Chapter 17

Fire Safety

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Contents

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 are discussed in the context of fire safety design and evaluation in the initial section of this chapter. Since basic data on fire behavior of wood products are needed to evaluate fire safety for wood construction, the second major section of this chapter covers fire performance characteristics of wood products. The chapter concludes with a discussion of flame-retardant treatments that can be used to reduce the combustibility of wood.

Fire Safety Design and Evaluation

Fire safety involves prevention, containment, detection, and evacuation. Fire prevention basically means preventing the 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. Design deficiencies are often responsible for spread of heat and smoke in a fire. Spread of a fire can be prevented with design methods that limit fire growth and spread within a compartment and with methods that contain fire to the compartment of origin. Egress, or the ability to escape from a fire, often is a critical factor in life safety. Early detection is essential for ensuring adequate time for egress.

Statutory requirements pertaining to fire safety are specified in the building codes or fire codes. These requirements fall into two broad categories: material requirements and building requirements. Material requirements include such things as combustibility, flame spread, and fire endurance. 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 is documented.

Most building codes in the United States are based on model building codes produced by the three building code organizations (Building Officials and Code Administrators International, Inc.; International Conference of Building Officials; and the Southern Building Code Congress International, Inc.). These three organizations are developing a single international building code that will replace the existing three model building codes. In addition to the building codes and the fire codes, the National Fire Protection Association's Life Safety Code provides guidelines for life safety from fire in buildings and structures. As with the model building codes, provisions of the life safety code are statutory requirements when adopted by local or State authorities.

In the following sections, various aspects of the building code provisions pertaining to fire safety of building materials are discussed under the broad categories of (a) types of construction, (b) fire growth within compartment, and (c) containment to compartment of origin. These are largely requirements for materials. Information on prevention and building requirements not related to materials (for example, detection) can be found in publications such as those listed at the end of this chapter. Central aspects of the fire safety provisions of the building codes are the classification of buildings by types of construction and the use or occupancy.

Types of Construction

Based on classifications of building type and occupancy, the codes set limits on the areas and heights of buildings. Major building codes generally recognize five classifications of construction based on types of materials and required fire resistance ratings. The two classifications known as fire-resistant construction (Type I) and noncombustible construction (Type II) basically restrict the construction to noncombustible materials. Wood is permitted to be used more liberally in the other three classifications, which are ordinary (Type III), heavy timber (Type IV), and light-frame (Type V). Heavy timber construction has wood columns, beams, floors, and roofs of certain minimum dimensions. Ordinary construction has smaller wood members used for walls, floors, and roofs including wood studs, wood joists, wood trusses, and wood I-joists. In both heavy timber and ordinary construction, the exterior walls must be of noncombustible materials. In light-frame construction, the walls, floors, and roofs may be of any dimension lumber and the exterior walls may be of combustible materials. Type II, III, and IV constructions are further subdivided based on fire-resistance requirements. Light-frame construction, or Type V, is subdivided into two parts, protected (1-hour) and unprotected. In protected light-frame construction, most of the structural elements have a 1-hour fire resistance rating. There are no general requirements for fire resistance for buildings of unprotected light-frame construction.

Based on their performance in the American Society for Testing and Materials (ASTM) E136 test, both untreated and fire-retardant-treated wood are combustible materials. However, the building codes permit substitution of fire-retardant-treated wood for noncombustible materials in some specific applications otherwise limited to noncombustible materials.

In addition to the type of construction, the 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 the 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.

Fire Growth Within Compartment

A second major set of provisions in the building codes are those that regulate the exposed interior surface of walls 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 E84, 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 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 codes, the classes for flame spread index are I (FSI of 0 to 25), II (FSI of 26 to 75), and III (FSI of 76 to 200). Some codes use A, B, and C instead of I, II, and III. 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 I and II, are generally prescribed for stairways and corridors that provide access to exits. In general, the more flammable classification (Class III) 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, there are no flammability restrictions on the interior finish and unclassified materials (that is, more than 200 FSI) can be used.

