings.

This report begins with a discussion of the mechanisms of flame spread over combustible materials while describing the NBCC prescriptive solutions that establish the acceptable fire performance of interior finish materials. It is noted that while flame spread ratings do give an indication of the fire performance of products in building fires, the data generated are not useful as input to fire models that predict fire growth in buildings.

The cone calorimeter test is then described in some detail. Basic data generated in the cone calorimeter on the time to ignition and heat release rates are shown to be fundamental properties of wood products which can be useful as input to fire models for predicting fire growth in buildings.

The report concludes with the recommendation that it would be useful to run an extensive set of cone calorimeter tests on SCL, glue-laminated timber and CLT products. The fundamental data could be most useful for validating models for predicting flame spread ratings of massive timber products and useful as input to comprehensive computer fire models that predict the course of fire in buildings. It is also argued that the cone calorimeter would be a useful tool in assessing fire performance during product development and for quality control purposes.

Acknowledgements

This project was financially supported by Forest Innovation Investment of British Columbia under the FII recipient agreement (FII – 13/14-073). Financial support was also provided Natural Resources Canada (NRCan) under the Transformative Technologies Program, which was launched to identify and accelerate the development and introduction of wood products in North America.

FPInnovations expresses its thanks to its industry members, NRCan (Canadian Forest Service), the Provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, New Brunswick, Newfoundland and Labrador, and the Yukon Territory for their continuing guidance and financial support.

Table of Contents

1 Objective

The objective of this literature review is to provide background material on the standard test methods utilized in Canada and other countries for assessing the flammability of materials.

This report begins with a discussion of the mechanisms of flame spread over combustible materials. Of significant importance to the acceptance of mass timber components, it has been shown that thicker wood products spread flames considerably slower than thin wood products. The test method employed in Canada to assess flame spread ratings is then described in addition to the NBCC prescriptive solutions that establish the acceptable fire performance of interior finish. It is observed that the large amount of material needed for flame spread testing is excessive for both product development and quality control purposes. Furthermore, it is noted that while flame spread ratings do give an indication of the fire performance of products in building fires, the data generated are not useful as input to fire models that predict fire growth in buildings.

The cone calorimeter test is described in some detail. Basic data generated in the cone calorimeter on the time to ignition and heat release rates are shown to be fundamental properties of wood products which can be useful as input to fire models for predicting fire growth in buildings. Furthermore, due to the small size of test specimens, the method can also be useful for product development and quality control purposes. This review also discusses mathematical models developed by two different research groups to predict the flame spread ratings of wood products from their performance in cone calorimeter tests. There is also a discussion of how either flame spread ratings or data from the cone calorimeter can be helpful in predicting how rapidly fire develops in a standard room fire scenario.

The report concludes with the recommendation that it would be useful to run an extensive set of cone calorimeter tests on SCL, glue-laminated timber (glulam) and CLT products. The fundamental data could be most useful for validating models for predicting flame spread ratings of massive timber products and useful as input to comprehensive computer fire models that predict the course of fire in buildings. It is also argued that the cone calorimeter would be a useful tool in assessing fire performance during product development and for quality control purposes.

This literature review has been conducted by a fire engineering consultant, per FPInnovations staff request and guidance.

2 Staff

Christian Dagenais, Eng, M.Sc	Scientist, Serviceability & Fire Group, FPInnovations
Jim Mehaffey, Ph.D.	CHM Fire Consultants Ltd.

3 Introduction

In recent decades, the wood industry has developed a number of innovative mass timber products. Among others, structural composite lumber (SCL) products, such as parallel strand lumber (PSL), laminated strand lumber (LSL) and laminated veneer lumber (LVL), have been used in the construction of buildings of combustible construction in Canada for some time. SCL are proprietary products manufactured in accordance with ASTM D5456 [1] standard and evaluated for conformance by the Canadian Construction Materials Center (CCMC).

Division B of the National Building Code of Canada (NBCC) [2], also called the "*acceptable solutions*", currently prescribe that mid- or high-rise buildings be of non-combustible construction. Although some combustible components are permitted in non-combustible construction, mass timber products are generally too thick to meet these provisions (i.e., limited to 25mm in thickness). As such, benefits could be obtained from developing "*alternative solutions*" to the NBCC acceptable solutions in order to permit the use of SCL for a building of any height for most occupancy classifications. However, such alternative solution requires better documentation of the fire performance of mass timber assemblies used as floors, walls and ceilings.

The spread of flames over the interior finish on walls and ceilings in a compartment within a building must be controlled to prevent rapid fire growth, potentially leading to flashover conditions. In buildings of non-combustible construction, Division B of the NBCC sets prescriptive limits on the surface flammability (flame spread rating) of interior finish and also restricts its thickness to no more than 25 mm. Mass timber products can be shown to meet the flame spread ratings in most applications and in fact to exhibit significantly lower (better) flame-spread ratings than 19 mm traditional lumber products.

4 Fundamentals of Flame Spread over Wood Products

4.1 Ignition of Wood Products

Before considering flame spread across a wood product, it is necessary to understand the dynamics of ignition. When a wood product is heated by a flame or by radiant heat source, the surface temperature begins to climb. When the surface temperature reaches approximately 200°C, the chemical structure of the wood begins to break down as the large molecules that make up wood begin to undergo pyrolysis [3]. As the temperature continues to climb, this pyrolysis process increases in intensity and volatiles begin to be liberated. At a significantly high temperature, the concentration of flammable volatiles above the wood surface is high enough that the air-volatile mixture can be ignited by a pilot (a spark or a small flame). This temperature is referred to as the piloted ignition temperature of the wood product and is typically around 375°C.

4.2 Flame Spread over Wood Products

Flame spread over any combustible material can be envisioned as a moving ignition front. Heat transfer from the flames can heat combustible material ahead of the flame and, once the material ahead of the flame reaches its piloted ignition temperature, the flame itself can act as the pilot. The flame thereby moves forward and the flame-spread process continues onward (Figure 1).

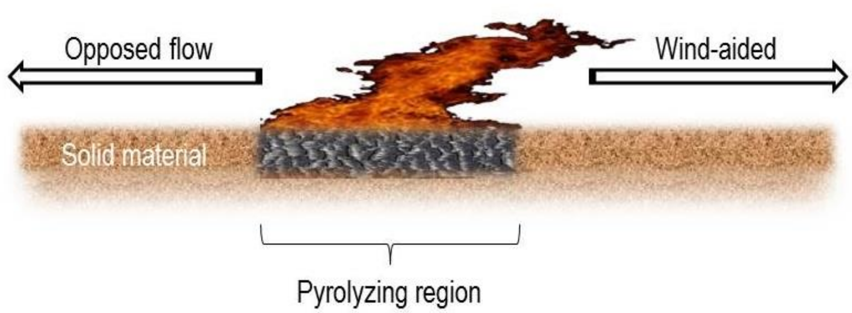

Figure 1 Flame spread modes over an horizontal surface

There are a number of factors which have an impact on the rate of flame spread over a combustible product. The most important factors for wood products are considered in some detail in the following sections.

4.2.1 Chemical Properties

The small variability in the chemical composition and anatomy of different species of trees translates into some variability in the flame spread ratings (flammability) of wood products made from different species. Furthermore, the quantity and type of resin or adhesive employing in the production of engineered wood products may have some impact on the products' flame spread ratings as well.

Evidently, fire retardant treatment has a large impact on the flammability of wood products. The definition of fire retardant treated wood (FRTW) in the NBCC is that wood must be pressure-impregnated with fire retardant chemicals in conformance with CSA O80 [4] such that it results in a flame spread rating of not more than 25. As shall be obvious later in this report this is a dramatic decrease in flame-spread rating as many wood products of thickness 19 mm have an inherent flame spread rating of about 100.

Most commercially available fire retardants work by altering the process of pyrolysis in treated wood products. During pyrolysis of typical wood products, about 20% of the wood is converted to char, 20% leaves as water vapour and 60% leaves as a flammable vapour. However, the chemical composition of the products of pyrolysis of FRTW is dramatically altered with about 45% of the wood being converted to char, 35% leaving as water vapour and 20% leaving as a flammable vapour [3]. Since the char left behind is denser and the vapour leaving FRTW is less flammable, flaming is less vigorous for FRTW than for untreated wood products so that flames spread across the surface of FRTW a lot slower than across untreated wood products.

