Wood as An Engineering Material: Fire Safety of Wood Construction

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CHAPTER 18

Fire Safety of Wood Construction

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Fire safety is an important concern in all types of construction. The high level of national concern for fire safety is reflected in limitations and design requirements in building codes. These code requirements and related fire performance data are discussed in the context of fire safety design and evaluation in the initial section of this chapter. Because basic data on fire behavior of wood products are needed to evaluate fire safety for wood construction, the second major section of this chapter provides additional information on fire behavior and fire performance characteristics of wood products. The chapter concludes with a discussion of fire-retardant treatments that can be used to reduce the combustibility of wood.

Fire Safety Design and Evaluation

Fire safety involves prevention, detection, evacuation, containment, and extinguishment. Fire prevention basically means preventing the sustained ignition of combustible materials by controlling either the source of heat or the combustible materials. This involves proper design, installation or construction, and maintenance of the building and its contents. Proper fire safety measures depend upon the occupancy or processes taking place in the building. Smoke and heat detectors can be installed to provide early detection of a fire. Early detection is essential for ensuring adequate time for egress. Egress, or the ability to escape from a fire, often is a critical factor in life safety. Statutory requirements pertaining to fire safety are specified in building codes or fire codes. Design deficiencies are often responsible for spread of heat and smoke in a fire. Spread of a fire can be prevented with designs that limit fire growth and spread within a compartment and contain fire to the compartment of origin. Sprinklers provide improved capabilities to extinguish a fire in its initial stages. These requirements fall into two broad categories: material requirements and building requirements. Material requirements include such things as combustibility, flame spread, and fire resistance. Building requirements include area and height limitations, firestops and draftstops, doors and other exits, automatic sprinklers, and fire detectors.

Adherence to codes will result in improved fire safety. Code officials should be consulted early in the design of a building because the codes offer alternatives. For example, floor areas can be increased if automatic sprinkler systems are added. Code officials have the option to approve alternative materials and methods of construction and to modify provisions of the codes when equivalent fire protection and structural integrity are documented.

Most current building codes in the United States are based on the model building code produced by the International Code Council (ICC) (*International Building Code*® (IBC)) and related *International Code*® (I-Codes®) documents). In addition to the documents of the ICC, the National Fire Protection Association's (NFPA's) Life Safety Code (NFPA 101) provides guidelines for life safety from fire in buildings and structures. NFPA also has a model building code known as NFPA 5000. The provisions of the ICC and NFPA documents become statutory requirements when adopted by local or state authorities having jurisdiction.

Information on fire ratings for different products and assemblies can be obtained from industry literature, evaluation reports issued by ICC Evaluation Service, Inc. (ICC-ES) and other organizations, and listings published by testing laboratories or quality assurance agencies. Products listed by Underwriters Laboratories, Inc. (UL), Intertek, and other such organizations are stamped with the rating information.

The field of fire safety engineering is undergoing rapid changes because of the development of more engineering and scientific approaches to fire safety. This development is evidenced by the publication of the fourth edition of *The Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering*. Steady advances are being made in the fields of fire dynamics, fire hazard calculations, fire design calculations, and fire risk analysis. Such efforts support the worldwide trend to develop alternative building codes based on performance criteria rather than prescriptive requirements. Additional information on fire protection can be found in various publications of the NFPA and SFPE.

In the following sections, various aspects of building code provisions pertaining to fire safety of building materials are discussed under the broad categories of (a) types of construction, (b) ignition, (c) fire growth within compartment, (d) containment to compartment of origin, and (e) exterior fires. These are largely requirements for materials. Information on prevention and building requirements not related to materials (for example, detection) can be found in NFPA publications.

Types of Construction

A central aspect of the fire safety provisions of building codes is the classification of buildings by types of construction and use or occupancy. Based on classifications of building type and occupancy, the codes set limits on areas and heights of buildings. Building codes generally recognize five classifications of construction based on types of materials and required fire resistance ratings. The two classifications known as Type I (fire-resistant construction) and Type II (noncombustible construction) basically restrict the building elements to noncombustible materials. Wood is permitted to be used more liberally in the other three classifications, which are Type III (ordinary), Type IV (heavy timber), and Type V (light-frame). Type III construction allows smaller wood members to be used for interior walls, floors, and roofs including wood studs, joists, trusses, and I-joists. For Type IV (heavy timber) construction, interior wood columns, beams, floors, and roofs are required to satisfy certain minimum dimensions and no concealed spaces are permitted. In both Types III and IV construction, exterior walls must be of noncombustible materials, except that fire-retardant-treated (FRT) wood is permitted within exterior wall assemblies of Type III construction when the requirements for fire resistance ratings are 2-h or less. In Type V construction, walls, floors, and roofs may be of any dimension lumber and the exterior walls may be of combustible materials. Types I, II, III, and V constructions are further subdivided into two parts—A (protected) and B (unprotected), depending on the required fire resistance ratings. In Type V-A (protected light-frame) construction, most of the structural elements have a 1-h fire resistance rating. No general fire resistance requirements are specified for buildings of Type V-B (unprotected light-frame) construction. The required fire resistance ratings for exterior walls also depend on the fire separation distance from the lot line, centerline of the street, or another building. Such property line setback requirements are intended to mitigate the risk of exterior fire exposure.

Based on their performance in the ASTM E 136 test (see list of fire test standards at end of chapter), both untreated and FRT wood are combustible materials. However, building codes permit substitution of FRT wood for noncombustible materials in some specific applications otherwise limited to noncombustible materials. Specific performance and treatment requirements are defined for FRT wood used in such applications.

In addition to type of construction, height and area limitations also depend on the use or occupancy of a structure. Fire safety is improved by automatic sprinklers, property line setbacks, or more fire-resistant construction. Building codes recognize the improved fire safety resulting from application of these factors by increasing allowable areas and heights beyond that designated for a particular type of construction and occupancy. Thus, proper site planning and building design may result in a desired building area classification being achieved with wood construction.

Ignition

The most effective ways to improve fire safety are preventive actions that will reduce or eliminate the risks of ignition. Some code provisions, such as those in electrical codes, are designed to address this issue. Other such provisions are those pertaining to separations between heated pipes, stoves, and similar items and any combustible material. In situations of prolonged exposures and confined spaces, wood has been known to ignite at temperatures much lower than the temperatures normally associated with wood ignition. To address this concern, a safe margin of fire safety from ignition even in cases of prolonged exposures can be obtained if surface temperatures of heated wood are maintained below about 80 °C, which avoids the incipient wood degradation associated with reduction in the ignition temperature.

Other examples of regulations addressing ignition are requirements for the proper installation and treatment of cellulosic installation. Proper chemical treatments of cellulosic insulation are required to reduce its tendency for smoldering combustion and to reduce flame spread. Cellulosic insulation is regulated by a product safety standard of the U.S. Consumer Product Safety Commission. One of the required tests is a smoldering combustion test. Proper installation around recessed light fixtures and other electrical devices is necessary.

Exterior Fire Exposure in the Wildland–Urban Interface

In areas subjected to wildfires, actions to remove ignition sources around the home or other structures and prevent easy fire penetration into such buildings can significantly improve the chances that a structure will survive a wildfire. This includes appropriate landscaping to create a defensible space around the structure. Particular attention should be paid to the removal of vegetation and other combustible exterior items (such as firewood, fence, landscape mulch) that are close to openings (vents, windows, and doors), combustible surfaces of the building, and soffits. Openings in building exteriors can allow the fire to penetrate into the building and cause interior ignitions. Building design and maintenance should be done to limit the accumulation of combustible debris that could be ignited by firebrands that originate from burning trees and buildings, with particular attention paid to nooks and crannies that allow accumulation of debris. The firebrands' distribution is such that they can cause destruction of unprotected structures that are some distance from the actual flames of the wildfire. Regardless of the type of material used for the exterior membrane, the type and placement of the joints of the membrane can affect the likelihood that a fire will penetrate the exterior membrane. For example, birdstops should be installed at the ends of clay tile barrel roof coverings to prevent firebrands from igniting the underlining substrate.

Rated roof covering materials are designated Class A, B, or C according to their performance in the tests described in ASTM E 108, Fire Tests of Roof Coverings. This test standard includes intermittent flame exposure, spread of flame, burning brand, flying brand, and rain tests. Each of the three classes has a different version of the pass–fail test. The Class A test is the most severe, Class C the least. In the case of the burning brand tests, the brand for the Class B test is larger than that for the Class C test. FRT wood shingles and shakes are available that carry a Class B or C fire rating. A Class A rated wood roof system can be achieved by using Class B wood shingles with specified roof deck and underlayment.

For other exterior applications, FRT wood is tested in accordance with ASTM E 84. An exterior treatment is required to have no increase in the listed flame spread index after being subjected to the rain test of ASTM D 2898. At the present time, a commercial treated-wood product for exterior applications is either treated to improve fire retardancy or treated to improve resistance to decay and insects, not both.

Various websites (such as www.firewise.org) provide additional information addressing the protection of homes in the wildland–urban interface. The national Firewise Communities program is a multi-agency effort designed to reach beyond the fire service by involving homeowners, community leaders, planners, developers, and others in the effort to protect people, property, and natural resources from the risk of wildland fire, before a fire starts. The Firewise Communities approach emphasizes community responsibility for planning in the design of a safe community and effective emergency response, along with individual responsibility for safer home construction and design, landscaping, and maintenance.

The ICC's International Wildland–Urban Interface Code provides model code regulations that specifically address structures and related land use in areas subjected to wildfires. NFPA 1144 is a standard that focuses on individual structure hazards from wildland fires. In response to losses due to wildfires, the California State Fire Marshal's Office (www.fire.ca.gov) has implemented ignition-resistant construction standards for structures in the wildland–urban interface. These test requirements intended to address ignitability of the structure are based on tests developed at the University of California for exterior wall siding and sheathing, exterior windows, under eave, and exterior decking.

