

Wood-Based Composite Materials

Panel Products, Glued-Laminated Timber, Structural Composite Lumber, and Wood–Nonwood Composite Materials

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The term composite is being used in this chapter to describe any wood material adhesively bonded together. Wood-based composites encompass a range of products, from fiberboard to laminated beams. Wood-based composites are used for a number of nonstructural and structural applications in product lines ranging from panels for interior covering purposes to panels for exterior uses and in furniture and support structures in buildings (Fig. 11–1). Maloney (1986) proposed a classification system to logically categorize the array of wood-based composites. The classification in Table 11-1 reflects the latest product developments.

The basic element for wood-based composites is the fiber, with larger particles composed of many fibers. Elements used in the production of wood-based composites can be made in a variety of sizes and shapes. Typical elements include fibers, particles, flakes, veneers, laminates, or lumber. Figure 11–2 shows the variation and relative size of wood elements. Element size and geometry largely dictate the product manufactured and product performance. Performance standards are in place for many conventional wood-based composite products (Table 11–2).

A variety of wood sources are appropriate for use in wood-based composites. Wood with localized defects (such as knots) can often be used effectively in wood-based composites. Reducing wood with defects to wood elements mitigates the influence of these characteristics in the manufactured products. Recovered wood from construction waste or industrial manufacturing processes, and wood derived from small-diameter timber, forest residues, or exotic and invasive species, may also be effectively used in wood-based composites. Because natural wood properties vary among species, between trees of the same species, and between pieces from the same tree, solid wood cannot match composite products in the uniformity and range of properties that can be controlled.

Table 11–1. Classification of wood-based composites^a**Veneer-based material**

Plywood
Laminated veneer lumber (LVL)
Parallel-strand lumber (PSL)

Laminates

Glue-laminated timbers
Overlaid materials
Laminated wood–nonwood composites^b
Multiwood composites (COM-PLY^c)

Composite material

Fiberboard (low-, medium-, or high-density)
Cellulosic fiberboard
Hardboard
Particleboard
Waferboard
Flakeboard
Oriented strandboard (OSB)
Laminated strand lumber (LSL)
Oriented strand lumber (OSL)

Wood–nonwood composites

Wood fiber–polymer composites
Inorganic-bonded composites

^aAdapted from Maloney (1986).

^bPanels or shaped materials combined with nonwood materials such as metal, plastic, and fiberglass.

^cRegistered trademark of APA–The Engineered Wood Association.

Scope

This chapter gives an overview of the general types and composition of wood-based composite products and the materials and processes used to manufacture them. It describes conventional wood-based composite panels and structural composite materials intended for general construction, interior use, or both. This chapter also describes wood–nonwood composites. Mechanical properties of these types of composites are presented and discussed in Chapter 12. Because wood-based composites come in a variety of forms, we briefly describe several of the most common commercial products.

This chapter is organized into three sections. The first section covers conventional wood-based composite panels. Materials, adhesives, and additives common to conventional wood-based composites are summarized. Specific products addressed include panel products such as plywood, oriented strandboard, particleboard, and fiberboard. Specialty composites are also discussed. The second section covers structural composite lumber, including glued-laminated timber, laminated veneer lumber, parallel strand lumber, laminated strand lumber, and oriented strand lumber. Wood–nonwood composites are discussed in the third section, including inorganic-bonded composites and wood–thermo-plastic composites. Books have been written about each of



Figure 11–1. Wood-based composites used in the new Centennial Research Facility at the Forest Products Laboratory. Glulam timbers support composite I-joists and plywood sheathing. (Photo by Steve Schmieding, Forest Products Laboratory.)

these categories, and the constraints of this chapter necessitate that the discussion be general and brief. References are provided for more detailed information.

Conventional Wood-Based Composite Panels

Conventional wood-based composites are manufactured products made primarily from wood with only a few percent resin and other additives. A useful way to classify conventional wood-based composites based on specific gravity, density, raw material, and processing methods is shown in Figure 11–3, which presents an overview of the most common types of commercial panel products discussed in this chapter and a quick reference to how these composite materials compare with solid wood from the standpoint of density and general processing considerations. The raw material classifications of fibers, particles, and veneers are shown on the left y-axis. Specific gravity and density are shown on the top and bottom horizontal axes (x-axes), respectively. The right y-axis, wet and dry processes, describes in general terms the processing method used to produce a particular product. Selection of wood elements, adhesives, and processing techniques all contribute to product performance. Figure 11–4 shows examples of some commercial wood-based composites.

Elements

The primary component of wood-based composites is the wood element, often 94% or more by mass. Common elements for conventional wood-based composites include veneers, strands, particles, and fibers. The physical characteristics of common elements can be seen in Figure 11–5. Properties of composite materials can be changed by changing the size and geometry of the elements and by combining, reorganizing, or stratifying elements.

Table 11–2. Commercial product or performance standards for wood-based composites

Product category	Applicable standard	Name of standard	Source
Plywood	PS 1–07	Voluntary product standard PS 1–07 construction and industrial plywood	NIST 2007
	PS 2–04	Voluntary product standard PS 2–04 performance standard for wood-based structural-use panels	NIST 2004
	HP–1–2004	Voluntary product standard HP–1–2004 hardwood and decorative plywood	HPVA 2004
Oriented strandboard (OSB)	PS 2–04	Voluntary product standard PS 2–04 performance standard for wood-based structural-use panels	NIST 2004
Particleboard	ANSI A 208.1–2009	Particleboard standard	CPA 2009a
Fiberboard	ANSI A 208.2–2009	MDF standard	CPA 2009b
	ANSI A 135.4–2004	Basic hardboard	CPA 2004a
	ANSI A 135.5–2004	Pre-finished hardboard paneling	CPA 2004b
	ANSI A 135.6–2006	Hardboard siding	CPA 2006
	ASTM C 208–08a	Cellulosic fiberboard	ASTM 2008c
Glued-laminated timber (glulam)	ANSI/AITC 190.1	American National Standard for Wood Products—structural glued-laminated timber	AITC 2007a
Structural composite lumber (including laminated veneer lumber (LVL), laminated strand lumber (LSL), and parallel strand lumber (PSL))	ASTM D 5456–07	Standard specification for evaluation of structural composite lumber products	ASTM 2008b

Adhesives

Bonding in most conventional wood-based composites is provided by thermosetting (heat-curing) adhesive resins. Chapter 9 provides a more thorough discussion of thermoset adhesive resins. Commonly used resin–binder systems include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, and isocyanate.

Phenol-Formaldehyde

Phenol-formaldehyde (PF) resins are typically used in the manufacture of construction plywood and oriented strandboard where exposure to weather during construction is a concern. Other moisture exposure situations, such as temporary weather exposure, occasional plumbing leaks, or wet foot traffic, may also necessitate the use of PF resins. PF resins are commonly referred to as phenolic resins. Phenolic resins are relatively slow-curing compared with other thermosetting resins. In hot-pressed wood-based composites, use of phenolic resin necessitates longer press times and higher press temperatures. Hot-stacking of pressed material shortly after emergence from the press is a fairly common

industrial practice, used to attain adequate resin cure without greatly extending press time. Significant heat exposure associated with pressing of phenolic-bonded composites commonly results in a noticeable reduction in their hygroscopicity. Cured phenolic resins remain chemically stable at elevated temperatures. Their bonds also are sometimes referred to as being “boil-proof” because of their ability to maintain composite dimensional and mechanical properties under wet conditions. The inherently darker color of PF resin compared with other resins may make them aesthetically unsuitable for product applications such as interior paneling and furniture.

Urea-Formaldehyde

Urea-formaldehyde (UF) resins are typically used in the manufacture of products used in interior applications, primarily particleboard and medium-density fiberboard (MDF), because moisture exposure leads to a breakdown of the bond-forming reactions. Excessive heat exposure will also result in chemical breakdown of cured UF resins, therefore UF-bonded panels are typically cooled after emergence

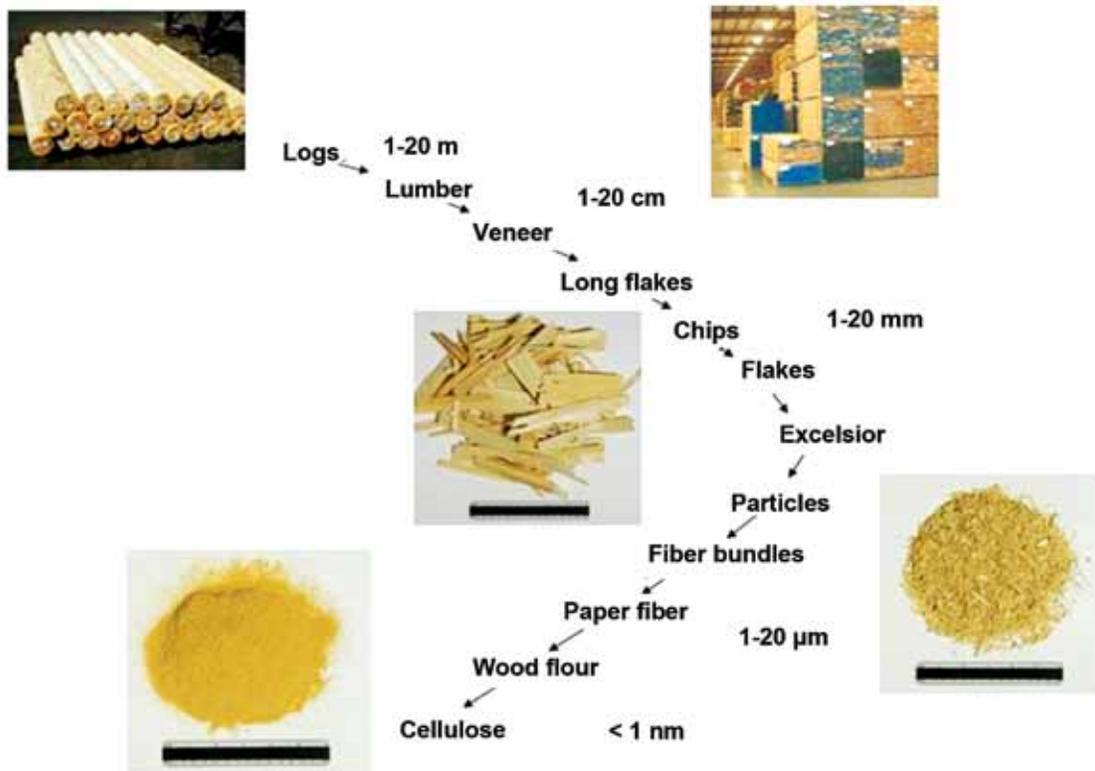


Figure 11-2. Basic wood elements, from largest to smallest (Kretschmann and others 2007).

from the press. Advantages of UF resins include lower curing temperatures than PF resins and ease of use under a variety of curing conditions. UF resins are the lowest cost thermosetting adhesive resins. They offer light color, which often is a requirement in the manufacture of decorative products. However, the release of formaldehyde from products bonded with UF is a growing health concern.

Melamine-Formaldehyde

Melamine-formaldehyde (MF) resins are used primarily for decorative laminates, paper treating, and paper coating. They are typically more expensive than PF resins. MF resins may, despite their high cost, be used in bonding conventional wood-based composites. MF resins are often used in combination with UF. MF-UF resins are used when an inconspicuous (light color) adhesive is needed and when greater water resistance than can be attained with UF resin is required.

Isocyanates

The isocyanate wood adhesive is a polymeric methylene diisocyanate (pMDI). It is used as an alternative to PF resin, primarily in composite products fabricated from strands. pMDI resins are typically more costly than PF resins but have more rapid cure rates and will tolerate higher moisture contents in the wood source. pMDI resin is sometimes used in core layers of strand-based composites, with slower-curing PF resin used in surface layers. Facilities that use

pMDI are required to take special precautionary protective measures because the uncured resin can result in chemical sensitization of persons exposed to it. Cured pMDI resin poses no recognized health concerns.

Bio-Based Adhesives

Bio-based adhesives, primarily protein glues, were widely used prior to the early 1970s in construction plywood. In the mid-1970s, they were supplanted by PF adhesives, on the basis of the superior bond durability provided by phenolics. The move toward “green” products has led to a renewed interest in bio-based adhesives. Several soy-protein-based resin systems, with bond durabilities similar to those provided by PF resins, have recently been developed and commercialized. Durable adhesive systems may also be derived from tannins or from lignin. Tannins are natural phenol compounds that are present in the bark of a number of tree species. The tannins can be extracted from bark, modified, and reacted with formaldehyde to produce an intermediate polymer that is a satisfactory thermosetting adhesive. Lignin-based resins have also been developed from spent pulping liquor, which is generated when wood is pulped for paper or chemical feedstocks. In the manufacture of wet-process fiberboard, lignin, which is an inherent component of lignocellulosic material, is frequently used as binder (Suchsland and Woodson 1986), although “natural” lignin bonding is sometimes augmented with small amounts of PF resin.

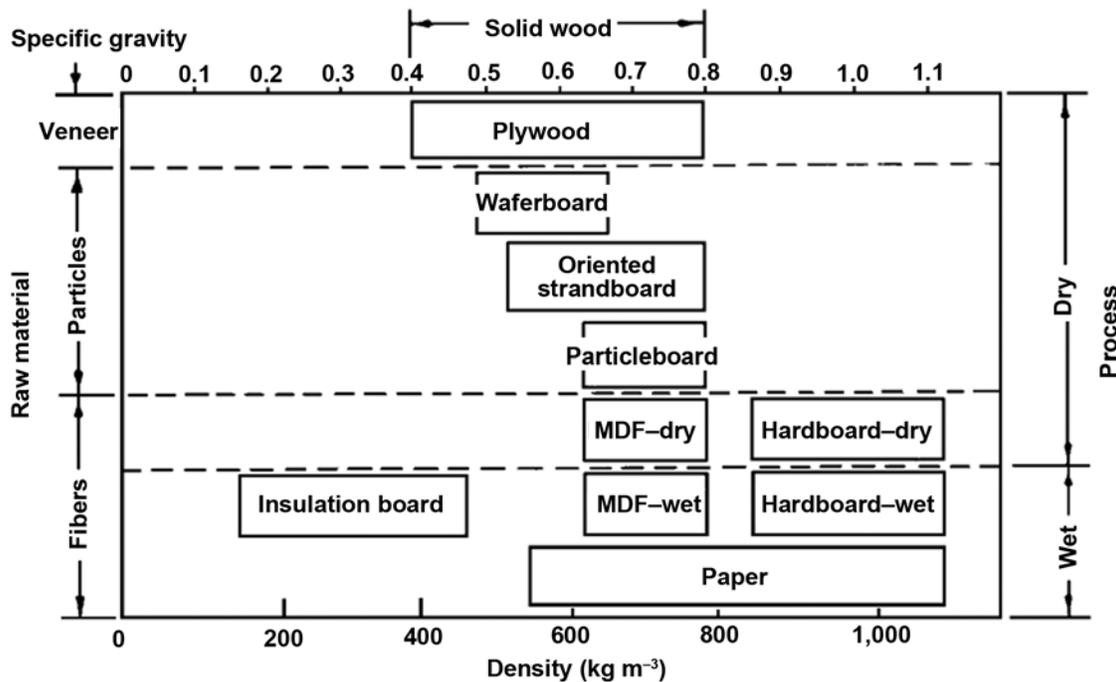


Figure 11–3. Classification of wood composite panels by particle size, density, and process (Suchsland and Woodson 1986). Note that insulation board is now known as cellulosic fiberboard.