Table 17–1. ASTM E84 flame spread indexes for 19-mm-thick solid lumber of various wood species as reported in the literature

Species[a]	Flame spread index[b]	Smoke developed index[b]	Source[c]
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[d]	122, —	CWC, UL
Pine, lodgepole	93	210	CWC
Pine, ponderosa	105–230[d]	—	UL
Pine, red	142	229	CWC
Pine, Southern (southern)	130–195	—	UL
Pine, western white	75[e]	—	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] 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.

[b] Data are as reported in the literature (dash where data do not exist). Changes in the ASTM E84 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.

[c] 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).

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

[e] 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.

The FSI for most domestic wood species is between 90 and 160 (Table 17–1). Thus, unfinished lumber, 10 mm or thicker, is generally acceptable for interior finish applications requiring a Class III rating. Flame-retardant treatments are usually necessary when a Class I or II flame spread index is required for a wood product. A few domestic softwood species can meet the Class II flame spread index and only require flame-retardant treatments to meet a Class I rating. A few imported species have reported FSIs of less than 25.

Additional FSI for many solid-sawn and panel products are provided in the American Forest and Paper Association's (AF&PA) design for code acceptance (DCA) No. 1, "Flame Spread Performance of Wood Products" (AWC 1999).

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.

Since the fire exposure is on the underside of a horizontal specimen in the ASTM E84 test, it is not suitable for materials that melt and drip or are not self-supporting. Code provisions pertaining to floors and floor coverings may be based on another test criterion, the critical radiant flux test (ASTM E648, Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source). The critical radiant flux apparatus is also used to test the flammability of cellulosic insulation (ASTM E970, Critical Radiant Flux of Exposed Attic Floor Insulation Using a Radiant Heat Energy Source). 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. Thus, low critical radiant flux reflects materials with high flammability. Typical requirements are for a minimum critical radiant flux level of 2.2 or 4.5 kW/m^2 depending on location and occupancy. Data in the literature indicate that oak flooring has a critical radiant flux of 3.5 kW/m^2 (Benjamin and Adams 1976).

There is also a smoldering combustion test for cellulosic insulation. Cellulosic insulation is regulated by a product safety standard of the U.S. Consumer Product Safety Commission (Interim Safety Standard for Cellulosic Insulation: Cellulosic Insulation Labeling and Requirements, 44FR 39938, 16CFR Part 1209, 1979; also Gen. Serv. Admin. Spec. HH–I–515d). Proper chemical treatments of cellulosic insulation are required to reduce its tendency for smoldering combustion and to reduce flame spread. Proper installation around recessed light fixtures and other electrical devices is necessary.

Other tests for flammability include those that measure heat release. Other flammability tests and fire growth modeling are discussed in the Fire Performance Characteristics of Wood section.

Rated roof covering materials are designated either Class A, B, or C according to their performance in the tests described in ASTM E108, Fire Tests of Roof Coverings. This test standard includes intermittent flame exposure, spread of flame, burning brand, flying brand, and rain tests. There is a different version of the pass/fail test for each of the three classes. Class A test is the most severe and 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. Leach-resistant fire-retardant-treated shingles are available that carry a Class B or C fire rating.

Information on ratings for different products can be obtained from industry literature, evaluation reports issued by the model code organizations, and listings published by testing laboratories or quality assurance agencies. Products listed by Underwriters Laboratories, Inc., and other such organizations are stamped with the rating information.

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. 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 (International Organization for Standardization (ISO) 9705, Fire Tests—Full-Scale Room Test for Surface Products). 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 E84 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. Fire endurance tests evaluate the relative performance of the assemblies during a post-flashover fire.

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 endurance ratings of structural members and assemblies are another major component of the building code provisions. 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. In the standard fire-resistance test (ASTM E119), there are 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°C or 181°C at a single location).

The self-insulating qualities of wood, particularly in the large wood sections of heavy timber construction, are 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.