Fire Growth within Compartment

Flame Spread

Important provisions in the building codes are those that regulate the exposed interior surface of walls, floors, and ceilings (that is, the interior finish). Codes typically exclude trim and incidental finish, as well as decorations and furnishings that are not affixed to the structure, from the more rigid requirements for walls and ceilings. For regulatory purposes, interior finish materials are classified according to their flame spread index. Thus, flame spread is one of the most tested fire performance properties of a material. Numerous flame spread tests are used, but the one cited by building codes is ASTM E 84 (also known as NFPA 255 and UL 723), the "25-ft tunnel" test. In this test method, the 508-mm-wide, 7.32-m-long specimen completes the top of the tunnel furnace. Flames from a burner at one end of the tunnel provide the fire exposure, which includes forced draft conditions. The furnace operator records the flame front position as a function of time and the time of maximum flame front travel during a 10-min period. The standard

Table 18–1. ASTM E 84 flame spread indexes for 19-mm-thick solid lumber of various wood species as reported in the literature[a]

Species[b]	Flame spread index[c]	Smoke developed index[c]	Source[d]
Softwoods			
Yellow-cedar (Pacific Coast yellow cedar)	78	90	CWC
Baldcypress (cypress)	145–150	—	UL
Douglas-fir	70–100	—	UL
Fir, Pacific silver	69	58	CWC
Hemlock, western (West Coast)	60–75	—	UL
Pine, eastern white (eastern white, northern white)	85, 120–215[f]	122, —	CWC, UL
Pine, lodgepole	93	210	CWC
Pine, ponderosa	105–230[e]	—	UL
Pine, red	142	229	CWC
Pine, Southern (southern)	130–195[f]	—	UL
Pine, western white	75[f]	—	UL
Redcedar, western	70	213	HPVA
Redwood	70	—	UL
Spruce, eastern (northern, white)	65	—	UL, CWC
Spruce, Sitka (western, Sitka)	100, 74	—, 74	UL, CWC
Hardwoods			
Birch, yellow	105–110	—	UL
Cottonwood	115	—	UL
Maple (maple flooring)	104	—	CWC
Oak (red, white)	100	100	UL
Sweetgum (gum, red)	140–155	—	UL
Walnut	130–140	—	UL
Yellow-poplar (poplar)	170–185	—	UL

[a] Additional data for domestic solid-sawn and panel products are provided in the AF&PA–AWC DCA No. 1, "Flame Spread Performance of Wood Products."

[b] In cases where the name given in the source did not conform to the official nomenclature of the Forest Service, the probable official nomenclature name is given and the name given by the source is given in parentheses.

[c] Data are as reported in the literature (dash where data do not exist). Changes in the ASTM E 84 test method have occurred over the years. However, data indicate that the changes have not significantly changed earlier data reported in this table. The change in the calculation procedure has usually resulted in slightly lower flame spread results for untreated wood. Smoke developed index is not known to exceed 450, the limiting value often cited in the building codes.

[d] CWC, Canadian Wood Council (CWC 1996); HPVA, Hardwood Plywood Manufacturers Association (Tests) (now Hardwood Plywood & Veneer Assoc.); UL, Underwriters Laboratories, Inc. (Wood-fire hazard classification. Card Data Service, Serial No. UL 527, 1971).

[e] Footnote of UL: In 18 tests of ponderosa pine, three had values over 200 and the average of all tests is 154.

[f] Footnote of UL: Due to wide variations in the different species of the pine family and local connotations of their popular names, exact identification of the types of pine tested was not possible. The effects of differing climatic and soil conditions on the burning characteristics of given species have not been determined.

prescribes a formula to convert these data to a flame spread index (FSI), which is a measure of the overall rate of flame spreading in the direction of air flow. In the building codes, the classes for flame spread index are A (FSI of 0 to 25), B (FSI of 26 to 75), and C (FSI of 76 to 200). Generally, codes specify FSI for interior finish based on building occupancy, location within the building, and availability of automatic sprinkler protection. The more restrictive classes, Classes A and B, are generally prescribed for stairways and corridors that provide access to exits. In general, the more flammable classification (Class C) is permitted for the interior finish of other areas of the building that are not considered exit ways or where the area in question is protected by automatic sprinklers. In other areas, no flammability restrictions are specified on the interior finish, and unclassified materials (that is, more than 200 FSI) can be used. The classification labels of I, II, and III have been used instead of A, B, and C.

The FSI for most domestic wood species is between 90 and 160 (Table 18–1). Thus, unfinished lumber, 10 mm or thicker, is generally acceptable for interior finish applications requiring a Class C rating. Fire-retardant treatments are necessary when a Class A flame spread index is required for a wood product. Some domestic softwood species meet the Class B flame spread index without treatment. Other domestic softwood species have FSIs near the upper limit of 200 for Class C. All available data for domestic hardwoods are for Class C. Some high-density imported hardwood species have FSIs in Class B. Additional FSI data for domestic solid-sawn and panel products are provided in the American Forest and Paper Association (AF&PA)–American Wood Council (AWC) design for code acceptance (DCA) No. 1 (see list of references at end of chapter). Report 128 of APA–The Engineered Wood Association (APA) discusses the flame spread indexes of construction plywood panels.

Code provisions pertaining to floors and floor coverings include those based on the critical radiant flux test (ASTM E 648). In the critical radiant flux test, the placement of the radiant panel is such that the radiant heat being imposed on the surface has a gradient in intensity down the length of the horizontal specimen. Flames spread from the ignition source at the end of high heat flux (or intensity) to the other end until they reach a location where the heat flux is not sufficient for further propagation. This is reported as the critical radiant flux (CRF). Thus, low CRF reflects materials with high flammability.

Depending on location and occupancy, building code requirements are for a minimum critical radiant flux level of 2.2 kW m^{-2} (0.22 W cm^{-2}) for Class II or 4.5 kW m^{-2} (0.45 W cm^{-2}) for Class I. These provisions are mainly intended to address the fire safety of some carpets. One section in the International Building Code (IBC) (Sec. 804) where this method is cited exempts wood floors and other floor finishes of a traditional type from the requirements. This method is also cited in standards of the National Fire Protection Association (NFPA) such as the Life Safety Code. Very little generic data is published on wood products tested in accordance with ASTM E 648. In one report published during the development of the test, a CRF of approximately 3.5 to 4.0 kW m^{-2} was cited for oak flooring (Benjamin and Davis 1979). Company literature for proprietary wood floor products indicates that such products can achieve CRF in excess of the 4.5 kW m^{-2} for Class I. For wood products tested in accordance with the similar European radiant panel test standard (EN ISO 9239-1 (2002)) (Östman and Mikkola 2006, Tsantaridis and Östman 2004), critical heat flux (CHF) ranged from 2.6 to 5.4 kW m^{-2} for 25 wood floorings tested without a surface coating. Most densities ranged from 400 to 600 kg m^{-3}. One additional wood flooring product had a CHF of 6.7 kW m^{-2}. Additional results for the wood flooring products tested with a wide range of coating systems indicated that the non-fire-retardant coatings may significantly improve the CHF to levels above 4.5 kW m^{-2}.

The critical radiant flux apparatus is also used to test the flammability of cellulosic insulation (ASTM E 970). There are many other test methods for flame spread or flammability. Most are used only for research and development or quality control, but some are used in product specifications and regulations of materials in a variety of applications.

Figure 18–1. Flashover in standard room test.

Other tests for flammability include those that measure heat release.

Flashover

With sufficient heat generation, the initial growth of a fire in a compartment leads to the condition known as flashover. The visual criteria for flashover are full involvement of the compartment and flames out the door or window (Figure 18–1). The intensity over time of a fire starting in one room or compartment of a building depends on the amount and distribution of combustible contents in the room and the amount of ventilation.

The standard full-scale test for pre-flashover fire growth is the room-corner test (ASTM E 2257). In this test, a gas burner is placed in the corner of the room, which has a single door for ventilation. Three of the walls are lined with the test material, and the ceiling may also be lined with the test material. Other room-corner tests use a wood crib or similar item as the ignition source. Such a room-corner test is used to regulate foam plastic insulation, a material that is not properly evaluated in the ASTM E 84 test. Observations are made of the growth of the fire and the duration of the test until flashover occurs. Instruments record the heat generation, temperature development within the room, and the heat flux to the floor. Results of full-scale room-corner tests are used to validate fire growth models and bench-scale test results. In a series of room-corner tests using a 100/300-kW burner and no test material on the ceiling, the ranking of the different wood products was consistent with their flame spread index in the ASTM E 84 test (White and others 1999). Another room-corner test standard (NFPA 286) is cited in codes as an alternative to ASTM E 84 for evaluating interior wall or ceiling finishes for Class A applications.

Smoke and Toxic Gases

One of the most important problems associated with evacuation during a fire is the smoke produced. The term smoke is frequently used in an all-inclusive sense to mean the mixture of pyrolysis products and air that is present near the fire site. In this context, smoke contains gases, solid particles, and droplets of liquid. Smoke presents potential hazards because it interacts with light to obscure vision and because it contains noxious and toxic substances. Generally, two approaches are used to deal with the smoke problem: limit smoke production and control the smoke that has been produced. The control of smoke flow is most often a factor in the design and construction of large or tall buildings. In these buildings, combustion products may have serious effects in areas remote from the actual fire site.

The smoke yield restrictions in building codes are also based on data from the ASTM E 84 standard. Smoke measurement is based on a percentage attenuation of white light passing through the tunnel exhaust stream and detected by a photocell. This is converted to the smoke developed index (SDI), with red oak flooring set at 100. Flame spread requirements for interior finish generally are linked to an added requirement that the SDI be less than 450. Available SDI data for wood products are less than 450 (Table 18–1).