Resin Choice

Often a particular resin will dominate for a particular product, but each has its advantages. Factors taken into account include materials to be bonded together, moisture content at time of bonding, mechanical property and durability requirements of the composite products, anticipated end-use of the product, and resin system costs.

PF, UF, and pMDI resins systems are expected to remain the dominant adhesives used for bonded wood-based composites. However, cost and reliable availability of petrochemicals may affect the relative predominance of PF, UF, and pMDI adhesives versus bio-based adhesives. More stringent regulation concerning emissions from formaldehyde-containing products (driven by concern over indoor air quality) may affect the continued commercial predominance of UF resin in interior products. For example, the California Air Resources Board (CARB) has established formaldehyde emission standards that cover hardwood plywood, particleboard, and MDF. As a result, bio-based adhesive and resin systems may gain market share compared with petroleum-based synthetic resins.

Additives

A number of additives are used in the production of conventional composite products. The most common additive is wax, which is used to provide products with some resistance to liquid water absorption. In flake-, particle-, and fiberboard products, wax emulsions provide limited-term

water resistance and dimensional stability when the board is wetted. Even small amounts (0.5% to 1%) act to retard the rate of liquid water pickup for limited time periods. These improved short-term water penetration properties are important for ensuring the success of subsequent secondary gluing operations and for providing protection upon accidental wetting of the product during and after construction. The addition of wax has practically no effect on water vapor sorption or dimensional changes associated with changes in humidity. Other additives used for specialty products include preservatives, moldicides, and fire retardants. Composites containing additives are more thoroughly discussed in the section on Specialty Composite Materials.

Plywood

Plywood is a panel product built up wholly or primarily of sheets of veneer called plies. It is constructed with an odd number of layers with the grain direction of adjacent layers oriented perpendicular to one another. A layer can consist of a single ply or of two or more plies laminated with their grain direction parallel. A panel can contain an odd or even number of plies but always an odd number of layers. The outside plies are called faces, or face and back plies. Inner plies are plies other than the face or back plies. The outer layers and all odd-numbered layers have their grain direction oriented parallel to the long dimension of the panel. The grain in even-numbered layers is perpendicular to the length of the panel. Inner plies whose grain direction runs parallel to that of the faces are termed “centers” whereas inner plies

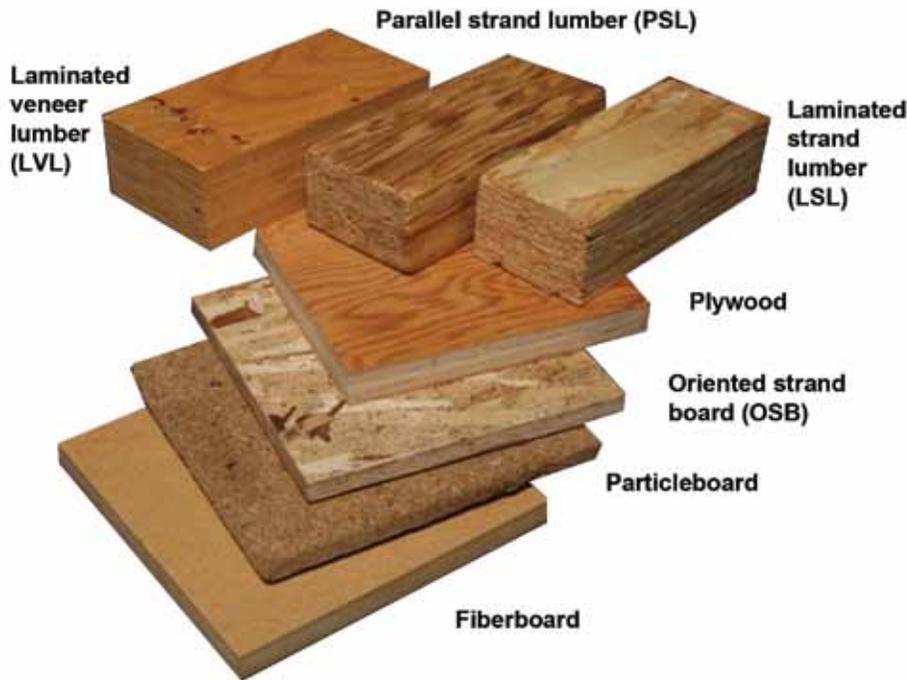


Figure 11–4. Examples of various composite products. From top left, clockwise: LVL, PSL, LSL, plywood, OSB, particleboard, and fiberboard.



Figure 11–5. Common wood elements used in wood-based composites from top left, clockwise: shavings, sawdust, fiber, large particles, wafers, and strands.

whose grain direction runs perpendicular to that of the faces are termed “crossbands.” To distinguish the number of plies (individual sheets of veneer in a panel) from the number of layers (number of times the grain orientation changes), panels are sometimes described as three-ply, three-layer or four-ply, three-layer, etc. The center layer may be veneer, lumber, particleboard, or fiberboard; however, all-veneer construction is most common in construction and industrial plywood.

Plywood panels are used in various applications, including construction sheathing, furniture, and cabinet panels.

Plywood is also used as a component in other engineered wood products and systems in applications such as prefabricated I-joists, box beams, stressed-skin panels, and panelized roofs.

Characteristics

The properties of plywood depend on the quality of the veneer plies, the order of layers, the adhesive used, and the degree to which bonding conditions are controlled during production. The durability of the adhesive-to-wood bond depends largely on the adhesive used but also on control of bonding conditions and on veneer quality. The grade of the panel depends upon the quality of the veneers used, particularly of the face and back.

Plywood panels have significant bending strength both along the panel and across the panel, and the differences in strength and stiffness along the panel length versus across the panel are much smaller than those differences in solid wood. Plywood also has excellent dimensional stability along its length and across its width. Minimal edge-swelling makes plywood a good choice for adhesive-bonded tongue-and-groove joints, even where some wetting is expected. Unlike most panels fabricated from particles, it undergoes minimal irreversible thickness swelling if wetted. The alternating grain direction of its layers makes plywood resistant to splitting, allowing fasteners to be placed very near the edges of a panel. In uses where internal knotholes and voids may pose a problem, such as in small pieces, plywood can be ordered with a solid core and face veneers.

Classes of Plywood

Two classes of plywood are commonly available, covered by separate standards: (a) construction and industrial plywood and (b) hardwood and decorative plywood.

Most construction and industrial plywood used in the United States is produced domestically, and U.S. manufacturers export some material. The bulk of construction and industrial plywood is used where performance is more important than appearance. However, some grades of construction and industrial plywood are made with faces selected primarily for appearance and are used either with clear natural finishes or lightly pigmented finishes. Construction and industrial plywood has traditionally been made from softwoods such as Douglas-fir and southern yellow pine. However, true firs, western hemlock, and western pines are also used (Bowyer and others 2007). A large number of hardwoods qualify for use under the standard. PF resin is the primary adhesive type used in construction and industrial plywood. Construction and industrial plywood is categorized by exposure capability and grade using Voluntary Product Standard PS 1-07 (NIST 2007).

Hardwood and decorative plywood is made of many different species, both in the United States and overseas. Well over half of all panels used in the United States are imported. Hardwood plywood is normally used in applications including decorative wall panels and furniture and cabinet panels where appearance is more important than strength. Most of the production is intended for interior or protected uses, although a very small proportion is made with adhesives suitable for exterior service, such as in marine applications. A substantial portion of all hardwood plywood is available completely finished. Hardwood and decorative plywood is categorized by species and characteristics of face veneer, bond durability, and composition of center layers (veneer, lumber, particleboard, MDF, or hardboard) (HP-1-2004, HPVA 2004).

Exposure Capability

Construction and industrial plywood is classified as either Exposure 1 or Exterior in Voluntary Product Standard PS 1-07 (NIST 2007). Exposure 1 plywood is intended for applications not permanently exposed to weather, whereas Exterior plywood is suitable for repeated wetting and drying, or long-term exposure to weather. Bond quality of plywood of either bond classification (Exposure 1 or Exterior) is evaluated by the same test procedure, but a higher level of performance in the test procedure is required for Exterior plywood. The test procedure involves water saturation, boiling, and high-temperature exposure (in excess of boiling temperature). The majority of construction and industrial plywood sold in North America is of Exposure 1 classification. Exposure 1 panels may undergo rain-wetting during building construction but will be protected from wetting after the building is enclosed.

Two exposure classes of hardwood and decorative plywood are recognized by ANSI/HPVA HP-1-2004, Exterior and Interior. The standard actually lists two different Exterior classes, Technical and Type I, but the bond performance requirements for these classes, as determined by test procedures outlined in the standard, are the same.

Plywood Grades

Plywood grades may indicate the intended use, a type of surface treatment, or the grades of the face and back veneers, and in some cases, a combination of these. Agencies that provide quality certification services for plywood mills have coined their own trademarked grade names for specified end uses through proprietary product standards. Grade stamps are used to identify plywood products (Figs. 11-6 and 11-7). An example of plywood CARB third-party identification is also shown in Figure 11-7.

Veneer quality is a factor in construction and industrial plywood based on visually observable characteristics. Knots, decay, splits, insect holes, surface roughness, number of surface repairs, and other defects are considered. Veneer species and characteristics are also a major factor in categorization of hardwood and decorative plywood.

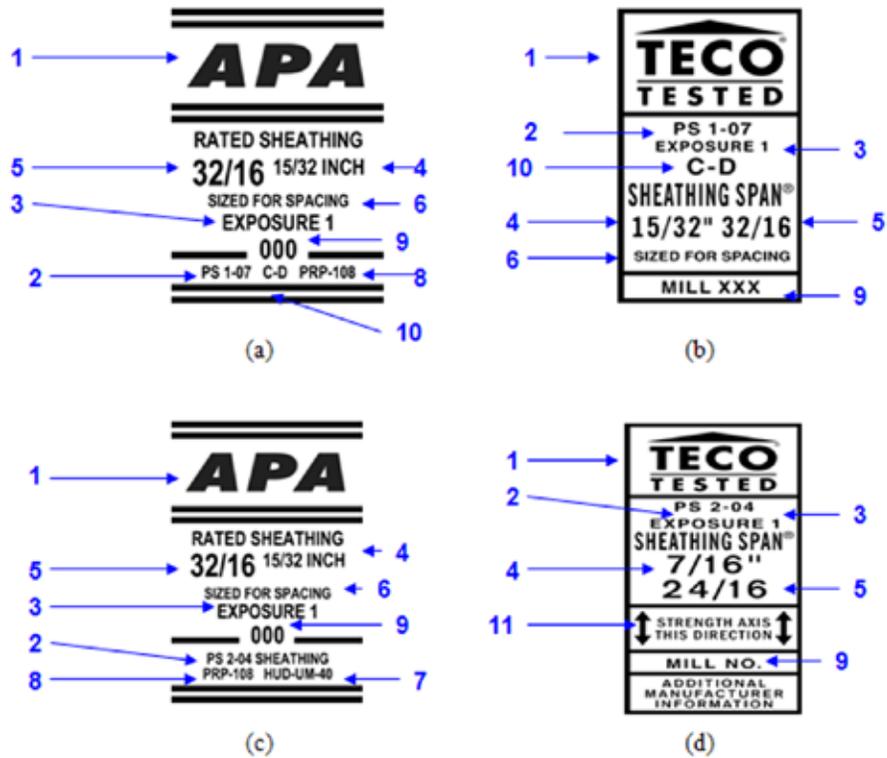
Specialty Plywood Panels

Plywood is easily pressure-treated with waterborne preservatives and fire retardants. Because plywood is not prone to irreversible thickness swelling, its bond integrity is unaffected by pressure treatment with waterborne chemicals. Treatment is typically performed by commercial entities specializing in treatment rather than by the plywood manufacturer. Treatments for plywood have been standardized (AWPA 2007a,b). This allows specification by reference to a commercial standard. Special grades of plywood are produced for specific uses such as boat construction, concrete form work, or special exterior applications such as highway signage.

Oriented Strandboard

Oriented strandboard (OSB) is an engineered structural-use panel manufactured from thin wood strands bonded together with water-resistant resin, typically PF or pMDI. It is used extensively for roof, wall, and floor sheathing in residential and commercial construction. The wood strands typically have an aspect ratio (strand length divided by width) of at least 3. OSB panels are usually made up of three layers of strands, the outer faces having longer strands aligned in the long-direction of the panel and a core layer that is counter-aligned or laid randomly using the smaller strands or fines. The orientation of different layers of aligned strands gives OSB its unique characteristics, including greater bending strength and stiffness in the oriented or aligned direction. Control of strand size, orientation, and layered construction allows OSB to be engineered to suit different uses.

OSB technology and the raw material used originally evolved from waferboard technology, for which aspen was



- 1) Third-party inspection agency
- 2) Conformance to indicated product standard
- 3) Exposure durability classification
- 4) Thickness
- 5) Span rating
- 6) Denotes panels that have been sized to allow for spacing of panel edges during installation to reduce the possibility of buckling
- 7) Recognition as a quality assurance agency
- 8) Performance rated panel standard indicating structural-use panel test procedures
- 9) Manufacturing mill identification number
- 10) Grade of face and core veneers
- 11) Strength axis (OSB only)

Figure 11-6. Typical grade stamps for plywood and OSB. (Courtesy of TECO, Sun Prairie, Wisconsin, and APA-The Engineered Wood Association, Tacoma, Washington. Used by permission.)

the predominant wood species used. As the industry learned to control strand size, placement, and orientation, the performance and utility of OSB products improved to the point that their performance was similar to that of structural plywood. As a result, product acceptance and the industry expanded as OSB began to replace softwood plywood in construction applications.

Raw Materials

In North America, aspen is the predominant wood used for OSB. Species other than aspen, such as Southern Pine, spruce, birch, yellow-poplar, sweetgum, sassafras, and beech, are also suitable raw materials for OSB production. High-density species such as beech and birch are often mixed with low-density species such as aspen to maintain panel properties (Bowyer and others 2007).

Manufacturing Process

To manufacture OSB, debarked logs are sliced into long, thin wood elements called strands. The strands are dried, blended with resin and wax, and formed into thick, loosely consolidated mats that are pressed under heat and pressure into large panels. Figure 11-8 shows an OSB manufacturing process. A more detailed description of each individual manufacturing step follows.