In recent years, 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 heavy timber construction (Type IV). In the other types of construction, the structural members and assemblies are required to have specified fire-resistance ratings. Details on the procedure for large timbers can be found in American Institute of Timber Construction (AITC) Technical Note 7 and the AF&PA DCA #2 "Design of Fire-Resistive Exposed Wood Members" (AWC 1985).

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. Available information indicates that laminated members glued with phenol, resorcinol, or melamine adhesives are at least equal in their fire resistance to a one-piece member of the same size. Laminated members glued with casein have only slightly less fire resistance.

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-hour 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 model codes and other publications such as the *Fire Resistance Design Manual* (Gypsum Association). 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.

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 AF&PA DCA No. 4 "Component Additive Method (CAM) for Calculating and Demonstrating Assembly Fire Endurance" (AWC 1991). More sophisticated mechanistic models are being 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. 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.

Fires in buildings can spread by the movement of hot fire gases through open channels in concealed spaces. Codes specify where firestops and draftstops are required in concealed spaces, and they must be designed to interfere with the passage of flames 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. Firestops are materials used to block off relatively small openings passing through building components such as floors and walls. Draftstops are barriers 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.

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.

Fire Safety Engineering

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 Society of Fire Protection Engineers Handbook of Fire Protection Engineering* and formation of fire safety engineering subcommittees in ISO and ASTM. 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 the various publications of the National Fire Protection Association (NFPA).

Fire Performance Characteristics of Wood

Wood will burn when exposed to heat and air. Thermal degradation of wood occurs in stages. The degradation process and the exact products of thermal degradation depend upon the rate of heating as well as the temperatures. The sequence of events for wood combustion is as follows:

- The wood, responding to heating, decomposes or pyrolyzes into volatiles and char. Char is the dominant product at internal temperatures less than 300°C, whereas volatiles become much more pronounced above 300°C.
- The volatiles, some of which are flammable, can be ignited if the volatile–air mixture is of the right composition in a temperature range of about 400°C to 500°C within the mixture. This gas-phase combustion appears as flames.
- With air ventilation, the char oxidation becomes significant around 200°C with two peaks in intensity reported at 360°C and 520°C. This char oxidation is seen as glowing or smoldering combustion until only ash residue remains. This solid-phase combustion will not proceed if flaming combustion prevents a supply of fresh air to the char surfaces.

Several characteristics are used to quantify this burning behavior of wood, including ignition from heat sources, growing rate of heat release leading to room flashover, flame spread in heated environments, smoke and toxic gases, flashover, and charring rates in a contained room.

Ignition

Ignition of wood takes place when wood is subject to sufficient heat and in atmospheres that have sufficient oxygen. Ignition can be of two types: piloted or unpiloted. Piloted ignition occurs in the presence of an ignition source (such as a spark or a flame). Unpiloted ignition is ignition that occurs where no pilot source is available. The wood surface is ignited by the flow of energy or heat flux from a fire or other heated objects. This flow of energy or heat flux can have both convective and radiative components.

Piloted ignition above a single flat surface has recently been studied in some depth because of the advent of fire growth research. The surface temperature of wood materials has been measured somewhere between 300°C to 400°C prior to piloted ignition. Surface temperature at ignition is an illusive quantity that is experimentally difficult to obtain. Equipment such as the Ohio State University (OSU) apparatus (ASTM E906), the cone calorimeter (ASTM 1354), and the lateral ignition and flame spread test (LIFT) apparatus (ASTM 1321) are used to obtain data on time to piloted ignition as a function of heater irradiance. Table 17–2 indicates the decrease in time to ignition with the increase in imposed heat flux for different species of wood measured with the OSU apparatus. Similar, perhaps identical, materials have been tested recently in cone calorimeter and LIFT apparatuses with somewhat similar results. 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. These properties are also material dependent; they depend heavily on density of the material and moisture content. A range of wood products tested have ignition surface temperatures of 300°C to 400°C and a critical ignition flux of between 10 and 13 kW/m^2 in the cone calorimeter. The ignition surface temperature is lower for low density woods. Estimates of piloted ignition in various scenarios can be obtained using the derived thermal properties and an applicable heat conduction model.