4.2.2 Thickness, Density, Specific Heat and Thermal Conductivity

The thickness and thermal properties of the wood product play important roles in the rate of flame spread across its surface. As noted above, during flame spread, heat is transferred from the flame to the surface just ahead of the flame front. The thermal penetration depth (d_h) into the specimen just ahead of the flame, is given by Equation (1).

$$d_h \cong \sqrt{\frac{k \cdot t}{\rho \cdot c}} \tag{1}$$

Where t is the duration of heating by the flame (s), d_h is the depth of heating (m), k is the thermal conductivity of the material (W m^{-1} K^{-1}), ρ is the density of the material (kg m^{-3}) and c is the specific heat of the material (J kg^{-1} K^{-1}).

A specimen is considered to be thermally thin if the thickness of the specimen (d_s) is lower than the thermal penetration depth (d_h), as per Equation (2).

$$d_s < d_h \tag{2}$$

If the solid is thermally thin, there is effectively no temperature gradient between the exposed and unexposed surfaces of a specimen. Heating of the exposed surface occurs rapidly and flame spread is fast. The rate of flame spread (V) can be shown to be inversely proportional to the thickness of the specimen as shown in Equation (3).

$$V \propto \frac{1}{\rho \cdot c \cdot d_s} \tag{3}$$

However, as the thickness is increased, there is a significant temperature gradient between the exposed face and unexposed face of a specimen. It takes longer for the exposed face to reach the specimen's piloted ignition temperature because heat is continuous being transferred by conduction deeper into the specimen. So the rate of flame spread continues to slow down with increasing thickness.

If the thickness of the specimen is greater than the thermal penetration depth during flame spread ($d_s > d_h$), then the specimen is considered thermally thick and the rate of flame spread no longer decreases with increasing thickness of the specimen. At that stage, the rate of flame spread no longer depends on the thickness of the material, but only on its thermal properties as depicted in Equation (4).

$$V \propto \frac{1}{k \cdot \rho \cdot c} \tag{4}$$

It is generally accepted that 32 mm represents a typical minimum thickness for wood products to behave as thermally thick solids. As such, traditional combustible finish products limited to 25 mm in thickness cannot be treated as thermally thick solids when performing a heat transfer analysis. They would most likely exhibit faster heat conduction, thus a faster time to ignition and flame spread as opposed to products thicker than the minimum thermal penetration depths. Examples of how the thickness of a specimen can impact the flammability of a wood product are presented later in this report.

4.2.3 Orientation

The relative orientation of the flame to the surface on which it is spreading plays an important role in the rate of flame spread. Flame spread in the same direction as air flow caused by wind or buoyancy is called wind-aided flame spread. Flame spread in a direction opposite to air flow is called opposed-flow flame spread. Wind-aided flame spread is typically much faster than opposed-flow flame spread.

Figure 2 illustrates the spread of flame along a floor, up a wall and across a ceiling. The spread of flame across the combustible floor depicted in Part (a) of the Figure is an example of opposed-flow flame spread. The buoyancy of the flame causes hot gas to rise above the flame and fresh air to approach the flame along the floor in opposite direction to the flame spread along the floor. Opposed-flow flame spread is typically quite slow. In Part (b), the flame has crossed the floor and is spreading up the wall. This is an example of wind-aided flame spread. The buoyancy of the flame causes hot gas and fresh air to move upward so that flame spread and air movement are in the same direction. The resultant wind-aided flame spread up the wall can be quite fast. In Part (c), the flame has climbed the wall and is spreading across the ceiling. This is also an example of wind-aided flame spread and it can also be quite fast.

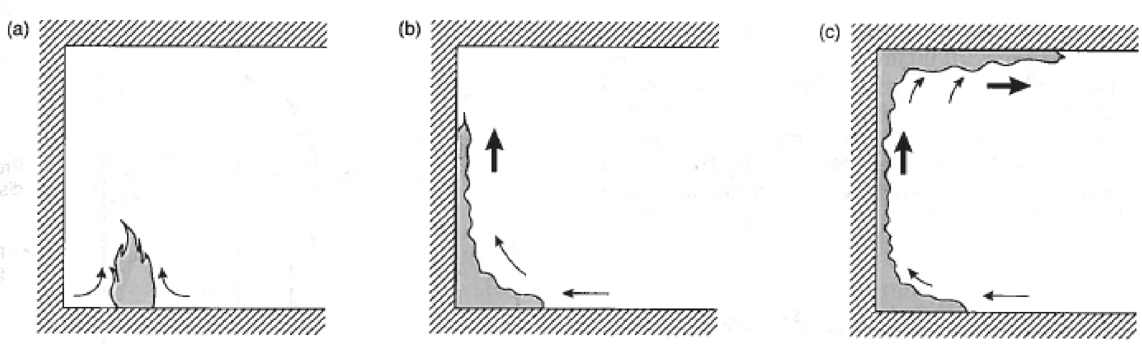

Figure 2 Orientation of combustible interior finish and the modes of flame spread over (a) a floor, (b) a wall and (c) a ceiling [5]

4.3 Flashover

In a room configuration, it is evident that a thin layer of smoke will begin to develop in Part (a) of Figure 2 and that the smoke layer will grow in depth and temperature during Parts (b) and Parts (c). The smoke layer will be deeper than the ceiling flames in Part (c) and due to the high temperatures of the smoke, flames will begin to move down the walls in a slow opposed-flow manner. If the temperature of the smoke layer approaches 600°C, the radiant heat emitted by the ceiling smoke layer will be so intense that all combustibles at floor level (or above) will simultaneously burst into flames. This transition to full room involvement is referred to as "flashover". As shall become evident in subsection 9 of this report, wall and ceiling linings that promote rapid flame spread also promote rapid flashover.

5 The Tunnel Test

The propensity of flames to spread across interior finish on the walls and ceiling of a room, and hence contribute to fire growth in a room, is regulated in terms of the interior finish's flame spread rating in Canada and in the USA. The test method employed to determine the flame spread ratings of interior finishes is the Steiner tunnel test which is designated as CAN/ULC-S102 [6] in Canada and as ASTM E84 [7] in the USA. There are some modest differences in the two methods as outlined below.

Figure 3, which is taken directly from CAN/ULC-S102, provides a schematic representation of the Steiner tunnel. The test equipment contains an internal horizontal tunnel 7.6 m long, 450 mm wide and 300 deep. The walls and the floor of the tunnel are constructed of insulating firebrick. One wall has observation windows along its length. The roof is removable and is constructed with a low density material of mineral composition insulation supported within a metal structure. Before testing, a 7.2 m specimen is mounted in the ceiling of the tunnel and a 13 mm somewhat dense mineral composition board is placed between the roof insulation material and the test specimen before testing.

During testing, flames from two burners (see Figure 4) are forced down the tunnel by a draught of air moving at 1.2 m s^{-1}.