During stranding, logs are debarked and then sent to a soaking pond or directly to the stranding process. Long log disk or ring stranders are commonly used to produce wood strands typically measuring 114 to 152 mm (4.5 to 6 in.) long, 12.7 mm (0.5 in.) wide, and 0.6 to 0.7 mm (0.023 to 0.027 in.) thick. Green strands are stored in wet bins and dried in a traditional triple-pass dryer, a single-pass dryer, a

<p>FORMALDEHYDE EMISSION 0.05 PPM MEETS CARB ATCM PHASE 2 REQUIREMENTS</p> <p>2 →</p> <p>LAY UP 16 3.6 MM THICK HP-SG-96</p> <p>3 ↗</p>	<p>SIMULATED ← 4 DECORATIVE FINISH ON PLYWOOD</p> <p>1 ↙</p>  <p>5 → MILL 000 SPECIALTY GRADE ← 6</p>	<p>FLAME SPREAD CLASS C 200 OR LESS ASTM E84 ← 7</p> <p>BOND LINE TYPE II ← 8 ANSI/HPVA HP-1-2004 ← 9</p>
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DESIGNATION KEY

1. **HPVA Laboratory Registered Trademark** - Hardwood Plywood & Veneer Association; CARB TPC-8.
2. **Formaldehyde Emissions Classification** - in accordance with *ASTM E1333 Standard Test Method for Determining Formaldehyde Concentrations in Air and Emissions Rates from Wood Products Using a Large Chamber*. Demonstrates compliance below California Air Resource Board (CARB), U.S. Department of Housing and Urban Development (HUD), and other approved regulations and standards on air emissions
3. **Structural Layup Description** – meets structural panel attributes as outlined in HPVA design guide *HP-SG-96, Structural Design Guide for Hardwood Plywood Wall Panels*
4. **Face Species or Finish Type** (not required for specialty or simulated finishes)
5. **HPVA Mill Number**
6. **Face/Back Veneer Grade** (grade of back follows face for industrial panels and is optional for specialty grade panels)
7. **Flame Spread Index Classification** - in accordance with *ASTM E84 Standard Test Method for Surface Burning Characteristics of Building Materials*
8. **Plywood Bond Line Type** – Type I (interior), Type II (exterior)
9. **ANSI/HPVA HP-1-2004** - Standard Governing Manufacture

SAMPLE HPVA TPC-8 CARB Certification Label:

HARDWOOD PLYWOOD & VENEER ASSOCIATION	
 <p>ARB TPC-8 MILL 000</p> <p>COMPANY NAME LOCATION</p> <p>PRODUCT LOT NUMBER:</p>	<p>INDUSTRIAL HARDWOOD PLYWOOD <u>ARB TPC-8 Certified</u></p> <hr/> <p>MEETS CARB ATCM</p> <p>FORMALDEHYDE EMISSIONS PHASE 2 0.05 PPM</p>

Figure 11–7. Typical grade stamps for hardwood plywood. (Courtesy of Hardwood Plywood & Veneer Association, Reston, Virginia. Used by permission.)

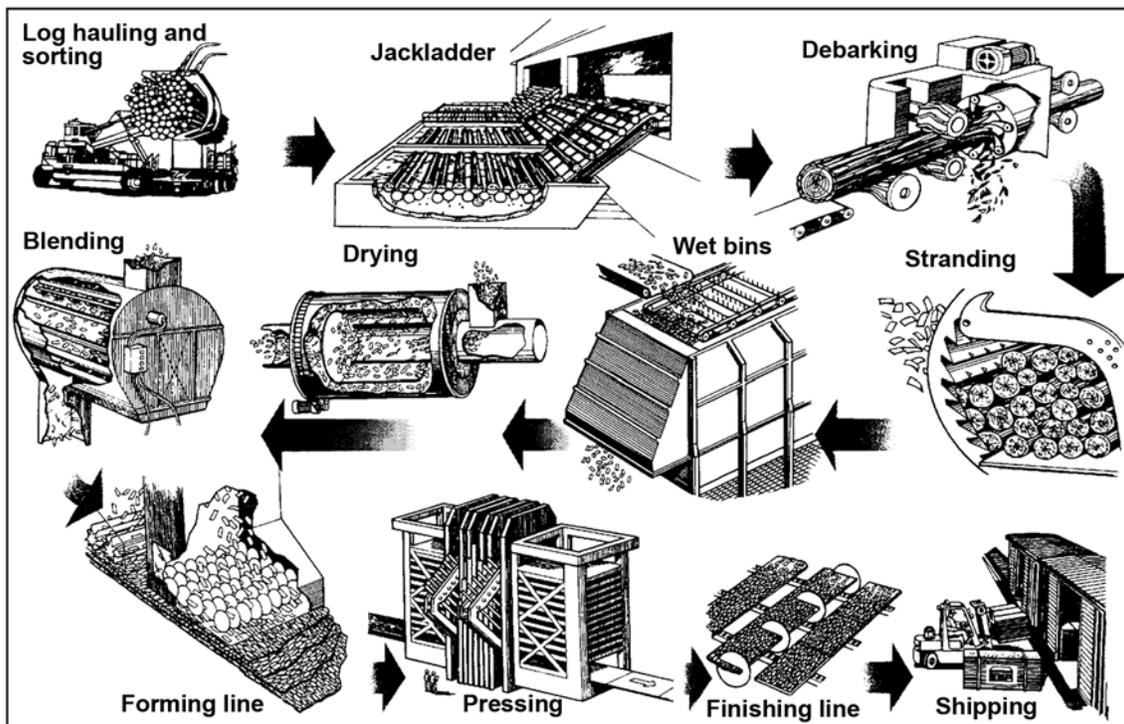


Figure 11-8. Schematic of OSB manufacturing process. (Courtesy of TECO, Sun Prairie, Wisconsin. Used by permission.)

combination triple-pass/single-pass dryer, or a three-section conveyor dryer. A recent development is a continuous chain dryer, in which the strands are laid on a chain mat that is mated with an upper chain mat and the strands are held in place as they move through the dryer. New drying techniques allow the use of longer strands, reducing surface inactivation of strands, and lowering dryer outfeed temperatures. Dried strands are screened and sent to dry bins.

Dried strands are blended with adhesive and wax in a highly controlled operation, with separate rotating blenders used for face and core strands. Typically, different resin formulations are used for face and core layers. Face resins may be liquid or powdered phenolics, whereas core resins may be phenolics or isocyanates. Several different resin application systems are used; spinning disk resin applicators are the most common.

The strands with adhesive applied are sent to mat formers. Mat formers take on a number of configurations, ranging from electrostatic equipment to mechanical devices containing spinning disks to align strands along the panel's length and star-type cross-orienters to position strands across the panel's width. All formers use the long and narrow characteristic of the strand to place it between spinning disks or troughs before it is ejected onto a moving screen or conveyor belt below the forming heads. Oriented layers of strands within the mat are dropped sequentially onto a moving conveyor. The conveyor carries the loose, layered mat into the press.

Once the mat is formed, it is hot-pressed. Hot-pressing consolidates the mat by heating it at 177 to 204 °C (350 to 400 °F), which cures the resin in 3–5 minutes. As many as sixteen 3.7- by 7.3-m (12- by 24-ft) panels may be formed simultaneously in a multiple-opening press. A more recent development is the continuous press which presses the mat between rollers as it is conveyed.

OSB Grade Marks and Product Certification

OSB that has been grade marked is manufactured to comply with voluntary industry product performance standards. Inspection or certification programs also generally require that the quality control system of a production plant meet specified criteria. OSB panels conforming to product performance standards are marked with grade stamps (Fig. 11-6).

Particleboard

Particleboard is produced by mechanically reducing the wood raw material into small particles, applying adhesive to the particles, and consolidating a loose mat of the particles with heat and pressure into a panel product. The particleboard industry initially used cut flakes as a raw material. However, economic concerns prompted development of the ability to use sawdust, planer shavings, and to a lesser extent, mill residues and other waste materials. To manufacture particleboard with good strength, smooth surfaces, and equal swelling, manufacturers ideally use a homogeneous raw material.

Chapter 11 Wood-Based Composite Materials

Particleboard is typically made in layers. But unlike OSB, the faces of particleboard usually consist of fine wood particles and the core is made of coarser material. The result is a smoother surface for laminating, overlaying, painting, or veneering. Particleboard is readily made from virtually any wood material and from a variety of agricultural residues. Low-density insulating or sound-absorbing particleboard can be made from kenaf core or jute stick. Low-, medium-, and high-density panels can be produced with cereal straw, which has been used in North America. Rice husks are commercially manufactured into medium- and high-density products in the Middle East.

All other things being equal, reducing lignocellulosic materials to particles requires less energy than reducing the same material into fibers. However, particleboard is generally not as strong as fiberboard because the fibrous nature of lignocellulosics (that is, their high aspect ratio) is not exploited as well. Particleboard is widely used in furniture, where it is typically overlaid with other materials for decorative purposes. It is the predominant material used in ready-to-assemble furniture. Particleboard can also be used in flooring systems, in manufactured houses, and as underlayment. Thin panels can also be used as a paneling substrate. Since most applications are interior, particleboard is usually bonded with a UF resin, although PF and MF resins are sometimes used for applications requiring more moisture resistance.

Manufacturing Process

Manufacturing particleboard is a dry process. The steps involved in particleboard manufacturing include particle preparation, particle classification and drying, adhesive application, mat formation, pressing, and finishing.

Standard particleboard plants use combinations of hogs, chippers, hammermills, ring flakers, ring mills, and attrition mills to obtain particles. Particles are classified and separated to minimize negative effect on the finished product. Very small particles (fines) increase particle surface area and thus increase resin requirements. Oversized particles can adversely affect the quality of the final product because of internal flaws in the particles. While some particles are classified through the use of air streams, screen classification methods are the most common. In screen classification, the particles are fed over a vibrating flat screen or a series of screens. The screens may be wire cloth, plates with holes or slots, or plates set on edge. Particles are typically conveyed by mechanical means. Sometimes damp conditions are maintained to reduce break-up of particles during conveying.

Desirable particles have a high degree of slenderness (long, thin particles), no oversize particles, no splinters, and no dust. Depending on the manufacturing process and board

configurations, specifications for the ideal particle size are different. For a common three-layer board, core particles are longer and surface particles shorter, thinner, and smaller. For a five-layer board, the particles for the intermediate layer between surface and core are long and thin, which builds a good carrier for the fine surface and gives the boards high bending strength and stiffness. Particleboard used for quality furniture uses much smaller core particles. The tighter core gives a better quality edge which allows particleboard to compete more favorably with MDF.

The raw materials (or furnish) do not usually arrive at the plant at a low enough moisture content for immediate use. Furnish that arrives at the plant can range from 10% to 200% dry basis moisture content. For use with liquid resins, for example, the furnish must be reduced to about 2% to 7% moisture content. The moisture content of particles is critical during hot-pressing operations and depends on whether resin is to be added dry or as a solution or emulsion. The moisture content of materials leaving the dryers is usually in the range of 4% to 8%. The main methods used to dry particles are rotary, disk, and suspension drying. A triple-pass rotary dryer consists of a large horizontal, heated, rotating drum. Operating temperatures depend on the moisture content of the incoming furnish. The drum is set at a slight angle, and material is fed into the high end and discharged at the low end. A series of flights forces the furnish to flow from one end to the other three times before being discharged. The rotary movement of the drum moves the material from input to output.

Frequently used resins for particleboard include UF and, to a much lesser extent, PF, MF, and isocyanates. The type and amount of resin used for particleboard depends on the type of product desired. Based on the weight of dry resin solids and oven-dry weight of the particles, the overall resin content can range between 4% and 10%, but usually ranges between 6% and 9% for UF resins. The resin content of the outer layers is usually higher (about 8% to 15%) than that of the core (about 4% to 8%). UF resin is usually introduced in water solutions containing about 50% to 65% solids. Besides resin, wax is added to improve short-term moisture resistance. The amount of wax ranges from 0.3% to 1% based on the oven-dry weight of the particles.

After the particles have been prepared, they are laid into an even and consistent mat to be pressed into a panel. This is accomplished in batch mode or by continuous formation. The batch system traditionally employs a caul or tray on which a deckle frame is placed. The mat is formed by the back-and-forth movement of a tray or hopper feeder. The production of three-layer boards requires three or more forming stations.

In more common continuous mat-forming systems the particles are distributed in one or several layers on traveling

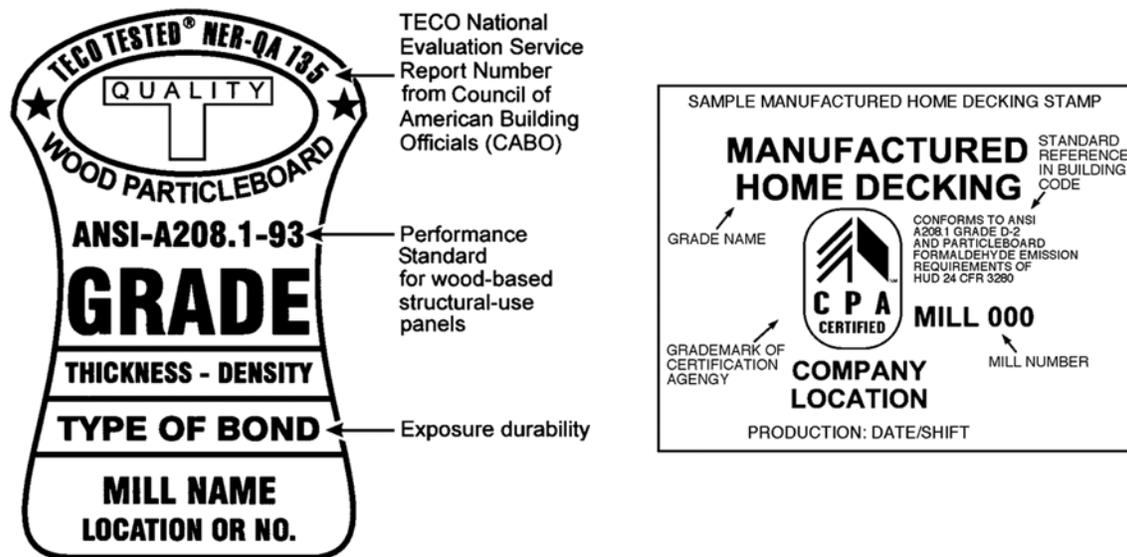


Figure 11-9. Examples of grade stamps for particleboard. (Courtesy of TECO, Sun Prairie, Wisconsin, and Composite Panel Association, Leesburg, Virginia. Used by permission.)

cauls or on a moving belt. Mat thickness is controlled volumetrically. Batch-formed or continuous-formed mats are often pre-pressed to reduce mat height and help consolidate the mat for pressing.

After pre-pressing, the mats are hot-pressed into panels. Presses can be divided into platen and continuous types. Further development in the industry has made possible the construction of presses for producing increasingly larger panel sizes in both single- and multi-opening presses. Both of these types of presses can be as wide as 3.7 m (12 ft). Multi-opening presses can be as long as 10 m (33 ft), and continuous presses, up to 30 m (100 ft) long.

After pressing, panels are trimmed to obtain the desired length and width and to square the edges. Trim losses usually amount to 0.5% to 8%, depending on the size of the panel, the process employed, and the control exercised. Trimmers usually consist of saws with tungsten carbide tips. After trimming, the panels are sanded or planed prior to packaging and shipping. Particleboards may also be veneered or overlaid with other materials to provide a decorative surface, or they may be finished with lacquer or paint. Treatments with fire-resistant chemicals are also available.

Particleboard Grade Marks and Product Certification

A grade mark on particleboard ensures that the product has been periodically tested for compliance with voluntary industry product performance standards. Inspection or certification programs also generally require that the quality control system of a production plant meets strict criteria. Particleboard panels conforming to these product performance standards are marked with grade stamps (Fig. 11-9).

Fiberboard

The term fiberboard includes hardboard, medium-density fiberboard (MDF), and cellulosic fiberboard. Several things differentiate fiberboard from particleboard, most notably the physical configuration of the wood element. Because wood is fibrous by nature, fiberboard exploits the inherent strength of wood to a greater extent than does particleboard.

To make fibers for composites, bonds between the wood fibers must be broken. Attrition milling, or refining, is the easiest way to accomplish this. During refining, material is fed between two disks with radial grooves. As the material is forced through the preset gap between the disks, it is sheared, cut, and abraded into fibers and fiber bundles. Refiners are available with single- or double-rotating disks, as well as steam-pressurized and unpressurized configurations.