In the 1970s, the apparatus known as the NBS smoke chamber was developed and approved as an ASTM standard for research and development (ASTM E 662). This test is a static smoke test because the specimen is tested in a closed chamber of fixed volume and the light attenuation is recorded over a known optical path length. The corresponding light transmission is reported as specific optical density as a function of time. Samples are normally tested in both flaming (pilot flame) and nonflaming conditions using a radiant flux of 25 kW m^{-2}. Some restrictions in product specifications are based on the smoke box test (ASTM E 662). As discussed in a later section, dynamic measurements of smoke can be obtained with the cone calorimeter (ASTM E 1354) and the room-corner test (ASTM E 2257).

Toxicity of combustion products is a concern. Fire victims are often not touched by flames but die as a result of exposure to smoke, toxic gases, or oxygen depletion. These life-threatening conditions can result from burning contents, such as furnishings, as well as from the structural materials involved. The toxicity resulting from the thermal decomposition of wood and cellulosic substances is complex because of the wide variety of types of wood smoke. Composition and the concentration of individual constituents depend on such factors as the fire exposure, oxygen and moisture present, species of wood, any treatments or finishes that may have been applied, and other considerations. The vast majority of fires that attain flashover do generate dangerous levels of carbon monoxide, independent of what is burning. Carbon monoxide is a particularly insidious toxic gas and is often generated in significant amounts in wood fires. Small amounts of carbon monoxide are particularly toxic because the hemoglobin in the blood is much more likely to combine with carbon monoxide than with oxygen, even with plenty of breathable oxygen (carboxyhemoglobin) present.

Containment to Compartment of Origin

The growth, intensity, and duration of the fire is the “load” that determines whether a fire is confined to the room of origin. Whether a given fire will be contained to the compartment depends on the fire resistance of the walls, doors, ceilings, and floors of the compartment. Requirements for fire resistance or fire resistance ratings of structural members and assemblies are another major component of the building code provisions. In this context, fire resistance is the ability of materials or their assemblies to prevent or retard the passage of excessive heat, hot gases, or flames while continuing to support their structural loads. Fire resistance ratings are usually obtained by conducting standard fire tests. The standard fire resistance test (ASTM E 119) has three failure criteria: element collapse, passage of flames, or excessive temperature rise on the non-fire-exposed surface (average increase of several locations exceeding 139 or 181 °C at a single location).

Doors can be critical in preventing the spread of fires. Doors left open or doors with little fire resistance can easily defeat the purpose of a fire-rated wall or partition. Listings of fire-rated doors, frames, and accessories are provided by various fire testing agencies. When a fire-rated door is selected, details about which type of door, mounting, hardware, and closing mechanism need to be considered.

Fires in buildings can spread by the movement of hot fire gases through open channels in concealed spaces. Codes specify where fireblocking and draftstops are required in concealed spaces, and they must be designed to interfere with the passage of the fire up or across a building. In addition to going along halls, stairways, and other large spaces, heated gases also follow the concealed spaces between floor joists and between studs in partitions and walls of frame construction. Obstruction of these hidden channels provides an effective means of restricting fire from spreading to other parts of the structure. Fireblockings are materials used to resist the spread of flames via concealed spaces within building components such as floors and walls. They are generally used in vertical spaces such as stud cavities to block upward spread of a fire. Draftstops are barriers intended to restrict the movement of air within concealed areas of a building. They are typically used to restrict horizontal dispersion of hot gases and smoke in larger concealed spaces such as those found within wood joist floor assemblies with suspended dropped ceilings or within an attic space with pitched chord trusses.

Exposed Wood Members

The self-insulating quality of wood, particularly in the large wood sections of heavy timber construction, is an important factor in providing a degree of fire resistance. In Type IV or heavy timber construction, the need for fire resistance requirements is achieved in the codes by specifying minimum sizes for the various members or portions of a building and other prescriptive requirements. In this type of construction, the wood members are not required to have specific fire resistance ratings. The acceptance of heavy timber construction is based on historical experience with its performance in actual fires. Proper heavy timber construction includes using approved fastenings, avoiding concealed spaces under floors or roofs, and providing required fire resistance in the interior and exterior walls.

The availability and code acceptance of a procedure to calculate the fire resistance ratings for large timber beams and columns have allowed their use in fire-rated buildings not classified as Type IV (heavy timber) construction. In the other types of construction, the structural members and assemblies are required to have specified fire resistance ratings. There are two accepted procedures for calculating the fire ratings of exposed wood members. In the first such procedure, the equations are simple algebraic equations that only need the dimensions of the beam or column and a load factor. Determination of the load factor requires the minimum dimension of column, the applied load as a percentage of the full allowable design load, and the effective column length. The acceptance of this procedure is normally limited to beams and column with nominal dimensions of 152 mm (6 in.) or greater and for fire ratings of 1 h or less. This procedure is applicable to glued-laminated timbers that utilize standard laminating combinations. Because the outer tension laminate of a glued-laminated beam is charred in a 1-h fire exposure, a core lamination of a beam needs to be removed and the equivalent of an extra nominal 51-mm- (2-in.-) thick outer tension lamination added to the bottom of the beam. Details on this procedure can be found in various industry publications (American Institute of Timber Construction (AITC) Technical Note 7, AF&PA-AWC DCA #2, APA Publication EWS Y245A) and the IBC.

A second more flexible mechanistic procedure was incorporated within the *National Design Specification for Wood Construction* (NDS®) in 2001 and is referred to as the NDS Method. As an explicit engineering method, it is applicable to all wood structural members covered under the NDS, including structural composite lumber wood members. Normal engineering calculations of the ultimate load capacity of the structural wood element are adjusted for reductions in dimensions with time as the result of charring. As discussed more in a later section, a char depth of 38 mm (1.5 in.) at 1 h is generally used for solid-sawn and structural glued-laminated softwood members. The char depth is adjusted upward by 20% to account for the effect of elevated temperatures on the mechanical properties of the wood near the wood–char interface. This procedure also requires that core lamination(s) of glued-laminated beams be replaced by extra outer tension laminate(s). A provision of the NDS procedure addresses the structural integrity performance criteria for timber decks, but the thermal separation criteria are not addressed. This second procedure was developed by the American Wood Council and is fully discussed in their Technical Report No. 10. Fire resistance tests on glued-laminated specimens and structural composite lumber products loaded in tension are discussed in FPL publications.

The fire resistance of glued-laminated structural members, such as arches, beams, and columns, is approximately equivalent to the fire resistance of solid members of similar size. Laminated members glued with traditional phenol, resorcinol, or melamine adhesives are generally considered to be at least equal in their fire resistance to a one-piece member of the same size. In recent years, the fire resistance performance of structural wood members manufactured with adhesives has been of intense interest. As a result of concerns about some adhesives that were being used in fingerjointed lumber, industry test protocols and acceptance criteria were developed to address this issue. When a wood-frame assembly is required to have a fire resistance rating, any finger-jointed lumber within the assembly must include the HRA designation for heat-resistant adhesives in the grademark. The designation is part of the Glued Lumber Policy of the American Lumber Standard Committee, Inc. The activities to address questions concerning the adhesives have included the development of ASTM standard test methods and revisions to the ASTM standard specifications for the applicable wood products.

Light-Frame Assemblies

Light-frame wood construction can provide a high degree of fire containment through use of gypsum board as the interior finish. This effective protective membrane provides the initial fire resistance rating. Many recognized assemblies involving wood-frame walls, floors, and roofs provide a 1- or 2-h fire resistance rating. Fire-rated gypsum board (Type X or C) is used in rated assemblies. Type X and the higher grade Type C gypsum boards have textile glass filaments and other ingredients that help to keep the gypsum core intact during a fire. Fire resistance ratings of various assemblies are listed in the IBC and other publications such as the Gypsum Association *Fire Resistance Design Manual*, AF&PA-AWC DCA #3, and product directories of listing organizations, such as UL and Intertek. Traditional constructions of regular gypsum wallboard (that is, not fire rated) or lath and plaster over wood joists and studs have fire resistance ratings of 15 to 30 min. In addition to fire-rated assemblies constructed of sawn lumber, there are rated assemblies for I-joists and wood trusses.

Fire-rated assemblies are generally tested in accordance with ASTM E 119 while loaded to 100% of the allowable design load calculated using the NDS. The calculation of the allowable design load of a wood stud wall is described in ASTM D 6513. Some wood stud wall assemblies were tested with a load equivalent to 78% of the current design load (NDS dated 2005) calculated using a l_e/d of 33. Less than full design load in the fire test imposes a load restriction on the rated assembly.

While fire resistance ratings are for the entire wall, floor, or roof assembly, the fire resistance of a wall or floor can be viewed as the sum of the resistance of the interior finish and the resistance of the framing members. In a code-accepted procedure, the fire rating of a light-frame assembly is calculated by adding the tabulated times for the fire-exposed membrane to the tabulated times for the framing. For example, the fire resistance rating of a wood stud wall with 16-mm-thick Type X gypsum board and rock wool insulation is computed by adding the 20 min listed for the stud wall, the 40 min listed for the gypsum board, and the 15 min listed for the rock wool insulation to obtain a rating for the assembly of 75 min. Additional information on this component additive method (CAM) can be found in the IBC and AF&PA DCA No. 4. More sophisticated mechanistic models have been developed.

The relatively good structural behavior of a traditional wood member in a fire test results from the fact that its strength is generally uniform through the mass of the piece. Thus, the unburned fraction of the member retains high strength, and its load-carrying capacity is diminished only in proportion to its loss of cross section. Innovative designs for structural wood members may reduce the mass of the member and locate the principal load-carrying components at the outer edges where they are most vulnerable to fire, as in structural sandwich panels. With high strength facings attached to a low-strength core, unprotected load-bearing sandwich panels have failed to support their load in less than 6 min when tested in the standard test. If a sandwich panel is to be used as a load-bearing assembly, it should be protected with gypsum wallboard or some other thermal barrier. In any protected assembly, the performance of the protective membrane is the critical factor in the performance of the assembly.