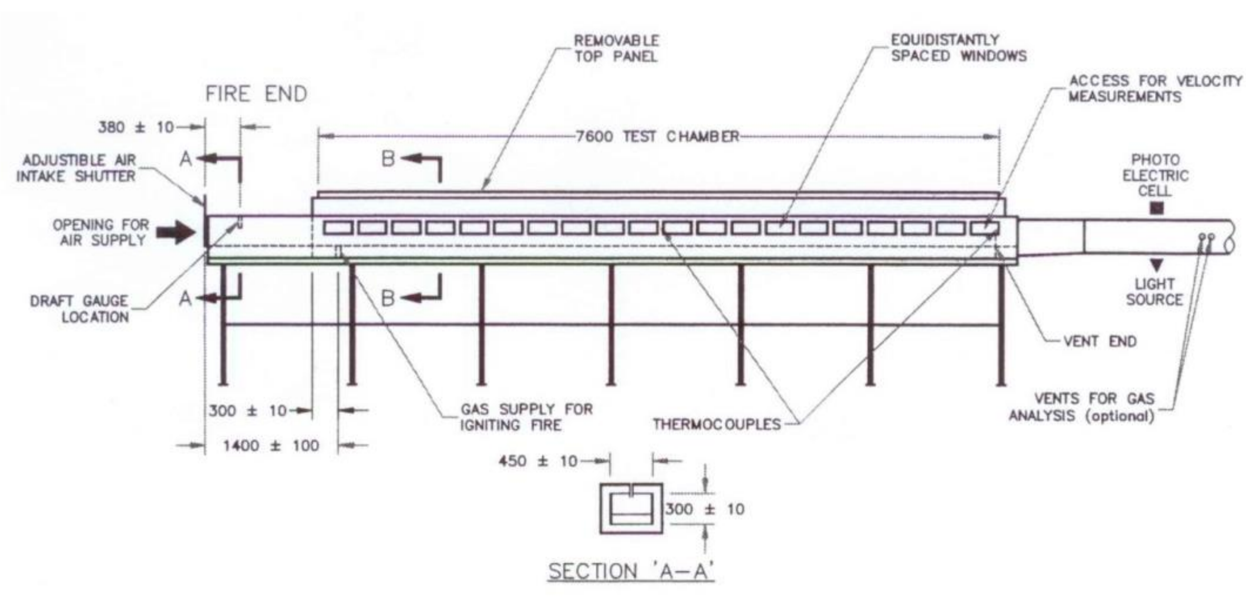

Figure 3 Schematic of the Steiner Tunnel [6]

Figure 4 Typical cross-section of the Tunnel test at B-B of Figure 3

Calibration of the equipment is achieved by mounting a 7.2 m long, 18 mm thick red-oak specimen on the tunnel's ceiling and adjusting the burner output so that it takes 5.5 minutes for flames to travel the entire length of the specimen. In a calibrated Steiner tunnel, the heat release rate of the burners is typically 79 to 90 kW [6, 8] and the burner flames typically engulf 1.37 m of the ceiling mounted specimen before ignition of the specimen and subsequent flame spread along the specimen.

As has been noted earlier, the fire hazard of interior finish materials is primarily due to the potential for rapid wind-aided flame spread over the surface. Clearly, the wind-aided tunnel test replicates this type of flame spread rather well.

The measurements consist of recording the flame front position as a function of time for a 10 minute period. A flame-spread value (FSV) is calculated on the basis of the area under the curve of flame tip location versus time (A_T). The area is calculated based on the flame extension; that is, based on the distance of the flame tip from the burner minus the length of the burner flame. Finally any flame recession is ignored in the calculation of A_T. The expressions for calculating FSV are:

$$FSV = 1.85 \cdot A_T \qquad \text{if } A_T \leq 29.7 \text{ m·min} \qquad (5)$$

$$FSV = \frac{1,640}{59.4 - A_T} \qquad \text{if } A_T > 29.7 \text{ m·min} \qquad (6)$$

The flame spread rating of a material is the average of the values of FSV from at least three tests. Although there is a different equation for calculating the FSV for materials that exhibits very fast flame spread early in a test, the equation only comes into play for low-density foamed plastic insulations so is not considered herein.

The American version of the Steiner tunnel test, ASTM E84 is similar to the Canadian version. There are however some differences. The method for ensuring good turbulence in the Canadian and American tunnel tests differs a little. In the USA, all products are mounted in the ceiling of the tunnel; whereas in Canada, while most materials are mounted in the ceiling, materials that melt, cannot support themselves or are intended to be flooring are mounted on the floor of the tunnel and tested in accordance with CAN/ULC-S102.2 [9].

Finally, the expression employed in the USA for calculating a FSV from A_T is a little different from that used in Canada and is reproduced below. Typically, the American expression predicts a flame-spread rating about 8 to 10% less than the Canadian expression.

$$FSV = 0.0282 \cdot A_T \qquad \text{if } A_T \leq 1783 \text{ m·sec} \qquad (7)$$

$$FSV = \frac{89{,}611}{3{,}566 - A_T} \qquad \text{if } A_T > 29.7 \text{ m·sec} \qquad (8)$$

A solid wood product typically has a FSR less than 150 and gypsum board (even when painted) has a FSR less than 25. Some composite wood products and some decorative pre-finished panel products have FSR exceeding 150 or even 200. FSR ratings that have been reported in the literature for some typical wood products are given in Table 1. The variability is a result of tests being conducted at different times (the test method has evolved) and in testing was carried out at different laboratories.

The entries for Douglas fir plywood in Table 1 demonstrate how the flame spread rating depends on the thickness of the test specimen: the thicker the specimen, the lower the flame-spread rating. This occurs despite the fact that the 13 mm mineral board above the test specimen is a poorer insulting material than the specimen. Presumably, this trend of decreasing flame-spread rating with increasing thickness levels off at the thickness at which the specimen becomes thermally thick.

Dagenais [10, 11] recently conducted flame spread tests conducted in accordance with CAN/ULC S102 on five thick mass timber products. All five products were thermally thick. The results are summarized in Table 2. Clearly these products exhibited considerably lower flame-spread ratings compared with the entries in Table 1.

Table 1 Flame spread rating of common wood and wood-based products [12]

Wood and wood-based products	Flame Spread Rating
Western red cedar	65 – 73
Douglas fir	67 – 117
Red oak	82 – 102
Eastern white pine	85
Douglas fir plywood 6 mm 9 mm 15 mm	 117 – 145 94 – 119 84 – 95

Table 2 Flame spread rating of mass timber components

Wood and wood-based products	Thickness	Flame Spread Rating
3-ply CLT E1 SPF Stress Grade V2 SPF Stress Grade	 105 mm 99 mm	 35 40
Parallel strand lumber (PSL)	89 mm	35
Laminated strand lumber (LSL)	89 mm	75

Flame spread ratings are useful means for ranking the flammability of interior finishes. As discussed in the next Section 6, flame spread ratings are therefore used in building codes to regulate the flammability of interior finish. Flame spread ratings are dimensionless, however, very test specific, and cannot be used as quantitative input data for mathematical models that predict fire growth rates or fire risk in buildings.

Since the Steiner tunnel test requires approximately 4 m² of material (for one test; 12 m² in total for CAN/ULC S102), it is often not practical to use tunnel testing to achieve a targeted flame spread rating during the development of innovative products. For similar reasons, the test is not suitable for quality control purposes during the manufacturing process. To address these problems, it would be advisable to develop correlations that could predict Steiner tunnel test performance on the basis of data from a small-scale test such as the cone calorimeter.

6 NBCC Requirements Governing Flame Spread Ratings

6.1 General Requirements – Group C Occupancies

The details of the provisions of the NBCC that regulate the combustibility and the flammability of interior finish depend upon a number of factors including, among others:

- Major occupancy classification of the building;
- Location in a building (exit, corridor, suite, etc.);
- Presence or absence of automatic sprinklers;
- Whether the building is permitted to be of combustible construction or must be of non-combustible construction;
- Whether the building is classified as a high building;
- Etc.

Rather than summarising all of these provisions, it has been decided to summarise only those applicable to apartment buildings as an example of the types of acceptable solutions presented in the NBCC. Apartment buildings are classified as Group C residential occupancies.

- **Walls within an apartment**:
  Whether the building is low-rise, mid-rise or high-rise, sprinklered or not, and of combustible or non-combustible construction, walls within an apartment can be lined with a product that has a flame-spread rating of 150 or less. Consequently most wood products are permitted;

- **Ceilings within an apartment**:
  - If the building is permitted to be of combustible construction, ceilings within an apartment can be lined with a product that has a flame-spread rating of 150 or less. Consequently most wood products would be permitted;
  - If the building is required to be of non-combustible construction, ceilings within an apartment must be lined with a product that has a flame-spread rating of 25 or less. Consequently gypsum board would be permitted.

- **Walls within public corridors**:
  - In an unsprinklered apartment building, walls in a public corridor can be lined with:
    - A product that has a flame-spread rating of 75 or less, or;
    - product that has a flame-spread rating of 150 or less on the lower half and a product that has a flame-spread rating of 25 or less on the upper half. Consequently wood wainscoting is permitted on the lower half and gypsum board on the upper half;

    - In a sprinklered apartment building, walls in a public corridor can be lined with a product that has a flame-spread rating of 150 or less. Consequently most wood products would be permitted on the entire wall surface.