Refining can be augmented by steaming or chemical treatments. Steaming the lignocellulosic weakens the lignin bonds between the cellulosic fibers. As a result, fibers are more readily separated and are usually less damaged than fibers processed by dry processing methods. Chemical treatments, usually alkali, are also used to weaken the lignin bonds. Although treatments help increase fiber quality and reduce energy requirements, they may also reduce yield and modify the fiber chemistry. For MDF, steam-pressurized refining is typical.

Fiberboard is normally classified by density and can be made by either dry or wet processes (Fig. 11-3). Dry processes are applicable to boards with high density (hardboard) and medium density (MDF). Wet processes are applicable to both high-density hardboard and low-density

cellulosic fiberboard. The following subsections briefly describe the manufacturing of high- and medium-density dry-process fiberboard, wet-process hardboard, and wet-process low-density cellulosic fiberboard. Suchsland and Woodson (1986) and Maloney (1993) provide more detailed information.

Dry-Process Fiberboard

Dry-process fiberboard is made in a similar fashion to particleboard. Resin (UF or MF–UF) and other additives are applied to the fibers by spraying in short-retention blenders or introduced as wet fibers are fed from the refiner into a blow-line dryer. Alternatively, some fiberboard plants add the resin in the refiner. The adhesive-coated fibers are then air-laid into a mat for subsequent pressing, much the same as mat formation for particleboard.

Pressing procedures for dry-process fiberboard differ somewhat from particleboard procedures. After the fiber mat is formed, it is typically pre-pressed in a band press. The densified mat is then trimmed by disk cutters and transferred to caul plates for the hardboard pressing operation; for MDF, the trimmed mat is transferred directly to the press. Many dry-formed boards are pressed in multi-opening presses. Continuous pressing using large, high-pressure band presses is also gaining in popularity. Panel density is constantly monitored by moisture sensors using infrared light as an indicator of panel quality.

MDF is frequently used in place of solid wood, plywood, and particleboard in many furniture applications. It is also used for interior door skins, mouldings, and interior trim components. ANSI A208.2 classifies MDF by physical and mechanical properties, and identifies dimensional tolerances and formaldehyde emission limits (CPA 2009b). An example of an MDF formaldehyde emissions certification tag is shown in Figure 11–10.

Wet-Process Hardboard

Wet-process hardboards differ from dry-process fiberboards in several significant ways. First, water is used as the fiber distribution medium for mat formation. The technology is really an extension of paper manufacturing technology. Secondly, some wet-process boards are made without additional binders. If the lignocellulosic contains sufficient lignin and if lignin is retained during the refining operation, lignin can serve as the binder. Under heat and pressure, lignin will flow and act as a thermosetting adhesive, enhancing the naturally occurring hydrogen bonds.

Refining is an important step for developing strength in wet-process hardboards. The refining operation must also yield a fiber of high “freeness” (that is, it must be easy to remove water from the fibrous mat). The mat is typically formed on a Fourdrinier wire, like papermaking, or on cylinder formers. The wet process employs a continuously traveling mesh screen, onto which the soupy pulp flows rapidly and

smoothly. Water is drawn off through the screen and then through a series of press rolls.

Wet-process hardboards are pressed in multi-opening presses heated by steam. The press cycle consists of three phases and lasts 6 to 15 min. The first phase is conducted at high pressure, and it removes most of the water while bringing the board to the desired thickness. The primary purpose of the second phase is to remove water vapor. The third phase is relatively short and results in the final cure. A maximum pressure of about 5 MPa (725 lb in⁻²) is used in the first and third phases. Heat is essential during pressing to induce fiber-to-fiber bond. A high temperature of up to 210 °C (410 °F) is used to increase production by causing faster vaporization of the water. Insufficient moisture removal during pressing adversely affects strength and may result in “springback” or blistering.

Wet-formed composite technology has lost market share compared with dry-formed technology over the past few decades because of processing speed and perceived environmental issues related to process water. However, wet-formed technology does offer unique opportunities for forming geometric shapes that yield enhanced structural performance and decrease weight, elimination of fiber drying prior to forming, and reduced need for adhesive resins. It also greatly increases the ability to use recovered paper and some other woody fibers. Recent advances in process wastewater recycling and remediation also bode well for wet-formed technologies. Wet-formed composite technology may become more important because of reduced energy demands, increased composite structural performance and decreased weight, and the virtual elimination of (or drastic reduction in) process water concerns.

Several treatments are used to increase dimensional stability and mechanical performance of hardboard. Heat treatment, tempering, and humidification may be done singularly or in conjunction with one another. Heat treatment—exposure of pressed fiberboard to dry heat—improves dimensional stability and mechanical properties, reduces water adsorption, and improves interfiber bonding. Tempering is the heat treatment of pressed boards, preceded by the addition of oil. Tempering improves board surface hardness, resistance to abrasion, scratching, scarring, and water. The most common oils used include linseed oil, tung oil, and tall oil. Humidification is the addition of moisture to bring the board moisture content to levels roughly equivalent to those anticipated in its end-use environment. Air of high humidity is forced through the stacks where it provides water vapor to the boards. Another method involves spraying water on the back side of the board. Typical hardboard products are prefinished paneling, house siding, floor underlayment, and concrete form board. A typical grade stamp for hardboard siding is shown in Figure 11–11.

Sample Bundle Tag for non-EPP MDF Certified to ANSI A208.2-2009.

**COMPLIES WITH ANSI A208.1-2009 AND
CALIFORNIA 93120 PHASE 1 FORMALDEHYDE
EMISSION LIMITS**



MILL 000

CALIFORNIA ARB APPROVED THIRD PARTY CERTIFIER TPC-1

**MANUFACTURER'S NAME
LOCATION
PRODUCTION SHIFT/CREW
PRODUCTION LOT/BATCH**

**Figure 11–10. Example of MDF formaldehyde emissions certification tag.
(Courtesy of Composite Panel Association, Leesburg, Virginia. Used by
permission.)**

Cellulosic Fiberboard

Cellulosic fiberboards are low-density, wet-laid panel products. In the manufacture of cellulosic fiberboard, the need for refining and screening is a function of the raw material available, the equipment used, and the desired end-product. Cellulosic fiberboards typically do not use a binder, and they rely on hydrogen bonds to hold the board components together. Sizing agents are usually added to the furnish (about 1%) to provide the finished board with a modest degree of water resistance and dimensional stability.

As in the manufacture of wet-process hardboard, cellulosic fiberboard manufacture is a modification of papermaking. A thick fibrous sheet is made from a low-consistency pulp suspension in a process known as wet felting. Felting can be accomplished through use of a deckle box, Fourdrinier screen, or cylinder screen. A deckle box is a bottomless frame that is placed over a screen. A measured amount of pulp suspension is put in the box and a vacuum is applied to remove most of the water. The use of a Fourdrinier screen for felting is similar to that for papermaking, except that line speeds are reduced to 8 to 18 m min⁻¹ (25 to 60 ft min⁻¹).

Cellulosic fiberboard formed in a deckle box is cold-pressed to remove the free water after the mat is formed. Compression rollers on the Fourdrinier machines squeeze

out the free water. The wet mats are then dried to the final moisture content. Dryers may be a continuous tunnel or a multideck arrangement. The board is generally dried in stages at temperatures ranging from 120 to 190 °C (248 to 374 °F). Typically, about 2 to 4 h is required to reduce moisture content to about 1% to 3%.

After drying, some boards are treated for specific applications. Boards may be given tongue-and-groove or shiplap edges or grooved to produce a plank effect. Other boards are laminated by means of asphalt to produce roof insulation.

Cellulosic fiberboard products include sound-deadening board, insulation boards, structural and nonstructural sheathings, backer board, and roof decking in various thicknesses. An example of a grade mark stamp for these cellulosic fiberboard products conforming to ASTM C 208 (ASTM 2008c) is shown in Figure 11–12.

Finishing Techniques

Several techniques are used to finish fiberboard: trimming, sanding, surface treatment, punching, and embossing. Trimming consists of reducing products into standard sizes and shapes. Generally, double-saw trimmers are used to saw the panels. Trimmers consist of overhead-mounted saws or multiple saw drives. If thickness tolerance is critical, hardboard

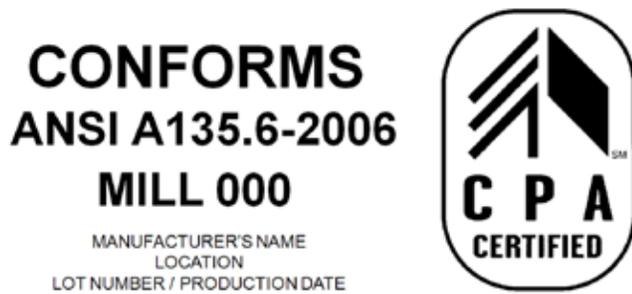


Figure 11–11. Typical grade stamp for hardboard siding. (Courtesy of Composite Panel Association, Leesburg, Virginia. Used by permission.)



Figure 11–12. Typical grade stamp for cellulose fiberboard. (Courtesy American Fiberboard Association, Palatine, Illinois. Used by permission.)

is sanded prior to finishing. S1S (smooth on one side) panels require this process. Sanding reduces thickness variation and improves surface paintability. Single-head, wide-belt sanders are used with 24- to 36-grit abrasive. Surface treatments improve the appearance and performance of boards. Panels are cleaned by spraying with water and then dried at about 240 °C (464 °F) for 30 s. Panel surfaces are then modified with paper overlay, paint, or stain or are printed directly on the panel. Punching changes panels into perforated sheets used as peg board. Embossing consists of pressing the unconsolidated mat of fibers with a textured form. This process results in a slightly contoured panel surface that can enhance the resemblance of the panel to that of sawn or weathered wood, brick, and other materials.

Specialty Composite Materials

Special-purpose composite materials are produced to obtain enhanced performance properties such as water resistance, mechanical strength, acidity control, and fire, decay, and insect resistance. Overlays and veneers can also be added to enhance both structural properties and appearance (Fig. 11–13).

Water-Repellant Composites

Sizing agents are used to increase the water repellency of wood-based composites. Sizing agents cover the surface of fibers, reduce surface energy, and increase fiber hydrophobicity. Sizing agents can be applied in two ways. In the first method, water is used as a medium to ensure thorough mixing of sizing and fiber. The sizing is precipitated from the water and is fixed to the fiber surface. In the second method, the sizing is applied directly to the fibers.

Common sizing agents include rosin, wax, and asphalt. Rosin is obtained from living pine trees, from pine stumps, and as a by-product of kraft pulping of pines. Rosin is added in amounts of less than 3% solids based on dry fiber weight. Waxes are high-molecular-weight hydrocarbons derived from crude oil. Wax is used in solid form in dry-process fiberboard production. For wet processes, wax is added in solid form or as an emulsion. Wax tends to lower strength properties to a greater extent than rosin does. Asphalt is also used to increase water resistance, especially in low-density wet-process cellulosic fiberboard. Asphalt is a black–brown solid or semi-solid material that liquefies when heated. Asphalt is added to the process water as an emulsion and precipitated onto fiber by the addition of alum.

Flame-Retardant Composites

Two general application methods are available for improving the fire performance of composites with fire-retardant chemicals. One method consists of pressure impregnating the wood with waterborne or organic solvent-borne fire retardant chemicals (AWPA 2007a). The second method consists of applying fire-retardant chemical coatings to the wood surface. The pressure impregnation method is usually more effective and longer lasting; however, this technique is standardized only for plywood. It is not generally used with structural flake, particle, or fiber composites, because it can cause swelling that permanently damages the wood–adhesive bonds in the composite and results in the degradation of some physical and mechanical properties of the composite. For wood in existing constructions, surface application of fire-retardant paints or other finishes offers a possible method to reduce flame spread.

Preservative-Treated Composites

Composites can be protected from attack by decay fungi and harmful insects by applying selected chemicals as wood preservatives. The degree of protection obtained depends on the kind of preservative used and the ability to achieve proper penetration and retention of the chemicals. Wood preservatives can be applied using pressurized or non-pressurized processes (AWPA 2007b). As in the application of fire-retardant chemicals, the pressurized application of wood preservatives is generally performed after manufacture and is standardized for plywood. Post-manufacture pressurized treatments are not standardized for all types of flake, particle, or fiber composite due to the potential for swelling. Preservatives can be added during the composite manufacturing process, but the preservative must be resistant to vaporization during hot pressing. Proprietary flakeboard and fiberboard products with incorporated nonvolatile preservatives have been commercialized. Common preservative treatments include ammoniacal copper quat (ACQ), copper azol (CA), and boron compounds.

Performance and Standards

Standards for conventional wood-based composite products are typically established under a series of internationally

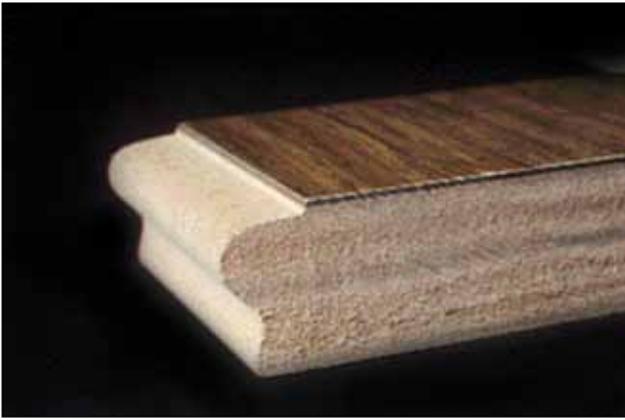


Figure 11–13. Medium-density fiberboard with veneer overlay. Edges can be shaped and finished as required by end product.

accredited consensus review processes involving users, producers, and general interests. Then, commercial wood composites are manufactured to conform to these commercial product or performance standards (Table 11–2). These product or performance standards are cited in the International Building Code (IBC) and other similar documents. The IBC is the model building code produced by the International Code Council (ICC), a non-profit organization established in 1994 dedicated to developing a single set of comprehensive and coordinated construction codes. Since the adoption of the first edition of the IBC in 2000, most building codes in the U.S. are based on the IBC. Previously, there were three model code organizations that produced model codes with largely regional acceptance. The ICC also produces the International Residential Code (IRC) and other related model code documents.

The ICC–Evaluation Service (ICC–ES) issues advisory reports on their evaluation of building products, components, methods, and materials for their compliance with the IBC. The ICC–ES was created in 2003 with the merger of the four existing evaluation services. ICC–ES also issues ICC–ES Acceptance Criteria documents for specific types of products that specify the performance criteria and the data that needs to be submitted for the evaluations. These evaluation reports and the acceptance criteria documents are available on the web site of the ICC–ES (www.icc-es.org).

Types of Product Standards

Product standards may be classified as manufacturing standards or performance standards. The best example of a manufacturing method standard is Voluntary Product Standard PS 1–07 for construction and industrial plywood (NIST 2007). Specifications in the standard include which wood species and grades of veneer may be used, what repairs are permissible, and how repairs must be made. Limited performance-based evaluations may also be specified in manufacturing standards for issues relating to adhesive durability and strength.

Standard PS 2–04 (NIST 2004) is a performance-based standard because it applies to all structural-use wood-based panels, including plywood and OSB. This standard includes performance requirements and test methods suitable for a given application (qualification) and also require that properties of a qualified product remain in control during production over time (certification). With respect to plywood, the PS 2–04 standard is not a replacement for PS 1–07, which contains necessary veneer-grade and adhesive-bond requirements as well as lay-up provisions, but it is broad enough to also include many plywood grades not covered under PS 1–07. PS 2–04 specifies that certification be performed by an independent third party.