Unprotected light-frame wood buildings do not have the natural fire resistance achieved with heavier wood members. In these, as in all buildings, attention to good construction details is important to minimize fire hazards. Quality of workmanship is important in achieving adequate fire resistance. Inadequate nailing and less than required thickness of the interior finish can reduce the fire resistance of an assembly. The method of fastening the interior finish to the framing members and the treatment of the joints are significant factors in the fire resistance of an assembly. The type and quantity of any insulation installed within the assembly may also affect the fire resistance of an assembly.

Any penetration in the membrane must be addressed with the appropriate fire protection measures. This includes the junction of fire-rated assemblies with unrated assemblies. Fire stop systems are used to properly seal the penetration of fire-rated assemblies by pipes and other utilities. Through-penetration fire stops are tested in accordance with ASTM E 814. Electrical receptacle outlets, pipe chases, and other through openings that are not adequately firestopped can affect the fire resistance. In addition to the design of walls, ceilings, floors, and roofs for fire resistance, stairways, doors, and firestops are of particular importance.

Fire-Performance Characteristics of Wood

Several characteristics are used to quantify the burning behavior of wood when exposed to heat and air, including thermal degradation of wood, ignition from heat sources, heat and smoke release, flame spread in heated environments, and charring rates in a contained room.

Thermal Degradation of Wood

As wood reaches elevated temperatures, the different chemical components undergo thermal degradation that affect wood performance. The extent of the changes depends on the temperature level and length of time under exposure conditions. At temperatures below 100 °C, permanent reductions in strength can occur, and its magnitude depends on moisture content, heating medium, exposure period, and species. The strength degradation is probably due to depolymerization reactions (involving no carbohydrate weight loss). The little research done on the chemical mechanism has found a kinetic basis (involving activation energy, pre-exponential factor, and order of reaction) of relating strength reduction to temperature. Chemical bonds begin to break at temperatures above 100 °C and are manifested as carbohydrate weight losses of various types that increases with the temperature. Literature reviews by Bryan (1998), Shafizadeh (1984), Atreya (1983), and Browne (1958) reveal the following four temperature regimes of wood pyrolysis and corresponding pyrolysis kinetics.

Between 100 and 200 °C, wood becomes dehydrated and generates water vapor and other noncombustible gases including CO_2, formic acid, acetic acid, and H_2O. With prolonged exposures at higher temperatures, wood can become charred. Exothermic oxidation reactions can occur because ambient air can diffuse into and react with the developing porous char residue.

From 200 to 300 °C, some wood components begin to undergo significant pyrolysis and, in addition to gases listed above, significant amounts of CO and high-boiling-point tar are given off. The hemicelluloses and lignin components are pyrolyzed in the range of 200 to 300 °C and 225 to 450 °C, respectively. Much of the acetic acid liberated from wood pyrolysis is attributed to deactylation of hemicellulose. Dehydration reactions beginning around 200 °C are primarily responsible for pyrolysis of lignin and result in a high char yield for wood. Although the cellulose remains mostly unpyrolyzed, its thermal degradation can be accelerated in the presence of water, acids, and oxygen. As the temperature increases, the degree of polymerization of cellulose decreases further, free radicals appear and carbonyl, carboxyl, and hydroperoxide groups are formed. Overall pyrolysis reactions are endothermic due to decreasing dehydration and increasing CO formation from porous char reactions with H_2O and CO_2 with increasing temperature. During this "low-temperature pathway" of pyrolysis, the exothermic reactions of exposed char and volatiles with atmospheric oxygen are manifested as glowing combustion.

The third temperature regime is from 300 to 450 °C because of the vigorous production of flammable volatiles. This begins with the significant depolymerization of cellulose in the range of 300 to 350 °C. Also around 300 °C, aliphatic side chains start splitting off from the aromatic ring in the lignin. Finally, the carbon–carbon linkage between lignin structural units is cleaved at 370 to 400 °C. The degradation reaction of lignin is an exothermic reaction, with peaks occurring between 225 and 450 °C; temperatures and amplitudes of these peaks depend on whether the samples were pyrolyzed under nitrogen or air. All wood components end their volatile emissions at around 450 °C. The presence of minerals and moisture within the wood tend to smear the separate pyrolysis processes of the major wood components. In this "high-temperature pathway," pyrolysis of wood results in overall low char residues of around 25% or less of the original dry weight. Many fire retardants work by shifting wood degradation to the "low-temperature pathway," which reduces the volatiles available for flaming combustion.

Above 450 °C, the remaining wood residue is an activated char that undergoes further degradation by being oxidized to CO_2, CO, and H_2O until only ashes remain. This is referred to as afterglow.

The complex nature of wood pyrolysis often leads to selecting empirical kinetic parameters of wood pyrolysis applicable to specific cases. Considering the degrading wood to be at low elevated temperature over a long time period and ignoring volatile emissions, a simple first-order reaction following the Arrhenius equation, $dm/dt = -mA \exp(-E/RT)$, was found practical. In this equation, m is mass of specimen, t is time, A is the preexponential factor, E is activation energy, R is the universal gas constant, and T is temperature in kelvins. The simplest heating environment for determination of these kinetic parameters is isothermal, constant pressure, and uniform flow gas exposures on a nominally thick specimen. As an example, Stamm (1955) reported on mass loss of three coniferous wood sticks (1 by 1 by 6 in.)—Southern and white pine, Sitka spruce, and Douglas-fir—that were heated in a drying oven in a temperature range of 93.5 to 250 °C. The fit of the Arrhenius equation to the data resulted in the values of $A = 6.23 \times 10^7$ s^{-1} and $E = 124$ kJ mol^{-1}. If these same woods were exposed to steam instead of being oven dried, degradation was much faster. With the corresponding kinetic parameters, $A = 82.9$ s^{-1} and $E = 66$ kJ mol^{-1}, Stamm concluded that steam seemed to act as a catalyst because of significant reduction in the value of activation energy. Shafizadeh (1984) showed that pyrolysis proceeds faster in air than in an inert atmosphere and that this difference gradually diminishes around 310 °C. The value of activation energy reported at large for pyrolysis in air varied from 96 to 147 kJ mol^{-1}.

In another special case, a simple dual reaction model could distinguish between the low- and high- temperature pathways for quantifying the effect of fire retardant on wood pyrolysis. The reaction equation, $dm/dt = (m_{\text{end}} - m)[A_1 \exp(-E_1/RT) + A_2 \exp(-E_2/RT)]$, was found suitable by Tang (1967). In this equation, m_{end} is the ending char mass, and subscripts 1 and 2 represent low- and high-temperature pathways, respectively. A dynamic thermogravimetry was used to span the temperature to 500 °C at a rate of 3 °C per minute using tiny wood particles. The runs were made in triplicate for ponderosa pine sapwood, lignin, and alpha-cellulose samples with five different inorganic salt treatments. Tang's derived values for the untreated wood are $m_{\text{end}} = 0.21$ of initial weight, $A_1 = 3.2 \times 10^5$ s^{-1}, $E_1 = 96$ kJ mol^{-1}, $A_2 = 6.5\text{e}{+}16$ s^{-1}, and $E_2 = 226$ kJ mol^{-1}. A well-known fire-retardant-treatment chemical, monobasic ammonium phosphate, was the most effective chemical tested in that char yield was increased to 40% and E_1 decreased to 80 kJ mol^{-1}, thereby promoting most volatile loss through the low-temperature pathway. The alpha-cellulose reacted to the chemicals similarly as the wood, while the lignin did not seem to be affected much by the chemicals. From this we conclude that flammable volatiles generated by the cellulose component of wood are significantly reduced with fire retardant treatment. For applications to biomass energy and fire growth phenomology, the kinetic parameters become essential to describe flammable volatiles and their heat of combustion but are very complicated (Dietenberger 2002). Modern pyrolysis models now include competing reactions to produce char, tar, and noncondensing gases from wood as well as the secondary reaction of tar decomposition.

Ignition

Ignition of wood is the start of a visual and sustained combustion (smoldering, glow, or flame) fueled by wood pyrolysis. Therefore the flow of energy or heat flux from a fire or other heated objects to the wood material to induce pyrolysis is a necessary condition of ignition. A sufficient condition of flaming ignition is the mixing together of volatiles and air with the right composition in a temperature range of about 400 to 500 °C. An ignition source (pilot or spark plug) is therefore usually placed where optimum mixing of volatiles and air can occur for a given ignition test. In many such tests the surface temperature of wood materials has been measured in the range of 300 to 400 °C prior to piloted ignition. This also coincides with the third regime of wood pyrolysis in which there is a significant production of flammable volatiles. However, it is possible for smoldering or