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. Since 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. Smoldering is thermal degradation that proceeds without flames or

Table 17–2. Flammability data for selected wood species

Species	Density[a] (kg/m^3)	Ignition time[b] (s) 18-kW/m^2 heat flux	Ignition time[b] (s) 55-kW/m^2 heat flux	Higher heating value[c] (MJ/kg)	Effective heat of combustion[d] (MJ/kg) 18-kW/m^2 heat flux	Effective heat of combustion[d] (MJ/kg) 55-kW/m^2 heat flux	Average heat release rate[b] (kW/m^2) 18-kW/m^2 heat flux	Average heat release rate[b] (kW/m^2) 55-kW/m^2 heat flux
Softwoods								
Pine, Southern	508	740	5	20.5	9.1	13.9	40.4	119.6
Redwood	312	741	3	21.1	10.7	14.2	39.0	85.9
Hardwoods								
Basswood	312	183	5	20.0	10.9	12.2	52.8	113.0
Oak, red	660	930	13	19.8	9.0	11.7	48.7	113.3

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

[b] Ignition times, effective heat of combustion, and average rate of heat release (HRR) obtained using an ASTM E906 heat release apparatus modified to measured heat release using oxygen consumption method. 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. Test was terminated prior to the usual increase in HRR to a second peak as the specimen is consumed.

[c] From oxygen bomb calorimeter test.

[d] Apparent effective heat of combustion based on average HRR and mass loss rate, which includes the moisture driven from the wood. See footnote b.

visible glowing. 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 ignition is called the self-accelerating decomposition temperature and includes the effects of specimen mass and air ventilation.

Unpiloted ignitions that involve wood exposed to low level external heat sources over very long periods is 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°C to 100°C have been recommended as safe surface temperatures for wood. Since thermal degradation is a prerequisite for ignition of the char layer, conservative criteria for determining safe working temperatures can be the temperature and duration needed for thermal degradation. Schaffer (1980) used a residual weight criterion of 40% of the initial weight to suggest that wood can safely be heated to 150°C for a year or more before satisfying this conservative predictor of heating time to reach an incipient smoldering state.

Building codes do not generally regulate building materials on the basis of ignition or ignitability. As a result, general fire safety design criteria have not been developed. Rather, this subject is considered in conjunction with limits on combustibility and flame spread.

Heat Release

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 higher heating value in Table 17–2). The typical gross heat of combustion averaged around 20 MJ/kg 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 E1354) is the most commonly used bench-scale HRR apparatus and is based on the oxygen consumption method. An average value of 13.1 kJ/g of oxygen consumed was the constant found for organic solids and is accurate with very few exceptions to within 5%. Thus, it is sufficient to measure the mass flow rate of oxygen consumed in a combustion system to determine the net HRR. The procedure known as ASTM E906 (the OSU apparatus) is a well-known and widely used calorimeter based on measurements of heat content of incoming and exiting air flow through the apparatus. Because of the errors caused by the heat losses and the fact that the mass flow rate is controlled in the OSU apparatus, several researchers have modified it to the oxygen consumption method. These bench-scale apparatuses use a radiant source to provide the external heat exposure to the test specimen. The imposed heat flux is kept constant at a specified heat flux level. The intermediate-scale apparatus (ASTM E1623) for testing 1- by 1-m assemblies or composites and the room full-scale test (ISO 9705) also use the oxygen consumption technique to measure the HRR of fires at larger scales.

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 E1354 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. A typical HRR profile as shown in Figure 17–1 for plywood begins 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 fire-retardant-treated wood products, the first HRR peak may be reduced or eliminated. Table 17–3 provides the peak and averaged HRR at 1-, 3-, and 5-min periods for various wood species.