The American National Standards for particleboard and MDF (ANSI A208.1 and A208.2 respectively) are sponsored by the Composite Panel Association (CPA) in Leesburg, Virginia (CPA 2009a, b). These performance standards require the composite products to show certain minimally acceptable physical and mechanical properties. The test requirements give some indication of product quality, but the tests were not specifically developed to correlate with performance of whole panels in specific end uses.

Role of Standards in Construction

Conventional wood-based composite panels and lumber elements manufactured in conformance with product standards (Table 11–2) are approved under the International Building Code. These wood-based composites can be used for construction applications such as sheathing for roofs, sub-flooring, and walls. Similarly, many types of wood-based composite lumber can be used for joists, purlins, stringers, beams, and columns.

Design properties and basic installation guidelines of structural-use panels have become standardized by the ICC. The ICC requires independent third-party certification of these panels, and several such third-party certification agencies exist, such as APA–The Engineered Wood Association (www.apawood.org) and TECO (www.tecotested.com). These agencies and others offer a variety of technical information on the proper selection, design, and installation of structural-use panels.

Plywood panels conforming to PS 1–07 are marked with grade stamps (Fig. 11–6a,b). Flake-based composites, such as OSB, are usually marketed as conforming to a product standard for sheathing or single-layer sub-flooring or underlayment and are also marked with grade stamps (Fig. 11–6c,d).

Structural-use panels are also span-rated. Span ratings refer to on-center spacing of support members (expressed in inches), with the long panel dimension (in plywood this is the same direction as the face grain) placed across the supports, assuming that there are at least two spans (a minimum of three supports). Span-rating of construction plywood and OSB simplifies materials specification in light-frame

construction by allowing specification without resorting to specific structural engineering design calculations. Panels in PS 2–04 are designated by application (wall, roof, sub-floor, or single floor) and by span rating. Specification by application and span is more convenient for builders than specification by species or species group, veneer grade, and panel thickness. A panel may be suitable for use as either roof sheathing or sub-flooring, with different span ratings for the two applications. Such panels will have a dual span-rating, the first (and larger) number indicating allowable span when used as roof sheathing, the second number indicating the allowable span when used as sub-flooring.

Glulam Timber

Structural glued-laminated timber (glulam) is one of the oldest glued engineered wood products. Glulam is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers, which are referred to as laminations, parallel to the length. Glulam is defined as a material that is made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum lamination thickness permitted is 50 mm (2 in.), and the laminations are typically made of standard 25- or 50-mm- (nominal 1- or 2-in.-) thick lumber. North American standards require that glulam be manufactured in an approved manufacturing plant. Because the lumber is joined end to end, edge to edge, and face to face, the size of glulam is limited only by the capabilities of the manufacturing plant and the transportation system.

Douglas Fir–Larch, Southern Pine, Hem–Fir, and Spruce–Pine–Fir (SPF) are commonly used for glulam in the United States. Nearly any species can be used for glulam timber, provided the mechanical and physical properties are suitable and gluing properties acceptable. Industry standards cover many softwoods and hardwoods, and procedures are in place for including other species.

Advantages

Compared with sawn timbers as well as other structural materials, glulam has several distinct advantages. These include size capability, architectural effects, seasoning, variation of cross sections, grades, and effect on the environment.

Size Capabilities

Glulam offers the possibility of manufacturing structural timbers that are much larger than the trees from which the component lumber was sawn. In the past, the United States had access to large trees that could produce relatively large sawn timbers. However, the present trend is to harvest smaller diameter trees on much shorter rotations, and nearly all new sawmills are built to accommodate relatively small logs. By combining the lumber in glulam, the production of

large structural elements is possible. Straight members up to 30 m (100 ft) long are not uncommon, and some span up to 43 m (140 ft). Sections deeper than 2 m (7 ft) have been used. Thus, glulam offers the potential to produce large timbers from small trees.

Architectural Effects

By curving lumber during the manufacturing process, a variety of architectural effects can be obtained with glulam that are impossible or very difficult with other materials (Fig. 11–14). The degree of curvature is controlled by the thickness of the laminations. Thus, glulam with moderate curvature is generally manufactured with standard 19-mm- (nominal 1-in.-) thick lumber. Low curvatures are possible with standard 38-mm (nominal 2-in.) lumber, whereas 13 mm (1/2 in.) or thinner material may be required for very sharp curves. As noted later in this chapter, the radius of curvature is limited to between 100 and 125 times the lamination thickness.

Seasoning Advantages

The lumber used in the manufacture of glulam must be seasoned or dried prior to use, so the effects of checking and other drying defects are minimized. This allows design on the basis of seasoned wood, which permits greater design values than can be assigned to unseasoned timber.

Varying Cross Sections

Structural elements can be designed with varying cross sections along their length as determined by strength and stiffness requirements. Similarly, arches often have varying cross sections as determined by design requirements.

Varying Grades

One major advantage of glulam is that a large quantity of lower grade lumber can be used within the less highly stressed laminations of the beams. Grades are often varied within the beams so that the highest grades are used in the highly stressed laminations near the top and bottom edges, with the lower grades used in the inner section (toward the center) of the beams. Species can also be varied to match the structural requirements of the laminations.

Types of Glulam Combinations

Bending Members

The configuring of various grades of lumber to form a glulam cross section is commonly referred to as a glulam combination. Glulam combinations subjected to flexural loads, called bending combinations, were developed to provide the most efficient and economical section for resisting bending stress caused by loads applied perpendicular to the wide faces of the laminations. This type of glulam is commonly referred to as a horizontally laminated member. Lower grades of laminating lumber are commonly used for the center portion of the combination, or core, where bending stress is low, while a higher grade of material is placed



Figure 11–14. Erected in 1934 at the Forest Products Laboratory in Madison, Wisconsin, this building is one of the first constructed with glued-laminated timbers arched, designed, and built using engineering principles.

on the outside faces where bending stress is relatively high. To optimize the bending stiffness of this type of glulam member, equal amounts of high-quality laminations on the outside faces should be included to produce a “balanced” combination. To optimize bending strength, the combination can be “unbalanced” with more high-quality laminations placed on the tension side of the member compared with the quality used on the compression side. For high-quality lumber placed on the tension side of the glulam combination, stringent requirements are placed on knot size, slope of grain, and lumber stiffness.

For compression-side laminations, knot size and slope-of-grain requirements are less stringent and only lumber stiffness is given high priority. In the case where the glulam member is used over continuous supports, the combination would need to be designed as a balanced member for strength and stiffness because of the exposure of both the top and bottom of the beam to tensile stresses. The knot and slope-of-grain requirements for this type of combination are generally applied equally to both the top and bottom laminations.

Axial Members

Glulam axial combinations were developed to provide the most efficient and economical section for resisting axial forces and flexural loads applied parallel to the wide faces of the laminations. Members having loads applied parallel to the wide faces of the laminations are commonly referred to as vertically laminated members. Unlike the practice for bending combinations, the same grade of lamination is used throughout the axial combination. Axial combinations may also be loaded perpendicular to the wide face of the

laminations, but the nonselective placement of material often results in a less efficient and less economical member than does the bending combination. As with bending combinations, knot and slope-of-grain requirements apply based on whether the axial member will be used as a tension or compression member.

Curved Members

Efficient use of lumber in cross sections of curved glulam combinations is similar to that in cross sections of straight, horizontally laminated combinations. Tension and compression stresses are analyzed as tangential stresses in the curved portion of the member. A unique behavior in these curved members is the formation of radial stresses perpendicular to the wide faces of the laminations. As the radius of curvature of the glulam member decreases, the radial stresses formed in the curved portion of the beam increase. Because of the relatively low strength of lumber in tension perpendicular-to-the-grain compared with tension parallel-to-the-grain, these radial stresses become a critical factor in designing curved glulam combinations. Curved members are commonly manufactured with standard 19- and 38-mm- (nominal 1- and 2-in.-) thick lumber. Naturally, the curvature that is obtainable with the standard 19-mm- (nominal 1-in.-) thick lumber will be sharper than that for the standard 38-mm- (nominal 2-in.-) thick lumber.

Tapered Straight Members

Glulam beams are often tapered to meet architectural requirements, provide pitched roofs, facilitate drainage, and lower wall height requirements at the end supports. The taper is achieved by sawing the member across one or more laminations at the desired slope. It is recommended that the taper cut be made only on the compression side of the glulam member, because violating the continuity of the tension-side laminations would decrease the overall strength of the member.

Standards and Specifications

Manufacture

The ANSI/AITC A190.1 standard of the American National Standards Institute (AITC 2007a) contains requirements for the production, testing, and certification of structural glulam timber in the United States. A standard for glulam poles, ANSI O5.2 (ANSI 2006), addresses special requirements for utility uses.

Derivation of Design Values

ASTM D 3737 (ASTM 2008a) covers procedures to establish design values for structural glulam timber. Properties considered include bending, tension, compression parallel to grain, modulus of elasticity, horizontal shear, radial tension, and compression perpendicular to grain.

Design Values and Procedures

Manufacturers of glulam timber have standardized the target design values in bending for beams. For softwoods, these design values are given in AITC 117, “Standard Specifications for Structural Glued-Laminated Timber of Softwood Species” (AITC 2004a). This specification contains design values and recommended modification of stresses for the design of glulam timber members in the United States. A comparable specification for hardwoods is AITC 119, “Standard Specifications for Structural Glued-Laminated Timber of Hardwood Species” (AITC 1996). For additional design information, see the *Timber Construction Manual* (AITC 2004b).

Manufacture

The manufacture of glulam timber must follow recognized national standards to justify the specified engineering design values. When glulam is properly manufactured, both the quality of the wood and the adhesive bonds should demonstrate a balance in structural performance.

The ANSI/AITC standard A190.1 (AITC 2007a) has a two-phase approach to all phases of manufacturing. First is the qualification phase, in which all equipment and personnel critical to the production of a quality product are thoroughly examined by a third-party agency and the strength of samples of glued joints is determined. In the second phase, after successful qualification, daily quality assurance procedures and criteria are established, which are targeted to keep each of the critical phases of the process under control. An employee is assigned responsibility for supervising the daily testing and inspection. The third-party agency makes unannounced visits to the plants to monitor the manufacturing process and the finished product and to examine the daily records of the quality assurance testing.

The manufacturing process can be divided into four major parts: (a) drying and grading the lumber, (b) end jointing the lumber, (c) face bonding, and (d) finishing and fabrication. In instances where the glulam will be used in high-moisture-content conditions, the member must also be pressure-treated with preservative.

A final critical step in ensuring the quality of glulam is protection of the glulam timber during transit and storage.

Lumber Drying and Grading

To minimize dimensional changes following manufacture and to take advantage of the increased structural properties assigned to lumber compared with large sawn timbers, the lumber must be properly dried prior to glulam manufacture. This generally means kiln drying. Matching the moisture content of the glulam timber at the time of manufacture to that which it will attain in application minimizes shrinkage and swelling, the main causes of checking. Most manufacturers use a continuous in-line moisture meter to check the

moisture content of each piece of lumber as it enters the manufacturing process. Pieces that have a high moisture level are removed and redried.

Grading standards published by the regional lumber grading associations describe the characteristics that are permitted in various grades of lumber. Manufacturing standards for glulam timber describe the combination of lumber grades necessary for specific design values (AITC 117) (AITC 2004). The rules for visually graded lumber are based entirely upon the characteristics that are readily apparent. The lumber grade description consists of limiting characteristics for knot sizes, slope of grain, wane, and several other characteristics.

Manufacturers generally purchase graded lumber and verify the grades through visual inspection of each piece and, if E-rated, testing of a sample. To qualify the material for some of the higher design stresses for glulam timber, manufacturers must also conduct additional grading for material to be used in the tension zone of certain beams. Another option is to purchase lumber manufactured under a quality assurance system that meets the required tensile strength. Another option practiced by at least one manufacturer has been to use laminated veneer lumber (LVL) to provide the required tensile strength.

End Jointing

To manufacture glulam timber in lengths beyond those commonly available for lumber, laminations must be made by end jointing lumber to the proper length. The most common end joint, a fingerjoint, is about 28 mm (1.1 in.) long. Other configurations are also acceptable, provided they meet specific strength and durability requirements. The advantages of fingerjoints are that they require only a short length of lumber to manufacture (thus reducing waste) and continuous production equipment is readily available. Well-made joints are critical to ensure adequate performance of glulam timber. Careful control at each stage of the process—determining lumber quality, cutting the joint, applying the adhesive, mating, applying end pressure, and curing—is necessary to produce consistent high strength joints.

Face Bonding

The assembly of laminations into full-depth members is another critical stage in manufacture. To obtain clear, parallel, and glueable surfaces, laminations must be planed to strict tolerances. The best procedure is to plane the two wide faces of the laminations just prior to the gluing process. This ensures that the final assembly will be rectangular and that the pressure will be applied evenly. Adhesives that have been pre-qualified are then spread, usually with a glue extruder. Phenol resorcinol is the most commonly used adhesive for face gluing, but other adhesives that have been adequately evaluated and proven to meet performance and durability requirements may also be used.

The laminations are then assembled into the required layout; after the adhesive is given the proper open assembly time, pressure is applied. The most common method for applying pressure is with clamping beds; the pressure is applied with either a mechanical or hydraulic system. This results in a batch-type process, and the adhesive is allowed to cure at room temperature from 6 to 24 h. Some newer automated clamping systems include continuous hydraulic presses and radio-frequency curing to shorten the face gluing process from hours to minutes. Upon completion of the face bonding process, the adhesive is expected to have attained 90% or more of its bond strength. During the next few days, curing continues, but at a much slower rate.

The face bonding process is monitored by controls in the lumber planing, adhesive mixing, and adhesive spreading and clamping processes. Performance is evaluated by conducting shear tests on samples cut off as end trim from the finished glulam timber. Thus, the adhesive bonds are expected to develop nearly the full strength of the wood soon after manufacture.

Finishing and Fabrication

After the glulam timber is removed from the clamping system, the wide faces are planed to remove the adhesive that has squeezed out between adjacent laminations and to smooth out any slight irregularities between the edges of adjacent laminations. As a result, the finished glulam timber is slightly narrower than nominal dimension lumber. The remaining two faces of the member can be lightly planed or sanded.

The appearance requirements of the beam dictate the additional finishing necessary at this point. Historically, three classifications of finishing have been included in the industry standard, AITC 110: Industrial, Architectural, and Premium (AITC 2001). Industrial appearance is generally applicable when appearance is not a primary concern, such as industrial plants and warehouses. Architectural appearance is suitable for most applications where appearance is an important requirement. Premium appearance is the highest classification. The primary difference among these classifications is the amount of knot holes and occasional planer skips that are permitted. A recently introduced classification, called Framing, consists of hit-and-miss planing and permits a significant amount of adhesive to remain on the surface. This finishing is intended for uses that require one member to have the same width as the lumber used in manufacture for framing into walls. These members are often covered in the finished structure.

The next step in the manufacturing process is fabrication, where the final cuts are made, holes are drilled, connectors are added, and a finish or sealer is applied, if specified. For various members, different degrees of prefabrication are done at this point. Trusses may be partially or fully

assembled. Moment splices can be fully fabricated, then disconnected for transportation and erection. End sealers, surface sealers, primer coats, and wrapping with waterproof paper or plastic all help to stabilize the moisture content of the glulam timber between the time it is manufactured and installed. The extent of protection necessary depends upon the end use and must be specified.