Table 18–2. Derived wood-based thermophysical parameters of ignitability

Material	Thickness (mm)	Density ($\mathrm{kg\ m^{-3}}$) ρ	Moisture content (%) M	Material emissivity	r^a	T_{ig} (K)	$k/\rho c^a$ ($\mathrm{m^2/s}$) $\times 10^7$	$k\rho c^a$ ($\mathrm{kJ^2\ m^{-4}\ K^{-2}\ s^{-1}}$)
Gypsum board, Type X	16.5	662	—	0.9	N/A	608.5	3.74	0.451
FRT Douglas-fir plywood	11.8	563	9.48	0.9	0.86	646.8	1.37	0.261
Oak veneer plywood	13	479	6.85	0.9	1.11	563	1.77	0.413
FRT plywood (Forintek)	11.5	599	11.17	0.9	0.86	650	1.31	0.346
Douglas-fir plywood (ASTM)	11.5	537	9.88	0.85	0.863	604.6	1.37	0.221
FRT Southern Pine plywood	11	606	8.38	0.9	1.43	672	2.26	0.547
Douglas-fir plywood (MB)	12	549	6.74	0.89	0.86	619	1.38	0.233
Southern Pine plywood	11	605	7.45	0.88	0.86	620	1.38	0.29
Particleboard	13	794	6.69	0.88	1.72	563	2.72	0.763
Oriented strandboard	11	643	5.88	0.88	0.985	599	1.54	0.342
Hardboard	6	1,026	5.21	0.88	0.604	593	0.904	0.504
Redwood lumber	19	421	7.05	0.86	1.0	638	1.67	0.173
White spruce lumber	17	479	7.68	0.82	1.0	621	1.67	0.201
Southern Pine boards	18	537	7.82	0.88	1.0	644	1.63	0.26
Waferboard	13	631	5.14	0.88	1.62	563	2.69	0.442

[a] Formulas for wood thermal conductivity k, heat capacity c, and density ρ, at elevated temperatures used to calculate thermal inertia $k\rho c$ and thermal diffusivity $k/\rho c$ are as follows:

$$k = r\left[(0.1941 + 0.004064M)(\rho_{od} \times 10^{-3}) + 0.01864\right](T_m/297 \times 10^{-3}) \quad \mathrm{kWm^{-1}K^{-1}}$$

$$c = 1.25(1 + 0.025M)(T_m/297) \quad \mathrm{kJkg^{-1}K^{-1}}$$

$$\rho_{od} = \rho/(1 + 0.01M) \quad \mathrm{kgm^{-3}}$$

where T_{ig} is ignition temperature, ambient temperature $T_a = 297$ K, mean temperature $T_m = (T_a + T_{ig})/2$, and the parameter r is an adjustment factor used in the calculation of the thermal conductivity for composite, engineered, or treated wood products (Dietenberger 2004).

glow to exist prior to flaming ignition if the imposed radiative or convective heating causes the wood surface to reach 200 °C or higher for the second regime of wood pyrolysis. Indeed, unpiloted ignition is ignition that occurs where no pilot source is available. Ignition associated with smoldering is another important mechanism by which fires are initiated.

Therefore, to study flaming or piloted ignition, a high heat flux (from radiant heater) causes surface temperature to rapidly reach at least 300 °C to minimize influence of unwanted smoldering or glow at lower surface temperatures. Surface temperature at ignition has been an elusive quantity that was experimentally difficult to obtain, but relatively recent studies show some consistency. For various horizontally orientated woods with specific gravities ranging from 0.33 to 0.69, the average surface temperature at ignition increases from 347 °C at imposed heat flux of 36 kW $\mathrm{m^{-2}}$ to 377 °C at imposed heat flux of 18 kW $\mathrm{m^{-2}}$. This increase in the ignition temperature is due to the slow decomposition of the material at the surface and the resulting buildup of the char layer at low heat fluxes (Atreya 1983). In the case of naturally high charring material such as redwood that has high lignin and low extractives, the measured averaged ignition temperatures were 353, 364, and 367 °C for material thicknesses of 19, 1.8, and 0.9 mm, respectively, for various heat flux values as measured in the cone calorimeter (ASTM E 1354) (Dietenberger 2004). This equipment along with the lateral ignition and flame spread test (LIFT) apparatus (ASTM E 1321) are used to obtain data on time to piloted ignition as a function of heater irradiance. From such tests, values of ignition temperature, critical ignition flux (heat flux below which ignition would not occur), and thermophysical properties have been derived using a transient heat conduction theory (Table 18–2). In the case of redwood, the overall piloted ignition temperature was derived to be 365 °C (638 K) in agreement with measured values, regardless of heat flux, thickness, moisture content, surface orientation, and thin reflective paint coating. The critical heat flux was derived to be higher on the LIFT apparatus than on the cone calorimeter primarily due to the different convective coefficients (Dietenberger 1996). However, the heat properties of heat capacity and thermal conductivity were found to be strongly dependent on density, moisture content, and internal elevated temperatures. Thermal conductivity has an adjustment factor for composite, engineered, or treated wood products. Critical heat fluxes for ignition have been calculated to be between 10 and 13 kW $\mathrm{m^{-2}}$ for a range of wood products. For exposure to a constant heat flux, ignition times for solid wood typically ranged from 3 s for heat flux of 55 kW $\mathrm{m^{-2}}$ to 930 s for heat flux of 18 kW $\mathrm{m^{-2}}$. Estimates of piloted ignition in various scenarios can be obtained using the derived thermal properties listed in Table 18–2 and an applicable heat conduction theory (Dietenberger 2004).

Some, typically old, apparatuses for testing piloted ignition measured the temperature of the air flow rather than the imposed heat flux with the time to ignition measurement. These results were often reported as the ignition temperature and as varying with time to ignition, which is misleading. When the imposed heat flux is due to a radiant source, such reported air flow ignition temperature can be as much as 100 °C lower than the ignition surface temperature. For a proper heat conduction analysis in deriving thermal properties, measurements of the radiant source flux and air flow rate are also required. Because imposed heat flux to the surface and the surface ignition temperature are the factors that directly determine ignition, some data of piloted ignition are inadequate or misleading.

Unpiloted ignition depends on special circumstances that result in different ranges of ignition temperatures. At this time, it is not possible to give specific ignition data that apply to a broad range of cases. For radiant heating of cellulosic solids, unpiloted transient ignition has been reported at 600 °C. With convective heating of wood, unpiloted ignition has been reported as low as 270 °C and as high as 470 °C. Unpiloted spontaneous ignition can occur when a heat source within the wood product is located such that the heat is not readily dissipated. This kind of ignition involves smoldering and generally occurs over a longer period of time. Continuous smoking is visual evidence of smoldering, which is sustained combustion within the pyrolyzing material. Although smoldering can be initiated by an external ignition source, a particularly dangerous smoldering is that initiated by internal heat generation. Examples of such fires are (a) panels or paper removed from the press or dryer and stacked in large piles without adequate cooling and (b) very large piles of chips or sawdust with internal exothermic reactions such as biological activities. Potential mechanisms of internal heat generation include respiration, metabolism of microorganisms, heat of pyrolysis, abiotic oxidation, and adsorptive heat. These mechanisms, often in combination, may proceed to smoldering or flaming ignition through a thermal runaway effect within the pile if sufficient heat is generated and is not dissipated. The minimum environmental temperature to achieve smoldering ignition decreases with the increases in specimen mass and air ventilation, and can be as low as air temperatures for large ventilating piles. Therefore, safe shipping or storage with wood chips, dust, or pellets often depends on anecdotal knowledge that advises maximum pile size or ventilation constraints, or both (Babrauskas 2003).

Unpiloted ignitions that involve wood exposed to low-level external heat sources over very long periods are an area of dispute. This kind of ignition, which involves considerable charring, does appear to occur, based on fire investigations. However, these circumstances do not lend themselves easily to experimentation and observation. There is some evidence that the char produced under low heating temperatures can have a different chemical composition, which results in a somewhat lower ignition temperature than normally recorded. Thus, a major issue is the question of safe working temperature for wood exposed for long periods. Temperatures between 80 and 100 °C have been recommended as safe surface temperatures for wood. As noted earlier, to address this concern, a safe margin of fire safety from ignition can be obtained if surface temperatures of heated wood are maintained below about 80 °C, which avoids the incipient wood degradation associated with reduction in ignition temperature.

Heat Release and Smoke

Heat release rates are important because they indicate the potential fire hazard of a material and also the combustibility of a material. Materials that release their potential chemical energy (and also the smoke and toxic gases) relatively quickly are more hazardous than those that release it more slowly. There are materials that will not pass the current definition of noncombustible in the model codes but will release only limited amounts of heat during the initial and critical periods of fire exposure. There is also some criticism of using limited flammability to partially define noncombustibility. One early attempt was to define combustibility in terms of heat release in a potential heat method (NFPA 259), with the low levels used to define low combustibility or noncombustibility. This test method is being used to regulate materials under some codes. The ground-up wood sample in this method is completely consumed during the exposure to 750 °C for 2 h, which makes the potential heat for wood identical to the gross heat of combustion from the oxygen bomb calorimeter. The typical gross heat of combustion averaged around 20 MJ kg^{-1} for ovendried wood, depending on the lignin and extractive content of the wood.

A better or a supplementary measure of degrees of combustibility is a determination of the rate of heat release (RHR) or heat release rate (HRR). This measurement efficiently assesses the relative heat contribution of materials—thick, thin, untreated, or treated—under fire exposure. The cone calorimeter (ASTM E 1354) is currently the most commonly used bench-scale HRR apparatus and is based on the oxygen consumption method. An average value of 13.1 kJ g^{-1} of oxygen consumed was the constant found for organic solids and is accurate with very few exceptions to within 5%. In the specific case of wood volatiles flaming and wood char glowing, this oxygen consumption constant was reconfirmed at the value of 13.23 kJ g^{-1} (Dietenberger 2002). Thus, it is sufficient to measure the mass flow rate of oxygen consumed in a combustion system to determine the net HRR. The intermediate-scale apparatus (ASTM E 1623) for testing 1- by 1-m assemblies or composites and the room full-scale test (ASTM E 2257) also use the oxygen consumption technique to measure the HRR of fires at larger scales.