- **Ceilings within public corridors**:
  Whether the building is low-rise, mid-rise or high-rise, sprinklered or not, and of combustible or non-combustible construction, ceilings within public corridors can be lined with a product that has a flame-spread rating of 25 or less. Consequently gypsum board is permitted.

- **Within exits**:
  Whether the building is low-rise, mid-rise or high-rise, sprinklered or not, and of combustible or non-combustible construction, walls and ceilings within exits can be lined with a product that has a flame-spread rating of 25 or less. Consequently gypsum board is permitted.

6.2 Special Considerations for Buildings of Non-Combustible Construction

In addition to the flame spread requirements of subsection 6.1 of this report, in a building required to be of non-combustible construction (i.e. not only in a building classified as a residential occupancy):

- Combustible interior wall finishes, other than foamed plastics, are permitted provided they
    - Are not more than 25 mm thick, and;
    - Have a FSR not more than 150 on any exposed surface, or any surface that would be exposed by cutting through the material in any direction, and;
- Combustible interior ceiling finishes, other than foamed plastics, are permitted provided they
    - Are not more than 25 mm thick except for exposed fire-retardant treated wood battens, and ;
    - Have a FSR not more than 25 on any exposed surface, or any surface that would be exposed by cutting through the material in any direction, or are of fire-retardant treated wood.

6.3 High Buildings

For a building classified as a high building by the NBCC, there are locations in the building where there are more stringent requirements for interior finishes than mentioned in subsection 6.1 of this report. In fact, requirements come into play for floors and for smoke developed classifications of interior finishes for some locations in a high building. It should be noted that, in addition to flame spread ratings, smoke developed classifications of interior finish are also determined in Steiner tunnel tests. Table 3 summarises the requirements for interior finishes in a high building.

As Table D-3.1.1.A in the NBCC indicates, for many wood products, the FSR does not exceed 150 and the smoke developed classification does not exceed 300. Therefore, they would be allowed on the walls and floors within apartments in a high building. However, traditional wood products would not be allowed on the ceilings, because their FSR exceed 25 (refer to subsection 6.1) and their smoke developed classifications exceed 50 (see Table 3).

Table 3 Provisions for interior finishes in high buildings

Location of Element	Maximum Flame-Spread Rating			Maximum Smoke-Developed Classification		
	Wall	Ceiling	Floor	Wall	Ceiling	Floor
Exits	25	25	25	50	50	50
Public corridors	See 6.1	See 6.1	300	100	50	500
Elevator floors & vestibules	25	25	300	100	100	300
Service spaces & rooms	25	25	25	50	50	50
All other locations	See 6.1	See 6.1	No limit	300	50	No limit

6.4 Fire-Retardant Treated Wood

Fire-retardant treated wood is defined in the NBCC as wood that has been pressure impregnated with fire retardant chemicals in conformance with CAN/CSA-O80 [4] and has a flame spread rating not more than 25. It can therefore be employed anywhere where combustible elements are permitted but must have a flame spread rating not more than 25. In high buildings it must also meet the smoke developed classifications outlined in subsection 6.3 and in buildings of non-combustible construction it must also meet the thickness specifications of subsection 6.2.

7 The Cone Calorimeter Test

7.1 The Apparatus

The ignitability, flammability (rate of heat release) and smoke production characteristics of combustible materials can be assessed using small-scale cone calorimeter tests conducted in compliance with ASTM E1354 [13] or ISO 5660 [14].

The cone calorimeter depicted in Figure 5, is a very modern apparatus. A truncated cone is heated electrically to produce a uniform radiant heat flux across the surface of a 10 cm by 10 cm test specimen. The most typical test configuration is for the specimen to be oriented horizontally in a sample holder. The specimen sits on a good insulating material which is lightweight mineral fibre blanket. A small spark igniter is placed just above the specimen. Following ignition, smoke and hot gases flow upwards through the truncated cone and into an exhaust hood. Within the exhaust system, the concentrations of various gases (especially CO_2, CO and O_2) are measured which allows for the calculation of the heat release rate of the burning specimen. Measurements of smoke obscuration can also be taken.

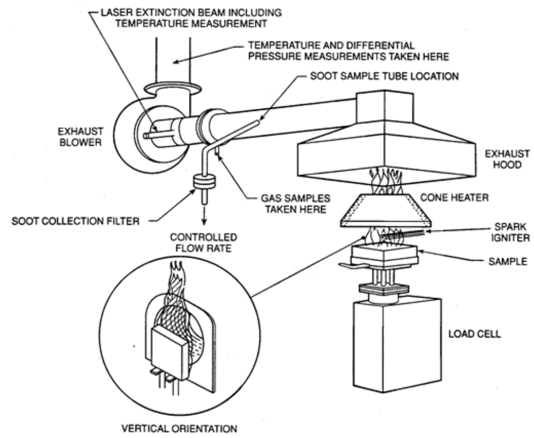

Figure 5 Schematic of a cone calorimeter

7.2 Time to Ignition

The cone calorimeter has been used extensively to study the time to piloted ignition of wood products (t_{ig}, in sec.) as a function of the incident radiant flux $\dot{q}_e''$ (kW m^{-2}). Perhaps the simplest way to present the ignition data for wood products as generated in the cone calorimeter is to plot $t_{ig}^{-1/2}$ versus $\dot{q}_e''$ as is done in Figure 6 for a thermally thick specimen of spruce. Discussions are currently made with respect to the exponent of the y-axis. As shown in Figure 6, sometimes the plot is a function of $t_{ig}^{-0.55}$ versus $\dot{q}_e''$. In both cases, the straight line on the graph is a best fit through the data.

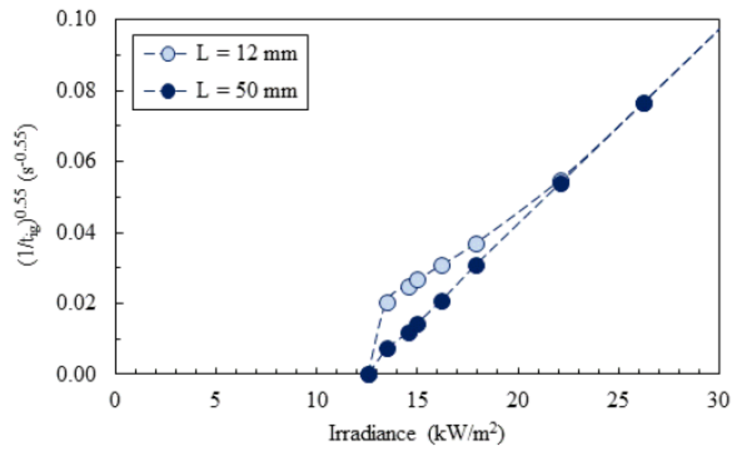

Figure 6 Ignition data generated in the cone calorimeter for generic oak specimen [15]

More rigorous representations of the data suggest it is better to plot $t_{ig}^{-0.55}$ versus $\dot{q}_e''$. In any case, it is clear from the figure that the time to ignition increases dramatically as the externally applied radiant heat flux decreases. For an external radiant heat flux of 60 kW m^{-2}, the time to ignition is only 10 s; for an external radiant heat flux of 40 kW m^{-2}, the time to ignition is 30 s; but for an external radiant heat flux of 20 kW m^{-2}, the time to ignition is 330 s (5.5 min). Note that the line intersects the x-axis ($\dot{q}_e''$) at 12.5 kW m^{-2}. This suggests that it would take an infinite amount of time for ignition to occur given an external heat flux of 12.5 kW m^{-2}. Consequently, 12.5 kW m^{-2} is referred to as the critical radiant flux for the ignition of spruce (and most solid wood products).