Preservative Treatment

In instances where the moisture content of the finished glulam timber will approach or exceed 20% (in most exterior and some interior uses), the glulam timber should be preservative-treated following AITC 109 (AITC 2007b). Three main types of preservatives are available: creosote, oilborne, and waterborne. Creosote and oilborne preservatives are applied to the finished glulam timbers. Some light oil solvent treatments can be applied to the lumber prior to gluing, but the suitability must be verified with the manufacturer. Waterborne preservatives are best applied to the lumber prior to the laminating and manufacturing process because they can lead to excessive checking if applied to large finished glulam timbers.

Structural Composite Lumber

Structural composite lumber (SCL) was developed in response to the increasing demand for high-quality lumber at a time when it was becoming difficult to obtain this type of lumber from the forest resource. Structural composite lumber products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber.

One type of SCL product is manufactured by laminating veneer with all plies parallel to the length. This product is called laminated veneer lumber (LVL) and consists of specially graded veneer. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressures and temperatures. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL). These types of SCL products can be manufactured from raw materials, such as aspen or other underutilized species, that are not commonly used for structural applications. Different widths of lumber can be ripped from SCL for various uses. Compared with similar size solid-sawn lumber, SCL often provides a stronger, more reliable structural member that can often span greater distances and has less dimensional change.

Structural composite lumber is a growing segment of the engineered wood products industry. It is used as a replacement for lumber in various applications and in the manufacture of other engineered wood products, such as prefabricated wood I-joists, which take advantage of engineering design values that can be greater than those commonly assigned to sawn lumber.

Laminated Veneer Lumber

Work in the 1940s on LVL targeted the production of high-strength parts for aircraft structures using Sitka spruce veneer. Research on LVL in the 1970s was aimed at defining the effects of processing variables for veneer up to 12.7 mm (1/2 in.) thick. Since the 1990s, production of LVL uses veneers 3.2 to 2.5 mm (1/8 to 1/10 in.) thick, which are hot pressed with phenol-formaldehyde adhesive into lengths from 2.4 to 18.3 m (8 to 60 ft) or more. Today LVL is commonly used as the flanges in composite I-joists.

Veneer for the manufacture of LVL must be carefully selected for the product to achieve the desired engineering properties. Veneers are often sorted using ultrasonic testing to ensure that the finished product will have the desired engineering properties.

End joints between individual veneers may be staggered along the product to minimize their effect on strength. These end joints may be butt joints, or the veneer ends may overlap for some distance to provide load transfer. Some producers provide structural end joints in the veneers using either scarf or fingerjoints. LVL may also be made in 2.4-m (8-ft) lengths, having no end joints in the veneer; longer pieces are then formed by end-jointing these pieces to create the desired length.

Sheets of LVL are commonly produced in 0.6- to 1.2-m (2- to 4-ft) widths in a thickness of 38 mm (1.5 in.). Continuous presses can be used to form a potentially endless sheet, which is cut to the desired length. Various widths of lumber can be manufactured at the plant or the retail facility.

Parallel Strand Lumber

Parallel strand lumber (PSL) is defined as a composite of wood strand elements with wood fibers oriented primarily along the length of the member. The least dimension of the strands must not exceed 6.4 mm (0.25 in.), and the average length of the strands must be a minimum of 150 times the least dimension. PSL is a proprietary product, sold as Paral-lam®. It is often used for large beams and columns, typically as a replacement of solid-sawn lumber or glulam.

Parallel strand lumber is manufactured using veneer about 3 mm (1/8 in.) thick, which is then clipped into strands about 19 mm (3/4 in.) wide. These strands are commonly at least 0.6 m (24 in.) long. The manufacturing process was designed to use the material from roundup of the log in the veneer cutting operation as well as other less than full-width veneer (Fig. 11–15). Thus, the process can utilize waste material from a plywood or LVL operation. Species commonly used for PSL include Douglas-fir, southern pines, western hemlock, and yellow-poplar, but there are no restrictions on using other species.

The strands are coated with a waterproof structural adhesive, commonly phenol-resorcinol formaldehyde, and oriented in a press using special equipment to ensure proper

orientation and distribution. The pressing operation results in densification of the material, and the adhesive is cured using microwave technology. Billets larger than those of LVL are commonly produced; a typical size is 0.28 by 0.48 m (11 by 19 in.). This product can then be sawn into smaller pieces, if desired. As with LVL, a continuous press is used so that the length of the product is limited by handling restrictions.

Laminated Strand Lumber and Oriented Strand Lumber

Laminated strand lumber (LSL) and oriented strand lumber (OSL) products are an extension of the technology used to produce oriented strandboard (OSB) structural panels. The products have more similarities than differences. The main difference is that the aspect ratio of strands used in LSL is higher than for OSB (AF&PA 2006). One type of LSL uses strands that are about 0.3 m (12 in.) long, which is somewhat longer than the strands commonly used for OSB. Waterproof adhesives are used in the manufacture of LSL. One type of product uses an isocyanate type of adhesive that is sprayed on the strands and cured by steam injection. This product needs a greater degree of alignment of the strands than does OSB and higher pressures, which result in increased densification. Both LSL and OSL are proprietary products; LSL is sold as TimberStrand®. Applications such as studs and millwork are common.

Advantages and Uses

In contrast with sawn lumber, the strength-reducing characteristics of SCL are dispersed within the veneer or strands and have much less effect on strength properties. Thus, relatively high design values can be assigned to strength properties for both LVL and PSL. Whereas both LSL and OSL have somewhat lower design values, they have the advantage of being produced from a raw material that need not be in a log size large enough for peeling into veneer. All SCL products are made with structural adhesives and are dependent upon a minimum level of strength in these bonds.

All SCL products are made from veneers or strands that are dried to a moisture content that is slightly less than that for most service conditions. Thus, little change in moisture content will occur in many protected service conditions. When used indoors, this results in a product that is less likely to warp or shrink in service. However, the porous nature of both LVL and PSL means that these products can quickly absorb water unless they are provided with some protection.

All types of SCL products can be substituted for sawn lumber products in many applications. Laminated veneer lumber is used extensively for scaffold planks and in the flanges of prefabricated I-joists, which take advantage of the relatively high design properties. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. The LSL and OSL products are used for band joists in

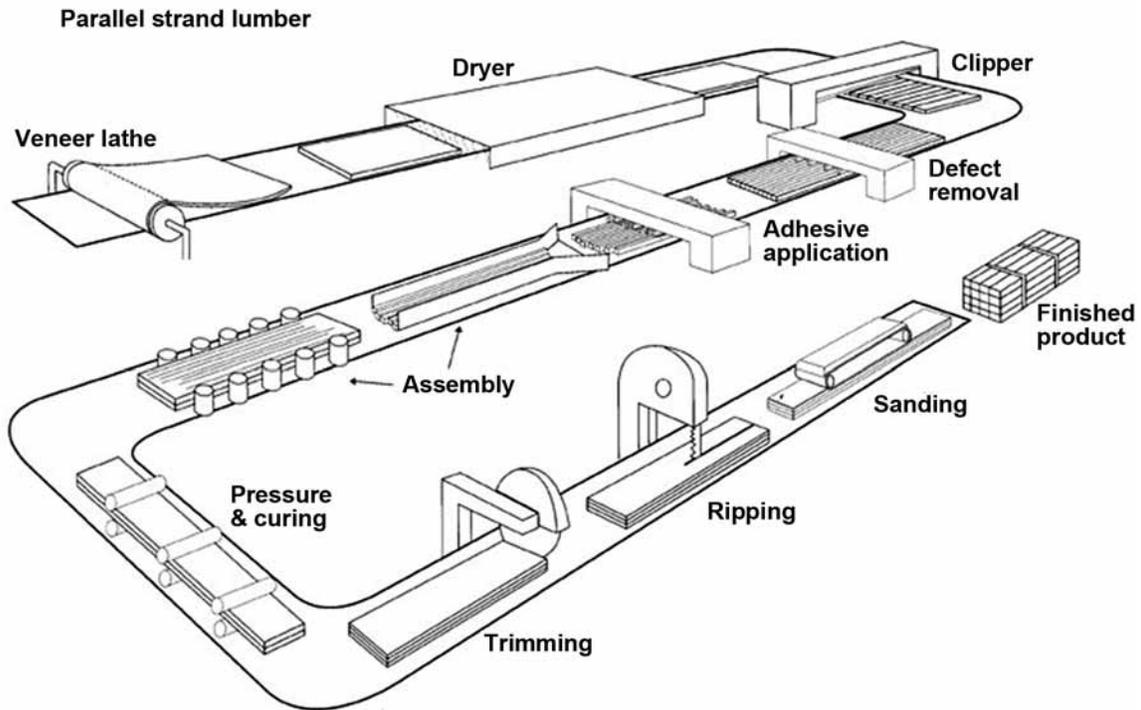


Figure 11–15. Generalized process for manufacturing PSL. (Courtesy of iLevel by Weyerhaeuser, Federal Way, Washington. Used by permission.)

floor construction and as substitutes for studs and rafters in wall and roof construction. Various types of SCL are also used in a number of nonstructural applications, such as the manufacture of windows and doors.

Standards and Specifications

The ASTM D 5456 (ASTM 2008b) standard provides methods to develop design properties for SCL products as well as requirements for quality assurance during production. Each manufacturer of SCL products is responsible for developing the required information on properties and ensuring that the minimum levels of quality are maintained during production. An independent inspection agency is required to monitor the quality assurance program.

Unlike lumber, no standard grades or design stresses have been established for SCL. Each manufacturer may have unique design properties and procedures. Thus, the designer should consult information provided by the manufacturer.

Wood–Nonwood Composite Materials

Wood may be combined with inorganic materials and with plastics to produce composite products with unique properties. Wood–nonwood composites typically contain wood elements suspended in a matrix material (for example in fiber-reinforced gypsum board, or in thermoplastic material), in which the proportion of wood elements may account for less than 60% of product mass.

The primary impetus for developing such products has come from one or more of the following research and development goals:

- Develop “green” or “environmentally benign” products with enhanced sustainability.
- Reduce material costs by combining a lower cost material (acting as a filler or extender) with an expensive material.
- Develop products that can utilize recycled materials and be recyclable in themselves.
- Produce composite products that exhibit specific properties that are superior to those of the component materials alone (for example, increased strength-to-weight ratio, improved abrasion resistance, enhance resistance to fire, decay, and insects).

Composites made from wood and other non-wood materials create enormous opportunities to match product performance to end-use requirements. The following discussion includes the most common type of wood–nonwood composites: inorganic-bonded and wood–thermoplastic composites.

Inorganic-Bonded Composite Materials

Inorganic-bonded wood composites have a long and varied history that started with commercial production in Austria in 1914. They are now used in many countries in the world, mostly in panel form. Applications include panel products, siding, roofing tiles, and precast building members.

Chapter 11 Wood-Based Composite Materials

Inorganic-bonded wood composites are molded products or boards that contain between 10% and 70% by weight wood particles or fibers and conversely 90% to 30% inorganic binder. Acceptable properties of an inorganic-bonded wood composite can be obtained only when the wood particles are fully encased, and the binder is a continuous matrix material. This differs considerably from conventional wood-based composites, where flakes or particles are “spot welded” by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than that of resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by the amount and type of the inorganic binder and the wood element as well as the density of the composites.

Inorganic-bonded composites include gypsum-bonded, cement-bonded, and ceramic-bonded composites. Magnesia and Portland cement are the most common cement binders. Gypsum and magnesia cement are sensitive to moisture, and their use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with gypsum or magnesia cement and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending wood elements with inorganic materials in the presence of water and allowing the inorganic material to cure or “set up” to make a rigid composite. Some inorganic-bonded composites are very resistant to deterioration by decay fungi, insects, and vermin. Most have appreciable fire resistance.

An advantage of inorganic-bonded composites is that their manufacture is adaptable to either end of the cost and technology spectrum. This is facilitated by the fact that no heat is required to cure the inorganic material. This versatility makes inorganic-bonded composites ideally suited to a variety of lignocellulosic materials. With a very small capital investment, satisfactory inorganic-bonded lignocellulosic composite building materials can be produced on a small scale using mostly unskilled labor. If the market for such composites increases, technology can be introduced to increase manufacturing throughput. The labor force can be trained concurrently with the gradual introduction of more sophisticated technology.

Gypsum-Bonded Composite Materials

Paper-faced gypsum boards have been widely used since the 1950s for the interior lining of walls and ceilings. They are commonly called drywall because they often replaced wet plaster systems. These panels are critical for good fire ratings in walls and ceilings. Paper-faced gypsum boards also find use as exterior wall sheathing. Gypsum sheathing panels are primarily used in commercial construction, usually over steel studding, and are distinguished from gypsum dry-

wall by their water repellent additives in the paper facings and gypsum core. The facings of drywall and of gypsum sheathing panels are adhered to the gypsum core, providing the panels with impact resistance, and bending strength and stiffness. The paper facings of gypsum panels are derived from recycled paper fiber.

An alternative to adhered facings is to incorporate lignocellulosic fiber (typically recycled paper fiber) in the gypsum core to make what are termed fiber-reinforced gypsum panels. In the production process, a paste of gypsum and water is mixed with the recycled paper fiber and extruded into a panel without facings. Shortly after formation, the panel is dried in an oven. Bonding occurs between the gypsum and the fiber as hydrate crystals form.

Fiber-reinforced gypsum panels are typically stronger and more resistant to abrasion and indentation than paper-faced drywall panels and also have a moderate fastener-holding capability. They are marketed for use as interior finish panels (drywall). Additives can provide a moderate degree of water resistance, for use as sheathing panels, floor underlayment, roof underlayment, or tile-backer board.

Cement-Bonded Composite Materials

The properties of cement-bonded composites are influenced by wood element characteristics (species, size, geometry, chemical composition), cement type, wood–water–cement ratio, environmental temperature, and cure time (Jorge and others 2004). They are heavier than conventional wood-based composites but lighter than concrete. Therefore they can replace concrete in construction, specifically in applications that are not subjected to loads. Wood–cement composites provide an option for using wood residues, or even agricultural residues. However, species selection can be important because many species contain sugars and extractives that retard the cure of cement (Bowyer and others 2007).

Magnesia-Cement-Bonded Composite Materials

Fewer boards bonded with magnesia cement have been produced than Portland-cement-bonded panels, mainly because of price. However, magnesia cement does offer some manufacturing advantages over Portland cement. First, the various sugars in lignocellulosics do not have as much effect on the curing and bonding. Second, magnesia cement is more tolerant of high water content during production. This opens up possibilities to use lignocellulosics not amenable to Portland cement composites, without leaching or other modification, and to use alternative manufacturing processes and products. Although composites bonded with magnesia cement are considered water sensitive, they are much less so than gypsum-bonded composites.

One successful application of magnesia cement is a low-density panel made for interior ceiling and wall applications. In the production of this panel product, wood wool (excelsior) is laid out in a low-density mat. The mat is then sprayed



Figure 11–16. Commercial cement-bonded composite panel. (Courtesy of Ty-Mawr Lime Ltd., UK. Used by permission.)

with an aqueous solution of magnesia cement, pressed, and cut into panels (Fig. 11–16).

Other processes have been suggested for manufacturing magnesia-cement-bonded composites. For example, a slurry of magnesia cement, water, and lignocellulosic fiber may be sprayed onto existing structures as fireproofing. Extrusion into a pipe-type profile or other profiles is also possible.

Portland-Cement-Bonded Composite Materials

The most widely used cement-bonded composites are those bonded with Portland cement. Portland cement, when combined with water, reacts in a process called hydration to solidify into a solid stone-like mass and bind aggregate materials. Successfully marketed Portland-cement-bonded composites consist of both low-density products made with excelsior and high-density products made with particles and fibers.