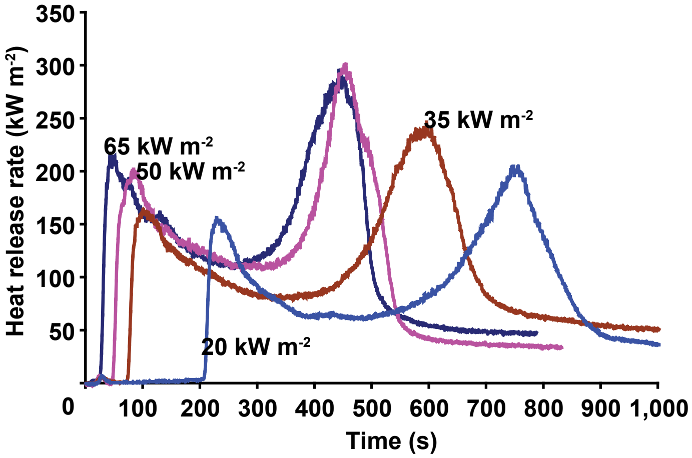

Figure 18–2. Heat release rate curves for 12-mm-thick oriented strandboard (OSB) exposed to constant heat flux of 20, 35, 50 and 65 kW m^{-2}.

The cone calorimeter is ideal for product development with its small specimen size of 100 by 100 mm. The specimen is continuously weighed by use of a load cell. In conjunction with HRR measurements, the effective heat of combustion as a function of time is calculated by the ASTM E 1354 method. Basically, the effective heat of combustion is the HRR divided by the mass loss rate as determined from the cone calorimeter test as a function of time. Typical HRR profiles, as shown in Figure 18–2, begin with a sharp peak upon ignition, and as the surface chars, the HRR drops to some minimum value. After the thermal wave travels completely through the wood thickness, the back side of a wood sample reaches pyrolysis temperature, thus giving rise to a second, broader, and even higher HRR peak. For FRT wood products, the first HRR peak may be reduced or eliminated.

Heat release rate depends upon the intensity of the imposed heat flux**.** Generally, the averaged effective heat of combustion is about 65% of the oxygen bomb heat of combustion (higher heating value), with a small linear increase with irradiance. The HRR itself has a large linear increase with the heat flux. This information along with a representation of the heat release profile shown in Figure 18–2 has been used to model or correlate with large scale fire growth such as the Steiner tunnel test and the room-corner fire test (Dietenberger and White 2001)

The cone calorimeter is also used to obtain dynamic measurements of smoke consisting principally of soot and CO in the overventilated fires and of white smoke during unignited pyrolysis and smoldering. The measurements are dynamic in that smoke continuously flows out the exhaust pipe where optical density and CO are measured continuously. This contrasts with a static smoke test in which the specimen is tested in a closed chamber of fixed volume and the light attenuation is recorded over a known optical path length. In the dynamic measurements of smoke, the appropriate smoke parameter is the smoke release rate (SRR), which is the optical density multiplied by the volume flow rate of air into the exhaust pipe and divided by the product of exposed surface area of the specimen and the light path length. Often the smoke extinction area, which is the product of SRR and the specimen area, is preferred because it can be correlated linearly with HRR in many cases. This also permits comparison with the smoke measured in the room-corner fire test because HRR is a readily available test result (Dietenberger and Grexa 2000). Although SRR can be integrated with time to get the same units as the specific optical density, they are not equivalent because static tests involve the direct accumulation of smoke in a volume, whereas SRR involves accumulation of freshly entrained air volume flow for each unit of smoke. Methods investigated to correlate smoke between different tests included alternative parameters such as particulate mass emitted per area of exposed sample. As pertaining to CO production, some amount of correlation has been obtained between the cone calorimeter's CO mass flow rate as normalized by HRR to the corresponding parameter measured from the post flashover gases during the room-corner fire test. Thermal degradation of white smoke from wood into simpler gases within the underventilated fire test room during post flashover is not presently well understood and can have dramatic effects on thermal radiation within the room, which in turn affects wood pyrolysis rates.

Flame Spread

The spread of flames over solids is a very important phenomenon in the growth of compartment fires. Indeed, in fires where large fuel surfaces are involved, increase in HRR with time is primarily due to increase in burning area. Much data have been acquired with the flame spread tests used in building codes. Table 18–1 lists the FSI and smoke index of ASTM E 84 for solid wood. Some consistencies in the FSI behavior of the hardwood species can be related to their density (White 2000). Considerable variations are found for wood-based composites; for example, the FSI of four structural flakeboards ranged from 71 to 189.

As a prescriptive regulation, the ASTM E 84 tunnel test is a success in the reduction of fire hazards but is impractical in providing scientific data for fire modeling or in useful bench-scale tests for product development. Other full-scale tests (such as the room-corner test) can produce quite different results because of the size of the ignition burner or test geometry. This is the case with foam plastic panels that melt and drip during a fire test. In the tunnel test, with the test material on top, a material that melts can have low flammability because the specimen does not stay in place. With an adequate burner in the room-corner test, the same material will exhibit very high flammability.

A flame spreads over a solid material when part of the fuel, ahead of the pyrolysis front, is heated to the critical condition of ignition. The rate of flame spread is controlled by how rapidly the fuel reaches the ignition temperature in response to heating by the flame front and external sources. The material's thermal conductivity, heat capacitance, thickness, and blackbody surface reflectivity influence the material's thermal response, and an increase in the values of these properties corresponds to a decrease in flame spread rate. On the other hand, an increase in values of the flame features, such as the imposed surface fluxes and spatial lengths, corresponds to an increase in the flame spread rate.

Flame spread occurs in different configurations, which are organized by orientation of the fuel and direction of the main flow of gases relative to that of flame spread. Downward and lateral creeping flame spread involves a fuel orientation with buoyantly heated air flowing opposite of the flame spread direction. Related bench-scale test methods are ASTM E 162 for downward flame spread, ASTM E 648 for horizontal flame spread to the critical flux level, and ASTM E 1321 (LIFT apparatus) for lateral flame spread on vertical specimens to the critical flux level. Heat transfer from the flame to the virgin fuel is primarily conductive within a spatial extent of a few millimeters and is affected by ambient conditions such as oxygen, pressure, buoyancy, and external irradiance. For most wood materials, this heat transfer from the flame is less than or equal to surface radiant heat loss in normal ambient conditions, so that excess heat is not available to further raise the virgin fuel temperature; flame spread is prevented as a result. Therefore, to achieve creeping flame spread, an external heat source is required in the vicinity of the pyrolysis front (Dietenberger 1994).

Upward or ceiling flame spread involves a fuel orientation with the main air flowing in the same direction as the flame spread (assisting flow). Testing of flame spread in assisting flow exists in both the tunnel tests and the room-corner burn tests. The heat transfer from the flame is both conductive and radiative, has a large spatial feature, and is relatively unaffected by ambient conditions. Rapid acceleration in flame spread can develop because of a large, increasing magnitude of flame heat transfer as a result of increasing total HRR in assisting flows (Dietenberger and White 2001). These complexities and the importance of the flame spread processes explain the many and often incompatible flame spread tests and models in existence worldwide.

Charring and Fire Resistance

As noted earlier in this chapter, wood exposed to high temperatures will decompose to provide an insulating layer of char that retards further degradation of the wood (Figure 18–3). The load-carrying capacity of a structural wood member depends upon its cross-sectional dimensions. Thus, the amount of charring of the cross section is the major factor in the fire resistance of structural wood members.

When wood is first exposed to fire, the wood chars and eventually flames. Ignition occurs in about 2 min under the standard ASTM E 119 fire-test exposures. Charring into the depth of the wood then proceeds at a rate of approximately 0.8 mm min^{-1} for the next 8 min (or 1.25 min mm^{-1}). Thereafter, the char layer has an insulating effect, and the rate decreases to 0.6 mm min^{-1} (1.6 min mm^{-1}). Considering the initial ignition delay, the fast initial charring, and then the slowing down to a constant rate, the average constant charring rate is about 0.6 mm min^{-1} (or 1.5 in. h^{-1}) (Douglas-fir, 7% moisture content). In the standard fire resistance test, this linear charring rate is generally assumed for solid wood directly exposed to fire. There are differences among species associated with their density, anatomy, chemical composition, and permeability. In a study of the fire resistance of structural composite lumber products, the charring rates of the products tested were similar to that of solid-sawn lumber. Moisture content is a major factor affecting charring rate. Density relates to the mass needed to be degraded and the thermal properties, which are affected by anatomical features. Charring in the longitudinal grain direction is reportedly double that in the transverse direction, and chemical composition affects the relative thickness of the char layer. Permeability affects movement of moisture being driven from the wood or that being driven into the wood beneath the char layer. Normally, a simple linear model for charring where t is time (min), C is char rate (min mm^{-1}), and x_c is char depth (mm) is

$$t = Cx_c \tag{18–1}$$

The temperature at the base of the char layer is generally taken to be 300 °C or 550 °F (288 °C). With this temperature criterion, empirical equations for charring rate have

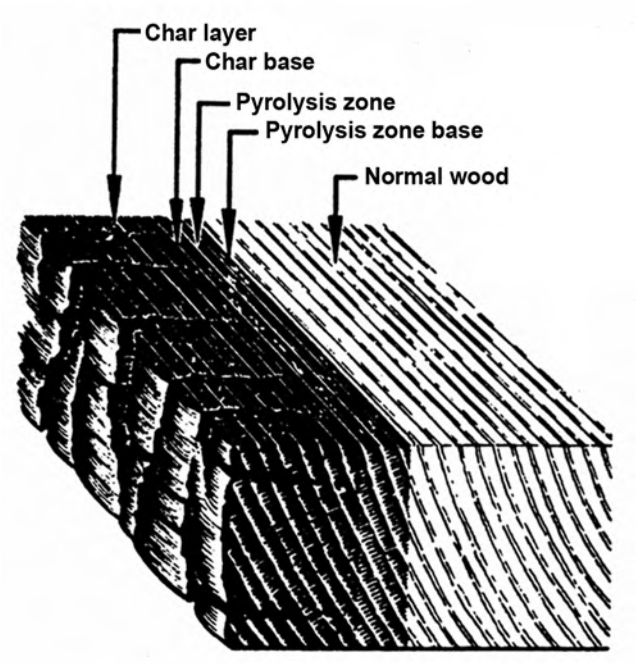

Figure 18–3. Illustration of charring of wood slab.