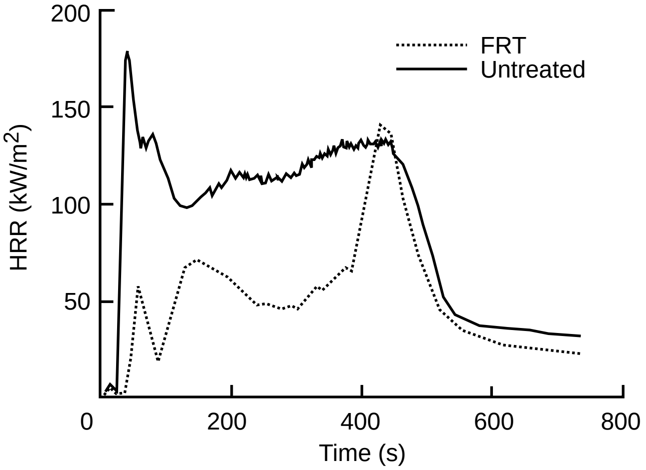

Figure 17–1. Heat release curves for untreated and FRT plywood exposed to 50-kW/m^2 radiance.

Heat release rate depends upon the intensity of the imposed heat flux. Table 17–2 provides the average effective heat of combustion and average HRR for four wood species and two levels of heat flux (18 and 55 kW/m^2). These results were obtained in an OSU apparatus modified by the Forest Products Laboratory (FPL). Similar values were also obtained in the cone calorimeter (Table 17–3). 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. Data indicate that HRRs decrease with increasing moisture content of the sample and are markedly reduced by fire-retardant treatment (Fig. 17–1).

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, the increase in HRR with time is primarily due to the increase in burning area. Many data have been acquired with the flame spread tests used in building codes. Table 17–1 lists the FSI and smoke index of ASTM E84 for solid wood. Some consistencies in the FSI behavior of the hardwood species can be related to their density. 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 E84 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 ISO 9705 room/corner test) also use both an ignition burner and the ensuing flame spread to assist flow but can produce quite different results because of the size of the ignition burner or the 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 since 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 a increase in the flame spread rate.

Table 17–3. Heat release data for selected wood species[a]

Species	Density[b] (kg/m^3)	Heat release rate (kW/m^2) Peak	60-s avg	180-s avg	300-s avg	Average effective heat of combustion[c] (MJ/kg)	Ignition time (s)
Softwoods							
Pine, red	525	209	163	143	132	12.9	24
Pine, white	359	209	150	117	103	13.6	17
Redcedar, eastern	—	175	92	95	85	11.7	25
Redwood	408	227	118	105	95	13.2	17
Hardwoods							
Birch	618	218	117	150	141	12.2	29
Maple, hard	626	218	128	146	137	11.7	31
Oak, red	593	214	115	140	129	11.4	28

[a] Data for 50-kW/m^2 heat flux in cone calorimeter. Tested in specimen holder without retaining frame. Specimens conditioned to 23°C, 50% relative humidity.

[b] Ovendry mass and volume.

[c] Tests terminated when average mass loss rate dropped below 1.5 g/s m^2 during 1-min period.

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 E162 for downward flame spread, ASTM E648 for horizontal flame spread to the critical flux level, and ASTM E1321 (LIFT apparatus) for lateral flame spread on vertical specimen to the critical flux level. The 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.

Upward or ceiling flame spread involves a fuel orientation with the main air flowing in the same direction as the flame spread (assisting flow). At present, there are no small-scale tests for upward flame spread potential. Thus, testing of flame spread in assisting flow exists mostly 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. These complexities and the importance of the flame spread processes explain the many and often incompatible flame spread tests and models in existence worldwide.

Smoke and Toxic Gases

One of the most important problems associated with fires is the smoke they produce. 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.

Currently, several bench-scale test methods provide comparative smoke yield information on materials and assemblies. Each method has entirely different exposure conditions; none is generally correlated to full-scale fire conditions or experience. Until the middle 1970s, smoke yield restrictions in building codes were almost always based on data from ASTM E84. The 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 development index (SDI), with red oak flooring set at 100. The flame spread requirements for interior finish generally are linked to an added requirement that the SDI be less than 450.