Low-density products may be used as interior ceiling and wall panels in commercial buildings. In addition to the advantages described for low-density magnesia-bonded composites, low-density composites bonded with Portland cement offer sound control and can be decorative. In some parts of the world, these panels function as complete wall and roof decking systems. The exterior of the panels is coated with stucco, and the interior is plastered. High-density panels can be used as flooring, roof sheathing, fire doors, load-bearing walls, and cement forms. Fairly complex shapes, such as decorative roofing tiles or non-pressure pipes, can be molded or extruded.

The largest volume of cement-bonded wood-based composite materials manufactured in North America is fiber-cement siding. Fiber-cement siding incorporates delignified wood fiber into a Portland cement matrix.

Problems and Solutions of Cement-Bonded Composite Materials

The use of cement for wood-based composites involves limitations and tradeoffs. Embrittlement of the lignocellulosic component is known to occur and is caused by the alkaline environment provided by the cement matrix. In addition, hemicellulose, starch, sugar, tannins, and lignin, each to a varying degree, affect the cure rate and ultimate strength of these composites. To make strong and durable composites, measures must be taken to ensure long-term stability of the lignocellulosic in the cement matrix. To overcome these problems, various schemes have been developed. The most common is leaching, whereby the lignocellulosic is soaked in water for 1 or 2 days to extract some of the detrimental components. However, in some parts of the world, the water containing the leachate is difficult to dispose of. Low water-cement ratios are helpful, as is the use of curing accelerators like calcium carbonate. Conversely, low-alkali cements have been developed, but they are not readily available throughout the world. Two other strategies involve the use of natural pozzolans and carbon dioxide treatment.

Pozzolans—Pozzolans are defined as siliceous or siliceous and aluminous materials that can react chemically with calcium hydroxide (slaked lime) at normal temperatures in the presence of water to form cement compounds. Some common pozzolanic materials include volcanic ash, fly ash, rice husk ash, and condensed silica fume. All these materials can react with lime at normal temperatures to make a natural water-resistant cement.

In general, when pozzolans are blended with Portland cement, they increase the strength of the cement but slow the cure time. More importantly, pozzolans decrease the alkalinity of the product.

Carbon Dioxide Treatment—In the manufacture of a cement-bonded lignocellulosic composite, the cement hydration process normally requires from 8 to 24 h to develop sufficient board strength and cohesiveness to permit the release of consolidation pressure. By exposing the cement to carbon dioxide, the initial hardening stage can be reduced to less than 5 min. This phenomenon results from the chemical reaction of carbon dioxide with calcium hydroxide to form calcium carbonate and water.

Reduction of initial cure time of the cement-bonded lignocellulosic composite is not the only advantage of using carbon dioxide injection. Certain species of wood have various amounts of sugars and tannins that interfere with the hydration or setting of Portland cement. Research has shown that the use of carbon dioxide injection reduces the likelihood that these compounds will inhibit the hydration process,

thus allowing the use of a wider range of species. In addition, research has demonstrated that composites treated with carbon dioxide can be twice as stiff and strong as untreated composites (Geimer and others 1992). Finally, carbon-dioxide-treated composites do not experience efflorescence (migration of calcium hydroxide to surface of material), so the appearance of the surface of the final product is not changed over time.

Ceramic-Bonded Composite Materials

In the last few years a new class of inorganic binders, non-sintered ceramic inorganic binders, has been developed. These non-sintered ceramic binders are formed by an acid–base aqueous reaction between a divalent or trivalent oxide and an acid phosphate or phosphoric acid. The reaction slurry hardens rapidly, but the rate of setting can be controlled. With suitable selection of oxides and acid-phosphates, a range of binders may be produced. Recent research suggests that phosphates may be used as adhesives, cements, or surface augmentation materials to manufacture wood-based composites (Jeong and Wagh 2003, Wagh and Jeong 2003).

As adhesives, the reaction slurry resulting from the acid–base reaction may be used as an adhesive similar to the current polymer resins. Thus, phosphate adhesives can be used to coat individual fibers and form a composite by binding the fibers to each other. The adhesives will behave much like current polymer resins and may be used with existing equipment. The binder content is typically 15% to 20 % by weight.

As a cement, phosphate binders can be used to produce bulk composites. When conventional cement is used in fiber-based products, typical cement loading is approximately 30% or higher; phosphate cements may be used in a similar manner. The slurry formed by the acid–base reaction may be mixed with fiber or any other extender to produce solid composites (Jeong and Wagh 2003).

Phosphate binders may also be used for coating wood-based composite panels to enhance surface properties. The phosphate slurry is very smooth; thin (<1 mm) coatings can be applied, suitable for providing fire or water resistance.

Wood–Thermoplastic Composite Materials

In North America and Europe, wood elements have been combined with thermoplastics for several decades. However, it is only in the past decade that wood–thermoplastic composites have become a widely recognized commercial product in construction, automotive, furniture, and other consumer applications (Oksman Niska and Sain 2008). Commercialization in North America has been primarily due to penetration into the construction industry, first as decking and window profiles, followed by railing, siding, and roofing. Interior molding applications are also receiving attention. The automotive industry in Europe has been a leader

in using wood–thermoplastic composites for interior panel parts and is leading the way in developing furniture applications. Manufacturers in Asia are targeting the furniture industry, in addition to interior construction applications. Continued research and development will expand the available markets and each application will penetrate the global marketplace.

Materials

Broadly defined, a thermoplastic softens when heated and hardens when cooled. Thermoplastics selected for use with wood generally melt or soften at or below the thermal degradation temperature of the wood element, normally 200 to 220 °C (392 to 428 °F). These thermoplastics include polypropylene, polystyrene, vinyls, and low- and high-density polyethylenes.

The term wood–thermoplastic composites is broad, and the class of materials can include fibers derived from wood or other natural sources. Geographical location often dictates the raw material choice. In North America, wood is the most common raw material, in Europe natural fibers such as jute, hemp, and kenaf are preferred, while rice hull flour and bamboo fiber are typical in Asia. The wood is incorporated as either fiber bundles with low aspect ratio (wood flour) or as single fibers with higher aspect ratio (wood fiber). Wood flour is processed commercially, often from post-industrial materials such as planer shavings, chips, and sawdust. Several grades are available depending upon wood species and particle size. Wood fibers, although more difficult to process than wood flour, can lead to superior composite properties and act more as a reinforcement than as a filler. A wide variety of wood fibers are available from both virgin and recycled resources.

Other materials can be added to affect processing and product performance of wood–thermoplastic composites. These additives can improve bonding between the thermoplastic and wood component (for example, coupling agents), product performance (impact modifiers, ultraviolet (UV) light stabilizers, flame retardants), and processability (lubricants).

Wood–thermoplastic composites are of two main types. In the first type, the wood element serves as a reinforcing agent or filler in a continuous thermoplastic matrix. In the second type, the thermoplastic serves as a binder to the wood elements much like conventional wood-based composites. The presence or absence of a continuous thermoplastic matrix may also determine the processability of the composite material. In general, if the matrix is continuous, conventional thermoplastic processing equipment may be used to process composites; however, if the matrix is not continuous, other processes may be required. For the purpose of discussion, we present two scenarios—composites with high and low thermoplastic content.

Composite Materials with High Thermoplastic Content

The vast majority of commercially available wood–thermoplastic composites have high thermoplastic content. In composites with high thermoplastic content, the thermoplastic component is a continuous matrix and the wood element serves as a reinforcement or filler. The wood content is typically less than 60% by weight. In the great majority of reinforced thermoplastic composites available commercially, inorganic materials (for example, glass, clays, and minerals) are used as reinforcements or fillers. Wood-based materials offer some advantages over inorganic materials: they are lighter, much less abrasive, and renewable. Wood elements reinforce the thermoplastic by stiffening and strengthening and can improve thermal stability of the product compared with that of unfilled material.

The manufacture of thermoplastic composites is usually a two-step process. The raw materials are first mixed together in one step, and the composite blend is then formed into a product in the second step. The combination of these steps is called in-line processing, and the result is a single processing step that converts raw materials to end products. In-line processing can be very difficult because of control demands and processing trade-offs. As a result, it is often easier and more economical to separate the processing into a compounding step and a forming step (Clemons 2002).

Compounding is the feeding and dispersing of the wood element in a molten thermoplastic to produce a homogeneous material. Various additives are added and moisture is removed during compounding. Compounding may be accomplished using either batch mixers (for example, internal and thermokinetic mixers) or continuous mixers (for example, extruders and kneaders).

The compounded material can be immediately pressed or shaped into an end product while still in its molten state or pelletized into small, regular pellets for future reheating and forming. The most common types of product-forming methods for wood–thermoplastic composites involve forcing molten material through a die (sheet or profile extrusion) or into a cold mold (injection molding), or pressing in calenders (calendering) or between mold halves (thermoforming and compression molding). Most wood–thermoplastic composites in North America are formed using profile extrusion. Products such as decking, siding, railings, and window profiles readily lend themselves to extrusion through a two-dimensional die (Fig. 11–17). Injection-molded applications such as consumer household goods and furniture parts are gaining importance (Fig. 11–18). Thermoforming or compression molding is the forming method of choice for the automotive industry.

Several factors must be considered when processing wood with thermoplastics. Moisture can disrupt many thermoplastic processes, resulting in poor surface quality, voids, and unacceptable parts. Either materials must be



Figure 11–17. Extruded wood–thermoplastic composites being evaluated for a siding application (Clemons and Stark 2007).

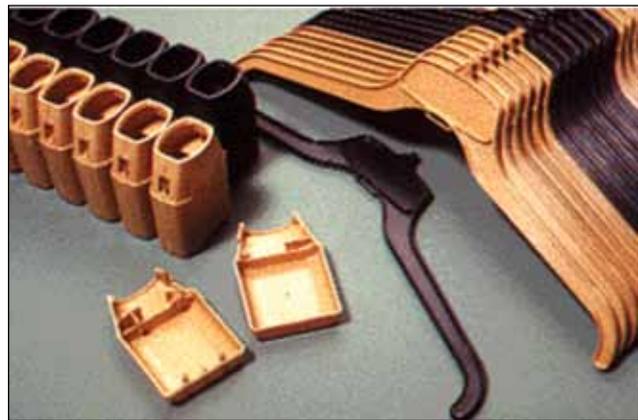


Figure 11–18. Injection-molded wood–thermoplastic composites in a variety of shapes and forms.

pre-dried or vented equipment must be used to remove moisture. The low thermal degradation temperature of wood must also be considered. As a general rule, melt temperatures should be kept below 200 °C (392 °F), except for short periods. Higher temperatures can result in the release of volatiles, discoloration, odor, and embrittlement of the wood component. Although processing wood flour in thermoplastics is relatively easy, the low bulk density and difficulty of dispersing fibrous materials in thermoplastics is more difficult. More intensive mixing and the use of special feeding equipment may be necessary to handle longer fibers.

Composite Materials with Low Thermoplastic Content

In composites with low thermoplastic content, the thermoplastic component is not continuous, acting more as a binder for the fiber much the same way as binders in conventional wood-based composites. Thermoplastic content is typically

Chapter 11 Wood-Based Composite Materials

less than 30% by weight. In their simplest form, lignocellulosic particles or fibers can be dry-blended with thermoplastic granules, flakes, or fibers and pressed into panel products. An alternative is to use the thermoplastic in the form of a textile fiber. The thermoplastic textile fiber enables a variety of lignocellulosics to be incorporated into a low-density, non-woven, textile-like mat. The mat may be a product in itself, or it may be consolidated into a high-density product.

Because the thermoplastic component remains molten when hot, different pressing strategies must be used than when thermosetting binders are used. Two options have been developed to accommodate these types of composites. In the first, the material is placed in the hot press at ambient temperature. The press then closes and consolidates the material, and heat is used to melt the thermoplastic component, which flows around the lignocellulosic component. The press is then cooled, “freezing” the thermoplastic so that the composite can be removed from the press. Alternatively, the material can be first heated in an oven or hot press. The hot material is then transferred to a cool press where it is quickly consolidated and cooled to make a rigid panel. Some commercial nonstructural wood–thermoplastic composite panels are made in this way.

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Mechanical Properties of Wood-Based Composite Materials

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The term *composite* is used to describe any wood material bonded together with adhesives. The current product mix ranges from fiberboard to laminated beams and components. In this chapter, wood-based composite materials are classified into the following categories: panel products (plywood, oriented strandboard (OSB), particleboard, fiberboard, medium-density fiberboard (MDF), hardboard); structural timber products (glued-laminated timber (glulam), laminated veneer lumber (LVL), laminated strand lumber, parallel strand lumber); and wood–nonwood composites (wood fiber–thermoplastics, inorganic-bonded composites).

Wood-based composites are used for a number of structural and nonstructural applications. Product lines include panels for both interior and exterior uses, furniture components, and support structures in buildings. Knowledge of the mechanical properties of these products is of critical importance to their proper use.

Wood-based composites are made from a wide range of materials—from fibers obtained from underutilized small-diameter or plantation trees to structural lumber. Regardless of the raw material used in their manufacture, wood-based composites provide uniform and predictable in-service performance, largely as a consequence of standards used to monitor and control their manufacture. The mechanical properties of wood composites depend upon a variety of factors, including wood species, forest management regimes (naturally regenerated, intensively managed), the type of adhesive used to bind the wood elements together, geometry of the wood elements (fibers, flakes, strands, particles, veneer, lumber), and density of the final product (Cai 2006).

A wide range of engineering properties are used to characterize the performance of wood-based composites. Mechanical properties are typically the most frequently used to evaluate wood-based composites for structural and nonstructural applications. Elastic and strength properties are the primary criteria to select materials or to establish design or product specifications. Elastic properties include modulus of elasticity (MOE) in bending, tension, and compression. Strength properties usually reported include modulus of rupture (MOR, bending strength), compression strength parallel to surface, tension strength parallel to surface, tension strength perpendicular to surface (internal bond strength), shear strength, fastener holding capacity, and hardness. Model

Table 12–1. Static bending properties of different wood and wood-based composites

Material	Specific gravity	Static bending properties			
		Modulus of elasticity		Modulus of rupture	
		GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)
Clear wood					
White oak	0.68	12.27	(1.78)	104.80	(15,200)
Red maple	0.54	11.31	(1.64)	92.39	(13,400)
Douglas-fir (Coastal)	0.48	13.44	(1.95)	85.49	(12,400)
Western white pine	0.38	10.07	(1.46)	66.88	(9,700)
Longleaf pine	0.59	13.65	(1.98)	99.97	(14,500)
Panel products					
Hardboard	0.9–1.0	3.10–5.52	(0.45–0.80)	31.02–56.54	(4,500–8,200)
Medium-density fiberboard	0.7–0.9	3.59	(0.52)	35.85	(5,200)
Particleboard	0.6–0.8	2.76–4.14	(0.40–0.60)	15.17–24.13	(2,200–3,500)
Oriented strandboard	0.5–0.8	4.41–6.28	(0.64–0.91)	21.80–34.70	(3,161–5,027)
Plywood	0.4–0.6	6.96–8.55	(1.01–1.24)	33.72–42.61	(4,890–6,180)
Structural timber products					
Glued-laminated timber	0.4–0.6	9.00–14.50	(1.30–2.10)	28.61–62.62	(4,150–9,080)
Laminated veneer lumber	0.4–0.7	8.96–19.24	(1.30–2.79)	33.78–86.18	(4,900–12,500)
Wood–nonwood composites					
Wood plastic		1.53–4.23	(0.22–0.61)	25.41–52.32	(3,684–7,585)

building codes in the United States stipulate that plywood used for structural applications such as subflooring and sheathing must meet the requirements of certain U.S. Department of Commerce standards. Voluntary Product Standard PS 1–07 for construction and industrial plywood (NIST 2007) and Performance Standard PS 2–04 for wood-based structural-use panels (NIST 2004) spell out the ground rules for manufacturing plywood and establishing plywood or OSB properties, respectively. These standards have evolved over time from earlier documents (O’Halloran 1979, 1980; APA 1981) and represent a consensus opinion of the makers, sellers, and users of plywood products as well as other concerned parties.