7.3 Rate of Heat Release

The cone calorimeter has also been used extensively to study the rate at which heat is released when wood products burn as a function of the incident radiant flux $\dot{q}_e''$ (kW m^{-2}). Figure 7 shows the heat release rates per unit area measured in cone calorimeter tests conducted on a 12 mm oriented strand board (OSB) at four different irradiances (incident radiant heat fluxes). There are several important features of these data that should be noted:

- As the incident radiant heat flux is increased, the time to ignition decreases as noted in subsection 7.2. For heat fluxes of 65 and 50 kW m^{-2} ignition occurs within a few seconds. For a heat flux of 35 kW m^{-2}, ignition occurs after about one minute and for 25 kW m^{-2} ignition occurs after about 3 minutes;
- Immediately following ignition the heat release rate reaches a peak value. The size of this peak increases as the incident radiant heat flux is increased;
- After the first peak in heat release rate, the heat release rate drops to a constant value (constant in time) as char forms on the surface of the specimen. The value of this constant heat release rate increases as the incident heat flux is increased;
- For all four incident heat fluxes, the heat release rate exhibits a second peak. This accelerated burning (accelerated heat release rate) occurs when the specimen has nearly burned through. Note that this second peak occurs sooner and has a higher peak value as the external heat flux is increased.

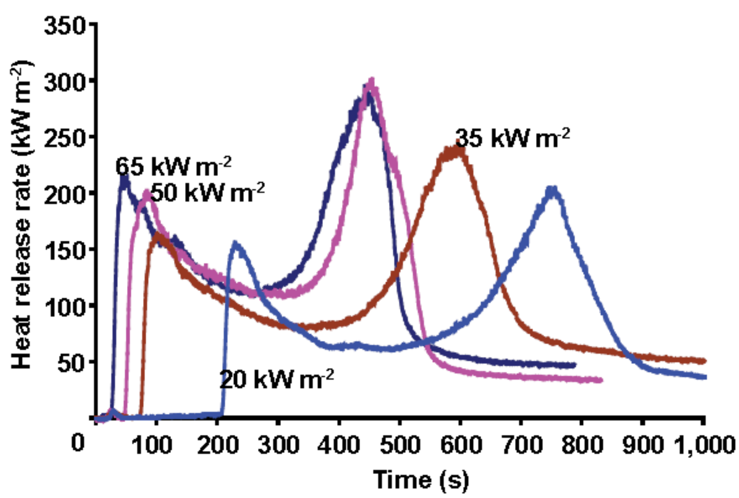

Figure 7 Heat release rate of Victorian ash for various incident radiant heat fluxes [16]

Dietenberger & White [17] have noted that while the test specimen in the cone calorimeter is backed by a low-density insulation material, in the tunnel test the test specimen is back by a high-density board. This high density board acts as a sufficiently effective heat sink in tunnel tests to remove the second peak in heat release rate observed in cone calorimeter tests.

Figure 8 shows the heat release rates measured in cone calorimeter tests conducted on medium-density fiberboards of various thicknesses when exposed to a radiant heat flux of 50 kW m^{-2} [18]. There are several important features of these data that should be noted:

- The time to ignition does not depend on the thickness of the specimen (for high incident heat fluxes);
- The timing of and peak value of the first peak in the heat release rate do not depend on the thickness of the specimen (for high incident heat fluxes);
- After the first peak in heat release rate, the heat release rate drops to a constant value (constant in time) as char forms on the surface of the specimen. The value of this constant heat release rate does not appear to depend on the thickness of the specimen;
- The second peak in the heat release rate occurs sooner and has a higher peak heat release rate as the thickness of the specimen is decreased because this accelerated burning (accelerated heat release rate) occurs when the specimen has nearly burned through;
- When exposed to a 50 kW m^{-2} incident radiant heat flux in the cone calorimeter, medium-density fiberboard specimens that are 10 mm, 19 mm or 28 mm thick behaved as thermally thin specimens whereas the 50 mm thick specimen behave as a thermally thick specimen

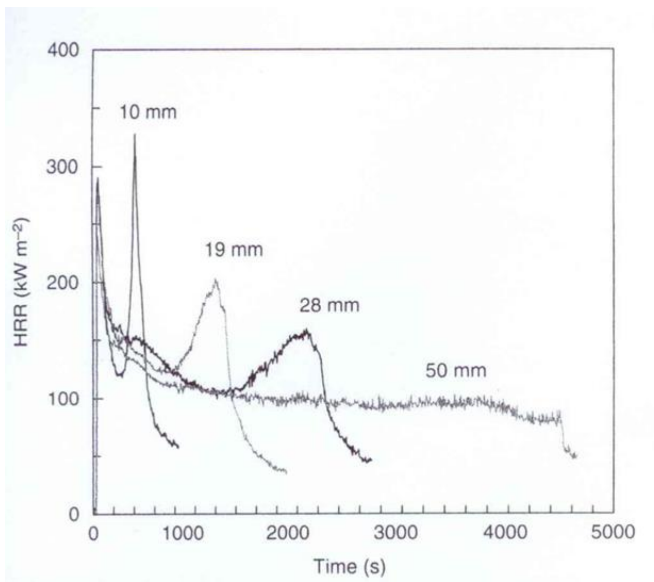

Figure 8 Heat releace rate of medium-density fiberboard of various thicknesses [18]

It was noted in Section 6 of this report, that the flame spread rating of a wood product increases as the thickness of the product is decreased. This is presumably caused by the same process as witnessed in cone calorimeter tests; namely, the heat release rate and the rate of flame spread must increase when the specimen has nearly burned through and this occurs sooner for thermally thin materials.

7.4 Degree of Combustibility (Canada)

The Canadian test method CAN/ULC-S135 [19] which assesses the degree of combustibility of building products has recently been cited in the NBCC. During a standard test conducted in compliance with CAN/ULC-S135, the specimen is mounted in a horizontal orientation in a cone calorimeter and subjected to an incident radiant flux of 50 kW m^{-2} in the presence of an electric spark igniter. The heat release rate and smoke characteristics are measured from the moment the specimen is subjected to the radiant heat and is continued for 15 min.

The NBCC states that a material is permitted to be used in non-combustible construction provided that, when tested in accordance with CAN/ULC-S135 at a heat flux of 50 kW m^{-2}:

a) Its average total heat release is no more than 3 MJ m^{-2};
b) Its total smoke extinction area is not more than 1.0 m^2; and
c) The test duration is extended beyond the time stipulated in CAN/ULC-S135 until it is clear that there is no further release of heat or smoke.

No structural composite lumber products and, in fact, very few combustible products pass this test. Consequently, this test method will not be discussed in any further detail.

7.5 The Cone Calorimeter as a Research Tool

Data generated in the cone calorimeter on mass loss rates, heat release rates, toxic gas generation, and smoke generation are finding much application in fire safety engineering applications. Such data are useful input into mathematical models predicting fire growth rates, toxicity and visibility in building fires. Much data has already been cataloged for a variety of building products on the time to ignition and rates of heat release for a wide range of incident heat flux scenarios. These data are being cataloged as a resource to fire protection engineers in such publications as the SFPE *Handbook of Fire Protection Engineering* [18].

7.6 How is the Cone Calorimeter Used Internationally in Building Regulations?

While the cone calorimeter has found only limited application in Canadian building codes, it is cited in the building regulations of several other counties.

In Japan, for example, interior finish is classified as being non-combustible, quasi-non-combustible or fire retardant based on its performance in a cone calorimeter test when subjected to an irradiance level of 50 kW m^{-2} [20]. The acceptance criteria employed in Japan are summarised in Table 4.

Table 4 Classification of Room Linings in Japan

Classification	Duration of Exposure[1]	Total Heat Released	Peak Rate of Heat Release[2]
Non-combustible	20 min[1]	≤ 8 MJ m^{-2}	≤ 200 kW m^{-2}
Quasi-non-combustible	10 min[1]	≤ 8 MJ m^{-2}	≤ 200 kW m^{-2}
Fire retardant	5 min[1]	≤ 8 MJ m^{-2}	≤ 200 kW m^{-2}

1. The specimen must not develop cracks on the back surface or distort excessively during exposure.
2. This rate may be exceeded for a period of time not exceeding 10 seconds.

The building code in Australia provides a method for classifying interior finish based on performance in a room-fire test (discussed in Section 8 of this report). As an alternative, it is possible to classify an interior finish using data obtained by testing it at an irradiance of 50 kW m^{-2} in a cone calorimeter [20].