Table 18–3. Charring rate data for selected wood species

		Wood exposed to ASTM E 119 exposure[a]				Wood exposed to a constant heat flux[b]					
						Linear charring rate[e] (min mm^{-1})		Thermal penetration depth d^g (mm)		Average mass loss rate (g m^{-2} s^{-1})	
Species	Density[c] (kg m^{-3})	Char contraction factor[d]	Linear charring rate[e] (min mm^{-1})	Nonlinear charring rate[f] (min mm$^{-1.23}$)	Thermal penetration depth[g] (mm)	18-kW m^{-2} heat flux	55-kW m^{-2} heat flux	18-kW m^{-2} heat flux	55-kW m^{-2} heat flux	18-kW m^{-2} heat flux	55-kW m^{-2} heat flux
Softwoods											
Southern Pine	509	0.60	1.24	0.56	33	2.27	1.17	38	26.5	3.8	8.6
Western redcedar	310	0.83	1.22	0.56	33	—	—	—	—	—	—
Redwood	343	0.86	1.28	0.58	35	1.68	0.98	36.5	24.9	2.9	6.0
Engelmann spruce	425	0.82	1.56	0.70	34	—	—	—	—	—	—
Hardwoods											
Basswood	399	0.52	1.06	0.48	32	1.32	0.76	38.2	22.1	4.5	9.3
Maple, hard	691	0.59	1.46	0.66	31	—	—	—	—	—	—
Oak, red	664	0.70	1.59	0.72	32	2.56	1.38	27.7	27.0	4.1	9.6
Yellow-poplar	504	0.67	1.36	0.61	32	—	—	—	—	—	—

[a] Moisture contents of 8% to 9%.

[b] Charring rate and average mass loss rate obtained using ASTM E 906 heat release apparatus. Test durations were 50 to 98 min for 18-kW m^{-2} heat flux and 30 to 53 min for 55-kW m^{-2} heat flux. Charring rate based on temperature criterion of 300 °C and linear model. Mass loss rate based on initial and final weight of sample, which includes moisture driven from the wood. Initial average moisture content of 8% to 9%.

[c] Based on weight and volume of ovendried wood.

[d] Thickness of char layer at end of fire exposure divided by original thickness of charred wood layer (char depth).

[e] Based on temperature criterion of 288 °C and linear model.

[f] Based on temperature criterion of 288 °C and nonlinear model of Equation (18–3).

[g] As defined in Equation (18–6). Not sensitive to moisture content.

been developed. Equations relating charring rate under ASTM E 119 fire exposure to density and moisture content are available for Douglas-fir, Southern Pine, and white oak. These equations for rates transverse to the grain are

$$C = (0.002269 + 0.00457\mu)\rho + 0.331 \quad \text{for Douglas-fir} \qquad (18\text{–}2a)$$

$$C = (0.000461 + 0.00095\mu)\rho + 1.016 \quad \text{for Southern Pine} \qquad (18\text{–}2b)$$

$$C = (0.001583 + 0.00318\mu)\rho + 0.594 \quad \text{for white oak} \qquad (18\text{–}2c)$$

where μ is moisture content (fraction of ovendry mass) and ρ is density, dry mass volume at moisture content μ (kg m^{-3}).

A nonlinear char rate model has been found useful. This alternative model is

$$t = m x_c^{1.23} \qquad (18\text{–}3)$$

where m is char rate coefficient (min mm$^{-1.23}$).

A form of Equation (18–3) is used in the NDS Method for calculating the fire resistance rating of an exposed wood member. Based on data from eight species (Table 18–3), the following equation was developed for the char rate coefficient:

$$m = -0.147 + 0.000564\rho + 1.21\mu + 0.532 f_c \qquad (18\text{–}4)$$

where ρ is density, ovendry mass and volume, and f_c is char contraction factor (dimensionless).

The char contraction factor is the thickness of the residual char layer divided by the original thickness of the wood layer that was charred (char depth). Average values for the eight species tested in the development of the equation are listed in Table 18–3. These equations and data are valid when the member is thick enough to be a semi-infinite slab. For smaller dimensions, the charring rate increases once the temperature has risen above the initial temperature at the center of the member or at the unexposed surface of the panel. As a beam or column chars, the corners become rounded.

Charring rate is also affected by the severity of the fire exposure. Data on charring rates for fire exposures other than ASTM E 119 have been limited. Data for exposure to constant temperatures of 538, 815, and 927 °C are available in Schaffer (1967). Data for a constant heat flux are given in Table 18–3.

The temperature at the innermost zone of the char layer is assumed to be 300 °C. Because of the low thermal conductivity of wood, the temperature 6 mm inward from the base of the char layer is about 180 °C. This steep temperature gradient means the remaining uncharred cross-sectional area of a large wood member remains at a low temperature and can continue to carry a load. Once a quasi-steady-state charring rate has been obtained, the temperature profile beneath the char layer can be expressed as an exponential term or a power term. An equation based on a power term is

$$T = T_{\mathrm{i}} + \left(300 - T_{\mathrm{i}}\right)\left(1 - \frac{x}{d}\right)^2 \qquad (18\text{–}5)$$

where T is temperature (°C), T_{i} initial temperature (°C), x distance from the char front (mm), and d thermal penetration depth (mm).

In Table 18–3, values for the thermal penetration depth parameter are listed for both the standard fire exposure and the constant heat flux exposure. As with the charring rate, these temperature profiles assume a semi-infinite slab. The equation does not provide for the plateau in temperatures that often occurs at 100 °C in moist wood. In addition to these empirical data, there are mechanistic models for estimating the charring rate and temperature profiles. The temperature profile within the remaining wood cross section can be used with other data to estimate the remaining load-carrying capacity of the uncharred wood during a fire and the residual capacity after a fire.

Fire-Retardant-Treated Wood

Wood products can be treated with fire retardants to improve their fire performance. Fire-retardant treatments results in delayed ignition, reduced heat release rate, and slower spread of flames. HRRs are markedly reduced by fire-retardant treatment (Fig. 18–4). In terms of fire performance, fire-retardant treatments are marketed to improve the flame spread characteristics of the wood products as determined by ASTM E 84, ASTM E 108, or other flammability tests. Fire-retardant treatment also generally reduces the smoke-developed index as determined by ASTM E 84. A fire-retardant treatment is not intended to affect fire resistance of wood products as determined by an ASTM E 119 test in any consistent manner. Fire-retardant treatment does not make a wood product noncombustible as determined by ASTM E 136 nor does it change its potential heat as determined by NFPA 259.

Because fire-retardant treatment does reduce the flammability of the wood product, FRT wood products are often used for interior finish and trim in rooms, auditoriums, and corridors where codes require materials with low surface flammability. Although FRT wood is not a noncombustible material, many codes have specific exceptions that allow the use of FRT wood and plywood in fire-resistive and noncombustible construction for framing of non-load-bearing partitions, nonbearing exterior walls, and roof assemblies. Fire-retardant-treated wood is also used for such special purposes as wood scaffolding and for the frame, rails, and stiles of wood fire doors.

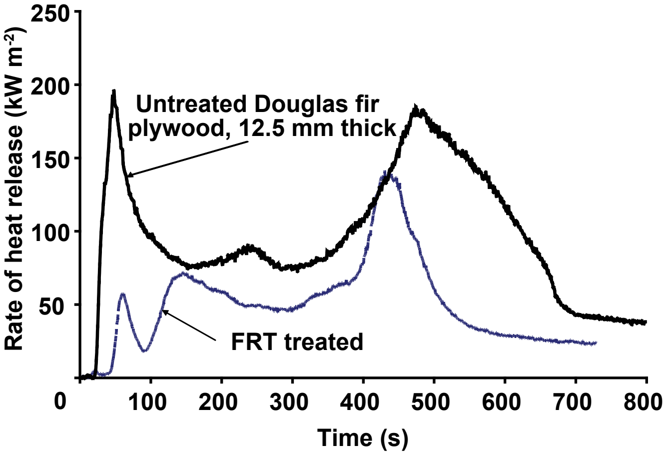

Figure 18–4. Heat release curves for untreated and fire-retardant-treated (FRT) Douglas-fir plywood, 12.5 mm thick.

To meet specifications in building codes and various standards, FRT lumber and plywood is wood that has been pressure treated with chemicals to reduce its flame spread characteristics. In the case of other composite wood products, chemicals can be added during the manufacture of the wood product. Fire-retardant treatment of wood generally improves the fire performance by reducing the amount of flammable volatiles released during fire exposure or by reducing the effective heat of combustion, or both. Both results have the effect of reducing HRR, particularly during the initial stages of fire, and thus consequently reducing the rate of flame spread over the surface. The wood may then self-extinguish when the primary heat source is removed. FRT products can be found in the Underwriters Laboratories, Inc., “Building Materials Directory,” evaluation reports of ICC Evaluation Service, Inc. (ICC–ES), and other such listings.

Pressure Treatments

In impregnation treatments, wood is pressure impregnated with chemical solutions using pressure processes similar to those used for chemical preservative treatments. However, considerably heavier absorptions of chemicals are necessary for fire-retardant protection. Penetration of chemicals into the wood depends on species, wood structure, and moisture content. Because some species are difficult to treat, the degree of impregnation needed to meet the performance requirements for FRT wood may not be possible.