In the 1970s, the apparatus known as the NBS smoke chamber was developed and approved as an ASTM standard for research and development (ASTM E662). 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.

The dynamic measurement of smoke in the heat release calorimeter (ASTM E906 and E1354) has recently gained increasing recognition and use. The E906 and E1354 tests are dynamic in that the smoke continuously flows out the exhaust pipe where the optical density is measured continuously. 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. 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.

Toxicity of combustion products is an area of concern. About 75% to 80% of fire victims are not touched by flame but die as a result of exposure to smoke, exposure to 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. The composition and the concentration of the individual constituents depend on such factors as the fire exposure, the oxygen and moisture present, the species of wood, any treatments or finishes that may have been applied, and other considerations. Toxicity data may be more widely available in the future with the recent adoption of a standard test method (ASTM E1678).

Carbon monoxide is a particularly insidious toxic gas. 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. This poisoning is called carboxyhemoglobin. Recent research has shown that the kind of fires that kill people by toxicity are principally those that reach flashover in a compartment or room some distance from the people. The vast majority of fires that attain flashover generate dangerous levels of carbon monoxide, independent of what is burning. The supertoxicants, such as hydrogen cyanide and neurotoxin, have been proven to be extremely rare, even in the laboratory. These factors impact the choice of test furnace and the adjustment methods used in a standardized toxicity test.

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. 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 endurance 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 E119 fire-test exposures. Charring into the depth of the wood then proceeds at a rate of approximately 0.8 mm/min for the next 8 min (or 1.25 min/mm). Thereafter, the char layer has an insulating effect, and the rate decreases to 0.6 mm/min (1.6 min/mm). 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 (or 1.5 in/h) (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. 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 the 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), and x_c is char depth (mm) is assumed:

$$t = Cx_c \tag{17–1}$$

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 been developed. Equations relating charring rate under ASTM E119 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

$$C = (0.002269 + 0.00457\mu)\rho + 0.331 \text{ for Douglas Fir} \tag{17–2a}$$

$$C = (0.000461 + 0.00095\mu)\rho + 1.016 \text{ for Southern Pine} \tag{17–2b}$$

$$C = (0.001583 + 0.00318\mu)\rho + 0.594 \text{ for White Oak} \tag{17–2c}$$

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

Table 17–4. Charring rate data for selected wood species

		Wood exposed to ASTM E119 exposure[a]				Wood exposed to a constant heat flux[b]					
						Linear charring rate[e] (min/mm)		Thermal penetration depth d[g] (mm)		Average mass loss rate (g/m^2 s)	
Species	Density[c] (kg/m^3)	Char contraction factor[d]	Linear charring rate[e] (min/mm)	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 E906 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 (17–3).

[g] As defined in Equation (17–6). Not sensitive to moisture content.

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

$$t = m x_c^{1.23} \tag{17–3}$$

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

Based on data from eight species (Table 17–4), the following equation was developed for the char rate coefficient:

$$m = -0.147 + 0.000564\rho + 1.21\mu + 0.532 f_c \tag{17–4}$$

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 17–4.

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 E119 have been limited. Data for exposure to constant temperatures of 538°C, 815°C, and 927°C are available in Schaffer (1967). Data for a constant heat flux are given in Table 17–4.

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. Moisture is driven into the wood as charring progresses. A moisture content peak is created inward from the char base. The peak moisture content occurs where the temperature of the wood is about 100°C, which is at about 13 mm from the char base.

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

$$T = T_i + (300 - T_i)(1 - x/d)^2 \tag{17–5}$$

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 17–4, 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.

Flame-Retardant Treatments

To meet building code and standards specifications, lumber and plywood are treated with flame retardants to improve their fire performance. The two general application methods are pressure treating and surface coating.

Fire-Retardant-Treated Wood

To meet the specifications in the building codes and various standards, fire-retardant-treated lumber and plywood is wood that has been pressure treated with chemicals to reduce its flame spread characteristics. Flame-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 the 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.