8 The Room Corner Test

8.1 The Test Method

Building code requirements and small-scale fire test methods for room linings (interior finish) vary from country to country. However, as countries around the world have begun to base regulations on fire safety engineering principles, there is a tendency to base product acceptance on performance in either a national fire test or performance in the international room-corner fire tests ISO 9705 [21]. The European Union, Japan, Australia and New Zealand all accept ISO 9705 data as one way of demonstrating compliance with building regulations [20]. Consequently, the room-corner test has recently become known as the "*the reference scenario*".

In ISO 9705, the test specimen lines the walls and ceiling of a small room with floor dimensions 2.4 m by 3.6 m and height of 2.4 m. The only opening to the room is a door of dimensions 0.8 m by 2.0 m (high) in one of the end walls. A burner is placed in a back corner opposite the open door. For the first 10 minutes of the test the heat release rate of the burner is set at 100 kW (equivalent in intensity to a wastepaper basket fire), and then at 300 kW for another 10 minutes. At 300 kW, the burner flames intermittently touch the ceiling of the room (assuming no contribution for the wall linings).

The primary purpose of the test is to observe how long it takes for the room to go to flashover; that is, the entire interior finish to become involved in fire. This time is referred to as the time to flashover. Much research has been conducted internationally to ensure that the results of national flammability tests are actually predictive of performance in the "*reference scenario*"; that is, the room-corner test.

8.2 Comparison of Room Corner Test Results and Tunnel Test Results

Over the years, FPInnovations and the National Research Council of Canada have undertaken research to compare the performance of building materials in the tunnel test with their performance in the room-corner test [22, 23]. The building materials employed in these studies together with their flame spread ratings (both as determined by ASTM E84 and by CAN/ULC S102 are summarised in Table 5.

Table 5 Flame spread rating of building materials

Building Product	Flame Spread Rating	
	ASTM E84	CAN/ULC S102
Gypsum board	15	16
FRT Douglas fir plywood	15	16
Douglas fir plywood	110	120
OSB	155	167
Polyurethane foam	~ 74	500
White oak boards	90	98
White pine boards	80	87

Note, as assessed by CAN/ULC S102, the products considered span a very large range of FSR: from 15 to 500. The value of 500 for polyurethane insulation results from the use of a rate of spread expression in CAN/ULC S101 that is not employed in ASTM E84. The results of the room-corner fire tests conducted over several decades are summarised in Table 6.

Table 6   Product performance in the room-corner fire test

Test	Wall Lining	Ceiling Lining	Flashover (min:s)
1	Gypsum board	Gypsum board	No flashover
2	FRT Douglas fir plywood	FRT Douglas fir plywood	10:40
3	FRT Douglas fir plywood	FRT Douglas fir plywood	10:20
4	Douglas fir plywood	Douglas fir plywood	3:10
5	Douglas fir plywood	Douglas fir plywood	2:45
6	OSB	OSB	2:15
7	Polyurethane foam	Polyurethane foam	0:13
8	Douglas fir plywood	Gypsum board	8:10
9	Gypsum // Douglas fir plywood	Gypsum board	No flashover
10	Gypsum // White oak boards	Gypsum board	No flashover
11	Gypsum // White pine boards	Gypsum board	No flashover

A brief discussion of the first seven tests follows:

- In Test 1, with the walls and ceiling lined with gypsum board whose flame-spread rating was 16, flashover never occurred during the entire 20 minute test;
- In Tests 2 and 3, with the walls and ceiling lined with FRT Douglas fir plywood whose flame spread rating was also 16, flashover occurred at 10:40 and 10:20 respectively. Flashover did not occur during the first 10 minutes of the test when the heat release rate of the burner was 100 kW; however, shortly after the heat release rate of the burner was increased to 300 kW flashover was observed;
- In Tests 4 and 5, with the walls and ceiling lined with Douglas fir plywood whose flame spread rating was 120, flashover occurred at 3:10 and 2:45 respectively. Flashover occurred while the heat release rate of the burner was 100 kW;
- In Test 6, with the walls and ceiling lined with OSB whose flame spread rating was 167, flashover occurred at 2:15. Once again flashover occurred while the heat release rate of the burner was 100 kW;
- In Test 7, with the walls and ceiling lined with a polyurethane insulation whose flame-spread rating was 500 (as assessed by CAN/ULC S102, flashover occurred after only 13 seconds.

Notice the strong trend in these tests: as the flame spread rating as assessed by CAN/ULC S102 is increased the time to flashover in the room-corner fire test decreases.

Now consider Test 8 in which the walls were lined with Douglas fir plywood (FSR = 120) and the ceiling with gypsum board (FSR = 16). Replacing the Douglas fir ceiling with the more common gypsum board ceiling causes the time to flashover to increase from about 3 minutes (Tests 4 and 5) to 8 minutes 10 seconds. This is a significant improvement in fire performance.

Finally, consider Tests 9, 10, and 11. In these tests, the bottom 1.0 m of the walls was lined with a wooden wainscoting. The upper 1.4 m of the walls and the entire ceiling were lined with gypsum board. Flashover did not occur in any of the tests. This gives some scientific credence to the NBCC provision that in an unsprinklered apartment building, walls in a public corridor can be lined with a product that has a FSR of 150 or less on the lower half and a product that has a FSR of 25 or less on the upper half.

Lastly, White *et al.* [24] also evaluated several lining products under different room/corner protocols and found that the ISO 9705 protocol produced results that were consistent with expected performance from the ASTM E84 test method. Figure 9 shows that a correlation between the time to flashover conditions in the room/corner test and the flame spread indices of products exists.

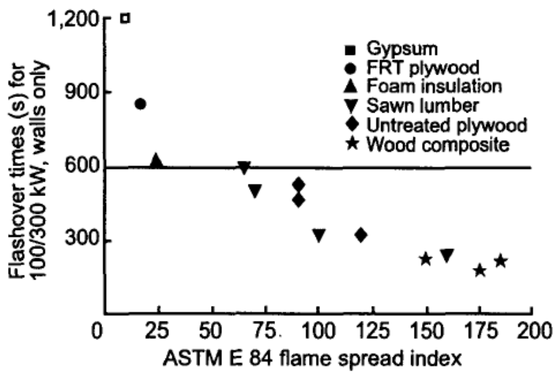

Figure 9 Times to flashover conditions and ASTM E84 flame spread index [24]

8.3 Comparison of Room Corner Test Results and Cone Calorimeter Test Results

Several studies have been undertaken to predict the time to flashover measured in full-scale room-corner tests on the basis of data measured in the small-scale cone calorimeter test. Perhaps the simplest of those correlations was the one presented in Equation (9) developed by Östman and Nussbaum [25].

$$T = a\frac{t\sqrt{\rho}}{HR} + b \qquad (9)$$

Where T is the time to flashover in the room-corner test (s), t is the time to ignition in the cone calorimeter at 25 kW m^{-2} (s), ρ is the density of the material being tested (kg m^{-3}), HR is the peak heat release rate per unit area at 50 kW m^{-2} (kJ m^{-2}), a is a constant taken as 2.76 x 10^6 J $kg^{-1/2}$ $m^{-1/2}$ and b is a constant taken as 46 s.

The interpretation of HR, the peak heat release rate per unit area at 50 kW m^{-2} requires some explanation. This is simply the area under the rate of heat release per unit area before the second peak in heat release rate is observed. As mentioned earlier, this second peak appears when the back surface of the test material begins to burn in the cone calorimeter test.

It is useful to observe the effect of each variable on the right-hand side of Equation (9):

- As t, the time to ignition in the cone calorimeter at 25 kW m^{-2}, increases T, the time to flashover in the room-corner test, increases. This makes sense as the longer the time to ignition, one would expect the longer the time to flashover;
- As ρ, the density of the material, increases, the time to flashover in the room-corner test, increases. This also makes sense as low-density combustible materials used as a room lining material drive a room fire to flashover quickly.
- As HR, the peak heat release rate per unit area at 50 kW m^{-2}, increases T, the time to flashover in the room-corner test, decreases. This also makes sense as the more heat release that is released in a short period of time, the faster the fire gases in the room will heat up.

9 Mathematical Models

9.1 Prediction of Flame-spread Ratings Based on Cone Calorimeter Data

Several calculation methods have been developed to predict ASTM E84 Steiner tunnel test performance based on cone calorimeter data. Most of these methods have significant limitations because they were developed for specific types of products.