Inorganic salts are the most commonly used fire retardants for interior wood products, and their characteristics have been known for more than 50 years. These salts include monoammonium and diammonium phosphate, ammonium sulfate, zinc chloride, sodium tetraborate, and boric acid. Guanylurea phosphate is also used. Chemicals are combined in formulations to develop optimum fire performance yet still retain acceptable hygroscopicity, strength, corrosivity, machinability, surface appearance, glueability, and paintability. Cost is also a factor in these formulations. Actual formulations of commercial fire-retardant treatments are generally proprietary. For the two interior fire-retardant treatments listed in American Wood Protection Association (AWPA) (formerly American Wood-Preservers' Association) standards, the chemicals listed are guanylurea phosphate and boric acid for FR-1 and phosphate, boric acid, and ammonia for FR-2. Species-specific information on the depth of chemical penetration for these two formulations can be found in Section 8.8 of AWPA Standard T1. Traditional fire-retardant salts are water soluble and are leached out in exterior applications or with repeated washings. Water-insoluble organic fire retardants have been developed to meet the need for leach-resistant systems. Such treatments are also an alternative when a low-hygroscopic treatment is needed. These water-insoluble systems include (a) resins polymerized after impregnation into wood and (b) graft polymer fire retardants attached directly to cellulose. An amino resin system based on urea, melamine, dicyandiamide, and related compounds is of the first type.

There are AWPA standards that describe methods for testing wood for the presence of phosphate or boron. Such tests can be used to determine the presence of fire-retardant treatments that contain these chemicals. AWPA Standard A9 is a method for analysis of treated wood and treating solutions by x-ray spectroscopy. The method detects the presence of elements of atomic number 5 or higher including B(5) and P(15). AWPA Standard A26 has a method for analysis of fire retardant FR1 solutions or wood by titration for the percentages of boric acid and guanylurea phosphate. AWPA Standard A3 describes methods for determining penetration of fire retardants. Included are two methods for boron-containing preservatives and fire retardants and one method for phosphorus-containing fire retardants. The compositions of commercial fire-retardant treatments are proprietary. In the case of boron, tests for its presence cannot distinguish between treatments for preservation and those for fire retardancy. Such chemical tests are not an indicator of the adequacy of the treatment in terms of fire retardancy. Small-scale fire tests such as the cone calorimeter (ASTM E 1354), oxygen index (ASTM D 2863), fire tube (ASTM E 69), and various thermal analysis methodologies can also be used to determine the presence of fire retardant treatment.

Performance Requirements

The IBC has prescriptive language specifying performance requirements for FRT wood. The fire performance requirement for FRT wood is that its FSI is 25 or less when tested according to the ASTM E 84 flame spread test and that it shows no evidence of significant progressive combustion when this 10-min test is continued for an additional 20 min. In addition, it is required that the flame front in the test shall not progress more than 3.2 m beyond the centerline of the burner at any given time during the test. In the IBC, FRT wood must be a wood product impregnated with chemicals by a pressure process or other means during manufacture. In applications where the requirement being addressed is not for "fire-retardant-treated wood" but only for Class A or B flame spread, the treatment only needs to reduce the FSI to the required level in the ASTM E 84 flame spread test (25 for Class A, 75 for Class B).

In addition to requirements for flame spread performance, FRT wood for use in certain applications is required to meet other performance requirements. Wood treated with inorganic fire-retardant salts is usually more hygroscopic than is untreated wood, particularly at high relative humidities. Increases in equilibrium moisture content of this treated wood will depend upon the type of chemical, level of chemical retention, and size and species of wood involved. Applications that involve high humidity will likely require wood with low hygroscopicity. Requirements for low hygroscopicity in the IBC stipulate that interior FRT wood shall have a moisture content of not more than 28% when tested in accordance with ASTM D 3201 procedures at 92% relative humidity.

Exterior fire-retardant treatments should be specified whenever the wood is exposed to weather, damp, or wet conditions. Exterior type treatment is one that has shown no increase in the listed flame spread index after being subjected to the rain test of ASTM D 2898. Although the method of D 2898 is often not specified, the intended rain test is usually Method A of ASTM D 2898. Method B of D 2898 includes exposures to UV bulbs in addition to water sprays, is described in FPL publications, and is an acceptable method in AWPA Standard U1 for evaluating exterior treatments. The ASTM D 2898 standard practice was recently revised to include Methods C and D. Method C is the "amended rain test" described in the acceptance criteria for classified wood roof systems (AC107) of the ICC Evaluation Service, Inc. Method D is the alternative rain test described in ASTM E 108 for roof coverings.

Fire-retardant treatment generally results in reductions in the mechanical properties of wood. Fire-retardant-treated wood is often more brash than untreated wood. For structural applications, information on mechanical properties of the FRT wood product needs to be obtained from the treater or chemical supplier. This includes the design modification factors for initial strength properties of the FRT wood and values for the fasteners. Adjustments to the design values must take into account expected temperature and relative humidity conditions. In field applications with elevated temperatures, such as roof sheathings, there is the potential for further losses in strength with time. Fire-retardant-treated wood that will be used in high-temperature applications, such as roof framing and roof sheathing, is also strength tested in accordance with ASTM D 5664 (lumber) or ASTM D 5516 (plywood) for purpose of obtaining adjustment factors as described in ASTM D 6841 (lumber) and ASTM D 6305 (plywood). The temperatures used to obtain the adjustment factors also become the maximum temperature that can be used in kiln drying of lumber or plywood after treatment.

Corrosion of fasteners can be accelerated under conditions of high humidity and in the presence of fire-retardant salts. For fire-retardant treatments containing inorganic salts, the types of metal and chemical in contact with each other greatly affect the rate of corrosion. Thus, information on proper fasteners also needs to be obtained from the treater or chemical supplier. Other issues that may require contacting the treater or chemical supplier include machinability, gluing characteristics, and paintability.

Fire-retardant treatment of wood does not prevent the wood from decomposing and charring under fire exposure (the rate of fire penetration through treated wood approximates the rate through untreated wood). Fire-retardant-treated wood used in doors and walls can slightly improve fire resistance of these doors and walls. Most of this improvement is associated with reduction in surface flammability rather than any changes in charring rates.

There are specifications for FRT wood issued by AWPA and NFPA. In terms of performance requirements, these specifications are consistent with the language in the codes. The AWPA standards C20 and C27 for FRT lumber and plywood have recently been deleted by AWPA. They have been replaced by AWPA "Use Category System Standards" for specifying treated wood. The specific provisions are Commodity H of Standard U1 and Section 8.8 of Standard T1. The fire protection categories are UCFA for interior applications where the wood is protected from exterior weather and UCFB for exterior applications where any water is allowed to quickly drain from the surface. Neither category is suitable for applications involving contact with the ground or with foundations. Commodity Specification H is fire-retardant treatment by pressure processes of solid sawn and plywood. The performance requirements for Commodity Specification H treatments are provided in Standard U1. Section 8.8 of Standard T1 provides information on the treatment and processing (that is, drying) of the products.

There is also NFPA standard 703 for FRT wood and fire-retardant coatings. In addition to the performance and testing requirements for FRT wood products impregnated with chemicals by a pressure process or other means during manufacture, this NFPA standard provides separate specifications for fire-retardant coatings.

For parties interested in developing new fire-retardant treatments, there are documents that provide guidelines on the data required for technical acceptance. In the AWPA Book of Standards, there is "Appendix B: Guidelines for evaluating new fire retardants for consideration by the AWPA." The ICC–ES has issued an "Acceptance criteria for fire-retardant-treated wood" (AC66), which provides guidelines for what is required to be submitted for their evaluation reports. There is also "Acceptance criteria for classified wood roof systems" (AC107). Because of the relative small size of the specimen, FPL uses the cone calorimeter in its research and development of new FRT products.

Fire-Retardant Coatings

For some applications, applying the fire-retardant chemical as a coating to the wood surface may be acceptable to the authorities having jurisdiction. Commercial coating products are available to reduce the surface flammability characteristics of wood. The two types of coatings are intumescent and nonintumescent. The widely used intumescent coatings "intumesce" to form an expanded low-density film upon exposure to fire. This multicellular carbonaceous film insulates the wood surface below from high temperatures. Intumescent formulations include a dehydrating agent, a char former, and a blowing agent. Potential dehydrating agents include polyammonium phosphate. Ingredients for the char former include starch, glucose, and dipentaerythritol. Potential blowing agents for the intumescent coatings include urea, melamine, and chlorinate parafins. Nonintumescent coating products include formulations of the water-soluble salts such as diammonium phosphate, ammonium sulfate, and borax.

NFPA standard 703 includes specifications for fire-retardant coatings. Because coatings are not pressure impregnated or incorporated during manufacture, fire-retardant coated wood is not FRT wood as defined in most codes or standards including NFPA 703. In NFPA 703, a fire-retardant coating is defined as a coating that reduces the flame spread of Douglas-fir and all other tested combustible surfaces to which it is applied by at least 50% or to a flame spread classification value of 75 or less, whichever is the lesser value, and has a smoke developed rating not exceeding 200 when tested in accordance with ASTM E 84, NFPA 255, or UL 723. There is no requirement that the standard test be extended for an additional 20 min as required for FRT wood. NFPA 703 differentiates between a Class A coating as one that reduces flame spread index to 25 or less and a Class B coating as one that reduces flame spread index to 75 or less.

Fire-retardant coatings for wood are tested and marketed to reduce flame spread. Clear intumescent coatings are available. Such coatings allow the exposed appearance of old structural wood members to be maintained while providing improved fire performance. This is often desirable in the renovation of existing structures, particularly museums and historic buildings. Studies have indicated that coatings subjected to outdoor weathering are of limited durability and would need to be reapplied on a regular basis.

Although their use to improve the resistance ratings of wood products has been investigated, there is no general acceptance for using coatings to improve the fire resistance rating of a wood member. There is a lack of full-scale ASTM E 119 test data to demonstrate their performance and validate a suitable calculation methodology for obtaining the rating.

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