The performance requirement for fire-retardant-treated wood is that its FSI is 25 or less when tested according to the ASTM E84 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. Underwriters Laboratories, Inc., assigns the designation FR–S to products that satisfy these requirements. In applications where the requirement is not for fire-retardant-treated wood but only for Class I or II flame spread, the flame-retardant treatments only need to reduce the FSI to the required level in the ASTM E84 flame spread test (25 for Class I, 75 for Class II). Various laboratories perform fire-performance rating tests on these treated materials and maintain lists of products that meet certain standards.

Fire-retardant-treated wood and plywood are often used for interior finish and trim in rooms, auditoriums, and corridors where codes require materials with low surface flammability. While fire-retardant-treated wood is not considered a noncombustible material, many codes have accepted the use of fire-retardant-treated wood and plywood in fire-resistive and noncombustible construction for the framing of nonload-bearing walls, roof assemblies, and decking. 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.

In addition to specifications for flame spread performance, fire-retardant-treated wood for use in certain applications is specified to meet other performance requirements. Wood treated with inorganic flame-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. The American Wood Preservers' Association (AWPA) Standards C20 and C27 requirements for low hygroscopicity (Interior Type A treatment) stipulate that the material shall have an equilibrium moisture content of not more than 28% when tested in accordance with ASTM D3201 procedures at 92% relative humidity.

Exterior flame-retardant treatments should be specified whenever the wood is exposed to exterior weathering conditions. The AWPA Standards C20 and C27 also mandate that an exterior type treatment is one that has shown no increase in fire hazard classification after being subjected to the rain test specified in ASTM D2898 as Method A.

For structural applications, information on the fire-retardant-treated wood product needs to be obtained from the treater or chemical supplier. This includes the design modification factors for initial strength properties of the fire-retardant-treated wood, including values for the fasteners. Flame-retardant treatment generally results in reductions in the mechanical properties of wood. Fire-retardant-treated wood is often more brash than untreated wood.

In field applications with elevated temperatures, such as roof sheathings, there is the potential for further losses in strength with time. For such applications in elevated temperatures and high humidity, appropriate design modification factors need to be obtained from the treater or chemical supplier. The AWPA Standards C20 and C27 mandate that fire-retardant-treated wood that will be used in high-temperature applications (Interior Type A High Temperature), such as roof framing and roof sheathing, be strength tested in accordance with ASTM D5664 (lumber) or ASTM D5516 (plywood) or by an equivalent methodology. Some flame-retardant treatments are not acceptable because of thermal degradation of the wood that will occur with time at high temperatures. Screw-withdrawal tests to predict residual in-place strength of fire-retardant-treated plywood roof sheathing have been developed (Winandy and others 1998).

Corrosion of fasteners can be accelerated under conditions of high humidity and in the presence of flame-retardant salts.

For flame-retardant treatments containing inorganic salts, the type of metal and chemical in contact with each other greatly affects 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.

Flame-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 endurance of these doors and walls. Most of this improvement is associated with the reduction in surface flammability rather than any changes in charring rates.

Flame-Retardant Pressure Treatments

In the 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 flame-retardant protection. Standards C20 and C27 of the AWPA recommend the treating conditions for lumber and plywood. The penetration of the chemicals into the wood depends on the species, wood structure, and moisture content. Since some species are difficult to treat, the degree of impregnation needed to meet the performance requirements for fire-retardant-treated wood may not be possible. One option is to incise the wood prior to treatment to improve the depth of penetration.

Inorganic salts are the most commonly used flame 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. These 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. Many commercial formulations are available. The AWPA Standard P17 provides information on formulations of some current proprietary waterborne treatments. The fire-retardant salts are water soluble and are leached out in exterior applications or with repeated washings. Water-insoluble organic flame 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 flame retardants attached directly to cellulose. An amino resin system based on urea, melamine, dicyandiamide, and related compounds is of the first type.

Flame-Retardant Coatings

For some applications, the alternative method of applying the flame-retardant chemical as a coating to the wood surface may be acceptable. Such 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 the 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.

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