9.1.1 White and Dietenberger Model

White & Dietenberger [17, 26] have developed a model that uses data from the cone calorimeter to estimate the flame spread rating of a building product as measured in the tunnel (ASTM E84). The flame spread rating is calculated from the equation (10):

$$FSR = -31.25 \cdot \ln(0.4 - 1.67 \cdot \beta) \qquad (10)$$

Where β is a dimensionless acceleration parameter that is calculated using data measured in the cone calorimeter at an irradiance of 50 kW m^{-2}, as given in Equation (11).

$$\beta = b + c \cdot \dot{Q}_p - w \cdot \tau \qquad (11)$$

Where b is a constant taken as – 0.085, c is a constant taken as 0.00188, $\dot{Q}_p$ is the peak heat release rate per unit area (kW m^{-2}), w is an exponential time decay coefficient (s^{-1}) and τ is a material time constant (s).

The exponential time decay coefficient and material time constants are determined as per Equations (12) and (13) respectively.

$$w = \frac{\dot{Q}_p}{1{,}000 \cdot Q_T \cdot \left(\frac{12.5}{\delta}\right)} \qquad (12)$$

$$\tau = \frac{4}{\pi} t_{ig} \qquad (13)$$

Where Q_T is the total heat released per unit area over the duration of the test (MJ m^{-2}), δ is the thickness of the material (mm) and τ is the time to ignition (s).

For thermally thin specimens, the test specimen is completely charred through the material thickness δ. The factor (12.5/δ) in the expression for the exponential time decay adjusts the numbers to the assumed completely charred 12.5 mm thick sample used in the model development.

Note that for a given material, as the thickness δ decreases, the exponential time decay coefficient w decreases, the acceleration parameter β increases and hence the flame-spread rating increases. This is precisely what the experimental findings in the tunnel have shown (see Table 1).

9.1.2 Janssens Model

Janssens *et al.* [8] has also developed a model that uses data from the cone calorimeter to estimate the flame spread rating of a building product as measured in the tunnel (ASTM E84). He modelled flame spread along the ceiling mounted specimen in the tunnel as a progression of an ignition front along the surface of the specimen. Shortly after the burners are turned on, the entire portion of the specimen above the burner flames is assumed to ignite. Janssens argues that the time to ignition of this portion of the specimen in the Steiner tunnel can be calculated per Equation (14).

$$t_{ig} = \left(\frac{\dot{q}''_{cr}}{b \cdot \dot{q}''_b} \right)^2 \tag{14}$$

Where t_{ig} is the time to ignition (s), $\dot{q}''_{cr}$ is the critical radiant flux required for ignition of the specimen (kW m^{-2}), $\dot{q}''_b$ is the rate of heat transfer from the burner flames to the specimen (kW m^{-2}) and b is an ignition parameter ($s^{-1/2}$).

Although there is both radiant and convective heat transfer from the burner flames to the test specimen, Janssens treats the heat transfer as an "effective" radiant heat transfer ($\dot{q}''_b$) taken as 35 kW m^{-2} based on data measured in the tunnel. Janssens further recommends that the ignition parameter and the critical radiant flux can be measured for various materials in the cone calorimeter. This can be done by running cone calorimeter tests on the material using several different applied heat fluxes and plotting $t_{ig}^{-1/2}$ versus $\dot{q}''_b$ where here $\dot{q}''_b$ is the applied radiant heat flux in the cone apparatus. In fact, it is quite common to report ignition data measured in the cone calorimeter in this fashion. The resultant curve is basically a straight line with slope taken as $\dot{q}''_b/b$. It is usually sufficient to know this ratio, but if necessary $\dot{q}''_{cr}$ can be determined from the graph as the radiant heat flux required to get ignition after 10 minutes of exposure in the cone. Ten minutes is relevant as it is the duration of a tunnel test. This is why the value of $\dot{q}''_{cr}$ for wood products reported in Janssens paper is higher than the more commonly cited 12.5 kW m^{-2}, which is the relevant critical radiant flux of wood products for exposure durations of 15 minutes or more. Once $\dot{q}''_{cr}$ is known it is possible to compute b. It should be noted that the ignition parameter b implicitly depends on the thermal properties and emissivity of the material, as well as its thickness.

A simple method was devised for predicting flame propagation along the specimen. At the start of the test, the burner flame impinges on the specimen to a distance of 1.37 m from the burners. At $t = t_{ig}$, this entire area in contact with the burner flame ignites. Janssens assumed that the new flame length due to the specimen igniting is additive with (merges with) the burner flame so that:

$$y_f = y_{f,0} + y_{f,s} \tag{15}$$

Where y_f is the flame length (m), $y_{f,0}$ is the burner flame length (taken as 1.37 m) and $y_{f,s}$ is the flame extension due to the burning specimen (m). Once again based on tunnel test data and fire dynamics principles, Janssens estimated the flame extension due to the burning specimen based on its heat release rate as follows:

$$y_{f,s} = K \cdot \dot{Q}'' \cdot y_p \tag{16}$$

Where $\dot{Q}''$ is the heat release rate per area (kW m^{-2}), y_p is the length of the pyrolysis zone (m) and K is an empirical constant. Using tunnel test data, Janssens determined that the empirical constant K is 0.01 m^2 kW^{-1}.

Considering Figure 10, the following observations can be made:

- Initially, as depicted in the schematic labelled $t = 0$, the burner flame impinges on the specimen from $y = 0$ to $y = y_{f,0}$;
- As the second schematic indicates, at $t = t_{ig}$ the area initially heated by the burner flame ignites. Consequently, the pyrolysis front progress to $y_{f,0}$ (that is, $y_p = y_{f,0}$) and the flame length increases according to Equations (15) and (16);
- As the third schematic indicates, if it is assumed that the incident heat flux from the specimen flame is 35 kW m^{-2}, the area between y_p and y_f at $t = t_{ig}$, will ignite t_{ig} seconds later at $t = 2t_{ig}$. As a result, the pyrolysis front and flame tip will advance again;
- As the fourth schematic suggest, the flame will eventually reach the end of the tunnel, unless the heat release rate from the burning segments decreases sufficiently in time to cause the flame tip to stagnate or recede.

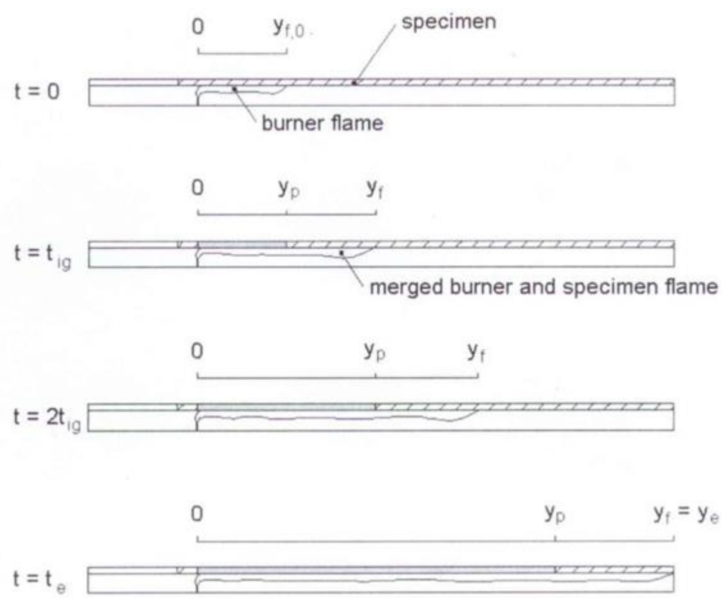

Figure 10 Flame propagation in the Steiner tunnel test [8]

Janssens assumed that the heat release rate in the tunnel is equal to that measured in the cone calorimeter at a heat flux representative of the thermal environment in the tunnel. Since the pyrolysis front and flame tip are considered to advance continuously, but discreetly in time steps of duration t_{ig} and are assumed to be remain at the same location in between these time steps, it is not possible to account for changes in the heat release rate over shorter time increments. Instead, it is necessary to employ the average heat release rate for subsequent periods each of duration t_{ig}; that is the ignition time in the tunnel.

The total heat release rate from the burning specimen can be calculated from the following Equation:

$$\dot{Q}(n \cdot t_{ig}) = x \sum_{i=1}^{n} \dot{Q}''\left[(n-1)t_{ig}\right] \cdot \left[y_p(i \cdot t_{ig}) - y_p((i-1)t_{ig})\right] \qquad (17)$$

Where x is the width of the specimen exposed in the tunnel test (0.45 m).

Substituting the result into Equation (16) and the result into Equation (15) the location of the flame front can be computed as a function of time. From this information, the area under the curve (A_T) can be calculated and hence the flame spread rating. A computer spreadsheet can be prepared to undertake these calculations.

Janssens employed this methodology assuming the heat flux from the flame to the specimen was 50, 35 or 25 kW m^{-2}. He found that employing 25 kW m^{-2} gave the best results.

10 Conclusion

Canadian design community, including the wood industry, would like to be able to develop alternative solutions to the NBCC acceptable solutions in order to permit the use of exposed mass timber components such as structural composite lumber (SCL), glue-laminated timber (glulam) or cross-laminated timber (CLT) products as interior finish in a building of any height and for most occupancy classifications. This requires better documentation of the fire performance of mass timber assemblies used as floors, walls and ceilings.

In buildings required to be of non-combustible construction, the NBCC sets prescriptive limits on the flame spread rating of interior finish and also restricts its thickness to no more than 25 mm. Tests run by FPInnovations have shown that thick slabs of SCL and CLT can meet the flame spread ratings in most applications. In fact SCL and CLT products exhibit significantly lower flame spread ratings than 19 mm traditional lumber products. Unfortunately though, mass timber products are too thick to meet the acceptable solutions of the NBCC. This effectively prevents the use of mass timber slabs as unprotected floors, walls or ceilings in buildings of non-combustible construction.

A methodology for developing alternative solutions could be based on the findings that mass wood products exhibit very low flame spread ratings in tunnel tests and low heat release rates during cone calorimeter tests. In fact, it is quite likely that raw data generated in cone calorimeter tests can be input into existing mathematical models to compute the flame spread ratings of mass timber products.

The number of possible “lay-ups” for SCL, glulam and CLT is potentially quite large. Running tunnel tests to demonstrate low flame spread ratings for all such products would require a great deal of material. However if it can be shown that data from the cone calorimeter can be used to calculate flame spread ratings, there could be a great savings in time and expense for assessing the fire performance of mass timber products. Furthermore, small-scale tests such as the cone calorimeter test could be much more useful than tunnel tests during product development and for quality control during production.

Finally, while flame spread ratings cannot be used as input in computer fire models, cone calorimeter data can. A catalog of cone calorimeter data for SCL, glulam and CLT products would permit the use of computer fire models to assist in determining the contribution to fire growth of such massive wood products for arbitrary room scenarios. This again could be useful for developing alternative solutions.

It is therefore advisable that cone calorimeter tests be conducted on SCL, glulam and CLT products. The literature suggests that it would be useful to run tests at irradiances of 25, 35 and 50 kW m^{-2}. It would also be advisable to run tests at a variety of thicknesses to determine when a product becomes thermally thick for a 10 minute exposure such as in the tunnel test or the first phase of a room-corner test. Once a product becomes thermally thick, further increases in thickness should have no appreciable impact of flame-spread ratings or cone calorimeter data.

11 References

[1] ASTM, ASTM D5456-09a: Standard Specification for Evaluation of Structural Composite Lumber Products, West Conshohocken (PA), USA: ASTM International, 2009.

[2] NRCC, National Building Code - Canada (volume 1), Ottawa, Ontario: National Research Council Canada, 2010.

[3] D. Drysdale, An Introduction to Fire Dynamics (Second Edition), John Wiley & Sons, 1998.

[4] CSA, CSA O80 Series-08 (R2012): Wood Preservation, Mississauga (Ontario): CSA Standards, 2012.

[5] Y. Hasemi, «Section 2 - Chapter 12: Surface Flame Spread,» chez *The SFPE Handbook of Fire Protection Engineering, 4th Edition*, Quincy (MA), Society of Fire Protection Engineers, 2008, pp. 2-278 - 2-290.

[6] ULC, Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies (ULC S102), Toronto, Ontario: Underwriters Laboratories of Canada, 2010.

[7] ASTM, ASTM E84-12: Standard Test Method for Surface Burning Characteristics of Building Materials, West Conshohocken (PA), USA: ASTM International, 2012.

[8] M. Janssens, J. Huczek et A. Sauceda, «Development of a Model of the ASTM E84 Steiner Tunnel Test,» chez *9th International Symposium on Fire Safety Science*, Karlsruhe, Germany, 2008.

[9] ULC, Standard Method of Test for Surface Burning Characteristics of Flooring Floor Coverings, and Miscellaneous Materals and Assemblies (ULC S102.2), Toronto, Ontario: Underwriters Laboratories of Canada, 2010.

[10] C. Dagenais, «Surface Burning Characteristics of Massive Timber Assemblies (Project No. 301006155),» FPInnovations, 2013.

[11] C. Dagenais, «Surface Burning Characteristics of V2 Stress Grade Cross-Laminated Timber (Project No.301007969),» FPInnovations, 2013.

[12] FCC, «Surface Flammability of Building Materials (TEC-49E),» Forintek Canada Corp., Ottawa (Ont.), 1996.

[13] ASTM, ASTM E1354 Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, West Conshohocken (PA), USA: ASTM International, 2013.

[14] ISO, ISO 5660: Reaction-to-fire tests - Heat release, smoke production and mass loss rate – Part 1: Heat release rate (cone calorimeter method), Geneva, Switzerland: International Standard Organization, 2002.

[15] M. L. Janssens, «Analysis of Cone Calorimeter Ignition Data: A Reappraisal,» chez *13th International Symposium Interflam*, Royal Holloway College, UK, 2013.

[16] R. H. White et M. A. Dietenberger, «Chapter 18: Fire Safety of Wood Construction,» chez *Wood Handbook: Wood as an Engineering Material*, Madison, WI, Forest Products Laboratory, 2010, pp. 18-1 - 18-22.

[17] M. A. Dietenberger et R. H. White, «Reaction-to-Ffire Testing and Modeling for Wood Products,» chez *12 Annual BCC Conference on Flame Retardancy*, Norwalk (CT), USA, 2008.

[18] V. Babrauskas, «Chapter 3-1: Heat Release Rates,» chez *The SFPE Handbook of Fire Protection Engineering (4th Edition)*, Quincy (MA), USA, National Fire Protection Association, 2008.

[19] ULC, Standard Test Method for the Determination of Combustibility Parameters of Building Materials Using an Oxygen Consumption Calorimeter (Cone Calorimeter) (ULC S135), Toronto (Ont.): Underwriters Laboratories of Canada, 2004.

[20] J. R. Mehaffey, Fire Performance of Interior Finishes, Room Linings and Structural Panel Products (Project Report No. 3638), Ottawa (Ontario), Canada: Forintek Canada Corp., 2006.

[21] ISO, ISO 9705: Fire Tests - Full-Scale Room Test for Surface Products, Geneva (Switzerland): International Standard Organization, 1993.

[22] J. R. Mehaffey, «Flammability of Building Materials and Fire Growth,» *Designing for Fire Safety: The Science and Its Application to Building Codes,* pp. 42-49, July/August 1988.

[23] J. R. Mehaffey, J. Huczek et M. Janssens, «Fire Performance of Wood-based Room Lining Materials,» chez *11th International Symposium Interflam*, London, UK, 2007.

[24] R. H. White, M. A. Dietenberger, H. Tran, O. Grexa, L. Richardons, K. Sumathipala et M. Janssens, «Comparison of Test Protocols for the Standard Room/Corner Test,» *Fire and Materials,* vol. 23, pp. 139-146, 1999.

[25] B. A. Östman et R. M. Nussbaum, «Correlation between Small-Scale Rate of Heat Release and Full-Scale Room Flashover for Surface Linings,» chez *2nd International Conference on Fire Safety Science*, Tokyo, Japan, 1988.

[26] R. H. White et M. A. Deitenberger, «Cone Calorimeter Evaluation of Wood Products,» chez *15th Annual BCC Conference on Flame Retardancy*, Norwalk (CT), USA, 2004.