Many of the questions that arise with wood-based composites have to do with their mechanical properties, especially how properties of one type of material compare with those of clear wood and other wood products. Although an extensive review that compares all properties of wood-based materials and products is beyond the scope of this chapter, Table 12–1 provides some insight to how static bending properties of these materials vary and how their properties compare with those of solid, clear wood. Although the mechanical properties of most wood composites might not be as high as those of solid wood, they provide very consistent and uniform performance.

The mechanical property data presented in this chapter were obtained from a variety of reports of research conducted to develop basic property information for a wide range of wood-based composite materials. The wood-based composites industry is very dynamic, with changes occurring frequently in the manufacture of these materials and corresponding changes in design information. Consequently,

this chapter primarily focuses on presenting fundamental mechanical property information for wood-based composite materials. *For design procedures and values, the reader is encouraged to contact the appropriate industry trade association or product manufacturers. Current design information can be readily obtained from their websites, technical handbooks, and bulletins.*

The organization of this chapter follows closely that of Chapter 5. Basic mechanical property information is presented following a brief background discussion of these products. A discussion of performance and testing standards covering their manufacture and use is also presented.

Elastic Properties

Modulus of Elasticity

Elasticity implies that deformations produced by low stress below the proportional limit are completely recoverable after loads are removed. When loaded to stress levels above the proportional limit, plastic deformation or failure occurs. Typically, the stress–strain curve for wood-based composites is linear below the proportional limit. The slope of the linear curve is the MOE. In compression or tensile tests, this slope is sometime referred to as Young’s modulus to differentiate it from bending MOE. Bending MOE is a measure of the resistance to bending deflection, which is relative to the stiffness. Young’s modulus is a measure of resistance to elongation or shortening of a member under tension or compression. The procedure to determine MOE is fully described in ASTM D 1037 for fiber- and particle-based panel products, ASTM D 3043 for structural wood-based panels, ASTM D 5456 for structural composite lumber products,

ASTM D 7031 for wood–plastic composites, and ASTM D 7341 for glulam products.

Shear Modulus

Shear modulus, also called modulus of rigidity, indicates the resistance to deflection of a member caused by shear stresses. Shear stress is different from tension or compression stress in that it tends to make one side of a member slip past the other side of a member adjacent to it. There are two main types of shear in different planes of wood-based panels: interlaminar shear and edgewise shear or shear through-the-thickness. Interlaminar shear is also commonly called planar shear (or rolling shear, or horizontal shear) in plywood panels to describe stress that acts between the veneers that are glued with grain direction in adjacent pieces perpendicular to one another. For example, when the plywood panel is loaded in the middle with its two ends simply supported, the layers or veneers tend to slip horizontally past each other as the panel bends. The glue-bonding between the laminates of veneers resists the slipping and often dictates the panel stiffness. Edgewise shear is also commonly called racking shear. The moduli of rigidity vary within and between species, resin application, moisture content, and specific gravity. The procedure to determine different shear moduli for fiber- and particle-based panels is described in ASTM D 1037 and for structural panels in ASTM D 3044.

Strength Properties

Strength refers to the maximum stress that can be developed in a member due to applied loads prior to failure. Mechanical properties most commonly measured and represented as “strength properties” for design include modulus of rupture in bending, tension strength parallel-to-surface, tension strength perpendicular-to-surface, compression strength parallel-to-surface, shear strength, fastener holding strength, and hardness. Strength tests are typically made on specimens at moisture equilibrium under prescribed conditions or after soaking. The procedures to determine strengths for wood-based composites are described in ASTM D 1037, ASTM D 3044, ASTM D 5456, ASTM D 3737, and ASTM D 7031.

Modulus of rupture reflects the maximum load-carrying capacity of a member in bending and is proportional to maximum moment borne by the specimen. Modulus of rupture is an accepted measure of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit (McNatt 1973).

Tension strength parallel-to-surface is the maximum stress sustained by a specimen from a test with tension forces applied parallel to the surface. Tests are made with the long dimension of the specimen cut both parallel and perpendicular to the long dimension of the board to determine the strength in each of the primary panel directions.

Tension strength perpendicular-to-surface (internal bond strength) is the maximum stress sustained by a specimen from a test with tension forces applied perpendicular to the surface. Tests are made on specimens in the dry condition to determine the resistance of the specimen to delamination or splitting in the direction perpendicular to the plane of the board.

Compression strength parallel-to-surface is the maximum stress sustained by a specimen from a test with compression forces applied parallel to the surface. Tests are made with the long dimension of the specimen cut both parallel and perpendicular to the long dimension of the board to determine the material’s resistance to crushing in each of the primary panel directions.

Interlaminar shear (planar shear) indicates the ability to resist internal slipping of one layer upon another within the panel. It is used to describe the glue line or bonding performance inside or between the test materials.

Hardness is measured as resistance to indentation using a modified Janka hardness test, measured by the load required to embed an 11.3-mm (0.444-in.) diameter ball to one-half its diameter.

Fastener holding strength is the maximum resistance to separate or withdraw a fastener in a plane normal to the testing face. It usually contains three tests: nail withdrawal, nail-head pull-through, and direct screw withdrawal.

Panel Products

Plywood

Plywood is separated into two general classes: (a) construction and industrial plywood and (b) hardwood and decorative plywood. Construction and industrial plywood are covered by Product Standard PS 1–07 (NIST 2007), and hardwood and decorative plywood are covered by American National Standard ANSI/HPVA–1–2004 (HPVA 2004). Each standard recognizes different exposure durability classifications, which are primarily based on moisture resistance of the adhesive and the grade of veneer used. In addition, model building codes require that plywood manufacturers be inspected and their products certified for conformance to PS 1–07, PS 2–04, APA PRP–108, or TECO PRP–133 (TECO 1991) by qualified independent third-party agencies on a periodic unannounced basis. With PS 1–07, as long as a plywood panel is manufactured using the veneer grades, adhesive, and construction established in the standard’s prescriptive requirements, the panel is by definition acceptable.

All hardwood plywood represented as conforming to American National Standard ANSI/HPVA–1–2004 (HPVA 2004) is identified by one of two methods: by marking each panel with the Hardwood Plywood & Veneer Association (HPVA) plywood grade stamp or by including a written statement with this information with the order or shipment.

Table 12–2. Selected properties of plywood sheathing products^a

Species	Specific gravity	Static bending									
		MOE		MOR		Fiber stress at proportional limit		Rail shear strength		Glue line shear strength	
		GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	GPa	(lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)
Baldcypress	0.50	7.58	(1.10)	39.23	(5,690)	29.4	(4,260)	5.6	(805)	2.7	(389)
Douglas-fir	0.53	7.45	(1.08)	41.37	(6,000)	39.3	(5,700)	3.8	(556)	1.4	(207)
Lauan	0.44	7.43	(1.08)	33.72	(4,890)	28.1	(4,070)	4.3	(628)	1.3	(192)
Western redcedar	0.41	8.55	(1.24)	37.37	(5,420)	33.3	(4,830)	4.6	(674)	1.7	(240)
Redwood	0.41	6.96	(1.01)	42.61	(6,180)	37.4	(5,420)	5.3	(769)	1.5	(220)
Southern Pine	0.57	7.70	(1.12)	37.09	(5,380)	26.2	(3,800)	5.5	(800)	1.6	(233)

^aFrom Biblis (2000).

If design calculations are desired, a design guide is provided by the APA–The Engineered Wood Association in *Plywood Design Specification* (PDS) and APA Technical Note N375B (APA 1995a,b). The design guide contains tables of grade stamp references, section properties, and allowable stresses for plywood used in construction of buildings and similar structures. Table 12–2 shows selected properties of various species of plywood.

Oriented Strandboard (OSB)

Oriented strandboard is an engineered, structural-use panel manufactured from thin wood strands bonded together with water-resistant adhesive under heat and pressure. It is used extensively for roof, wall, and floor sheathing in residential and commercial construction. Design capacities of performance-rated products, which include OSB and waferboard, can be determined by using procedures outlined in Technical Note N375B (APA 1995a). In this reference, allowable design strength and stiffness properties, as well as nominal thickness and section properties, are specified based on the span rating of the panel. Additional adjustment factors based on panel grade and construction are also provided. Table 12–3 shows selected properties of OSB obtained from the literature.

Under PS 2–04, a manufacturer is required to enter into an agreement with an accredited testing agency to demonstrate that its panels conform to the requirements of the chosen standard. The manufacturer must also maintain an in-plant quality control program in which panel properties are regularly checked, backed by a quality assurance program administered by an independent third-party. The third-party agency must visit the mill on a regular unannounced basis. The agency must confirm that the in-plant quality control program is being maintained and that panels meet the minimum requirements of the standard.

Particleboard

Particleboard is typically made in three layers. The faces of the board consist of fine wood particles, and the core is

made of the coarser material (Chap. 11). Particleboard is used for furniture cores and case goods, where it is typically overlaid with other materials for decorative purposes. Particleboard can be used in flooring systems, in manufactured houses, for stair treads, and as underlayment. Requirements for grades of particleboard and particleboard flooring products are specified by the American National Standard for Particleboard A208.1-1999 (CPA 1999). Table 12–4 represents some of selected properties of different particleboard manufacturers.

Hardboard

Basic hardboard physical properties for selected products are presented in ANSI A135.4–2004 (CPA 2004a). The uses for hardboard can generally be grouped as construction, furniture and furnishings, cabinet and store work, appliances, and automotive and rolling stock. Typical hardboard products are prefinished paneling (ANSI A135.5–2004 (CPA 2004b)), house siding (ANSI A135.6–2006 (CPA 2006)), floor underlayment, and concrete form board. Table 12–5 shows selected physical and mechanical properties of hardboard from different manufacturers. Hardboard siding products come in a great variety of finishes and textures (smooth or embossed) and in different sizes. For application purposes, the Composite Panel Association (CPA) classifies siding into three basic types:

Lap siding—boards applied horizontally, with each board overlapping the board below it

Square edge panels—siding intended for vertical application in full sheets

Shiplap edge panel siding—siding intended for vertical application, with the long edges incorporating shiplap joints

The type of panel dictates the application method. The CPA administers a quality conformance program for hardboard for both panel and lap siding. Participation in this program is voluntary and is open to all (not restricted to CPA members). Under this program, hardboard siding products are

Table 12–3. Selected properties of oriented strandboard (OSB) products

Reference	Species	Mill no.	Specific gravity	Bending MOE				Bending MOR				Internal bond	
				Parallel		Perpendicular		Parallel		Perpendicular			
				GPa	($\times 10^6$ lb in ⁻²)	GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)
Biblis (1989)	Southern Pine	1	0.80	4.41	(0.640)	2.89	(0.419)	23.8	(3,445)	24.2	(3,515)	0.57	(83)
		2	0.70	4.78	(0.694)	2.61	(0.378)	26.0	(3,775)	22.1	(3,205)	0.28	(41)
		3	0.68	5.75	(0.834)	3.17	(0.460)	32.0	(4,645)	23.8	(3,445)	0.32	(47)
Pu and others (1992)	Southern Pine	4	0.51	4.41	(0.640)	2.40	(0.348)	21.8	(3,161)	25.4	(3,685)	0.23	(34)
		5	0.60	5.67	(0.822)	2.61	(0.378)	27.8	(4,039)	27.1	(3,925)	0.28	(41)
		6	0.58	4.41	(0.640)	2.97	(0.431)	23.9	(3,473)	28.7	(4,165)	0.26	(38)
	Aspen	7	0.65	6.28	(0.911)	2.03	(0.294)	32.2	(4,672)	30.4	(4,405)	0.43	(62)
		8	0.66	5.69	(0.825)	1.92	(0.278)	31.6	(4,584)	32.0	(4,645)	0.41	(60)
		9	0.74	6.31	(0.915)	2.79	(0.404)	34.7	(5,027)	33.7	(4,885)	0.34	(50)
Wang and others (2003a)	Southern Pine	10	0.63	5.01	(0.726)	2.26	(0.327)	30.2	(4,379)	16.8	(2,436)	0.36	(52)
		11	0.66	5.30	(0.769)	2.32	(0.336)	28.1	(4,075)	14.4	(2,088)	0.43	(62)
		12	0.67	5.12	(0.742)	2.56	(0.371)	30.7	(4,452)	21.1	(3,060)	0.32	(46)
		13	0.66	4.91	(0.712)	2.24	(0.325)	28.3	(4,104)	19.8	(2,871)	0.38	(55)
	Hardwood mixture	14	0.68	5.15	(0.747)	1.77	(0.257)	26.9	(3,901)	11.8	(1,711)	0.28	(40)
		15	0.67	5.87	(0.851)	1.40	(0.204)	33.9	(4,916)	7.8	(1,131)	0.23	(33)
		16	0.70	6.73	(0.976)	2.25	(0.326)	36.9	(5,351)	15.8	(2,291)	0.45	(66)
	Aspen	17	0.63	6.50	(0.943)	3.10	(0.450)	38.0	(5,510)	21.5	(3,118)	0.28	(41)
		18	0.62	7.90	(1.146)	3.10	(0.450)	38.8	(5,626)	23.2	(3,364)	0.46	(66)
		19	0.61	6.10	(0.885)	2.50	(0.363)	30.7	(4,452)	19.7	(2,857)	0.34	(49)
20		0.61	6.50	(0.943)	1.80	(0.261)	35.5	(5,148)	13.7	(1,987)	0.25	(36)	
21		0.66	6.75	(0.979)	2.45	(0.356)	37.3	(5,409)	19.3	(2,799)	0.38	(55)	
22		0.63	5.80	(0.840)	2.40	(0.348)	26.9	(3,901)	17.9	(2,596)	0.40	(58)	

Table 12–4. Selected properties of industrial particleboard products^a

Mill	Moisture content (%)	Specific gravity	Static bending properties				Tensile properties				Internal bond	
			Modulus of elasticity		Modulus of rupture		Modulus of elasticity		Ultimate tensile stress			
			GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)
A	8.7	0.71	3.0	(0.44)	16.8	(2,430)	2.2	(0.32)	7.72	(1,120)	0.79	(115)
B	9.1	0.72	3.5	(0.51)	20.6	(2,990)	2.6	(0.38)	9.38	(1,360)	1.07	(155)
C	9.8	0.76	3.5	(0.51)	18.9	(2,740)	2.3	(0.34)	8.27	(1,200)	1.00	(145)
H	8.0	0.77	4.0	(0.58)	22.8	(3,310)	3.0	(0.44)	10.89	(1,580)	1.17	(170)
J	8.5	0.72	3.0	(0.43)	17.2	(2,500)	1.9	(0.28)	7.45	(1,080)	0.45	(65)
K	9.1	0.68	2.8	(0.40)	15.2	(2,206)	1.6	(0.23)	5.58	(810)	0.31	(45)
L	9.3	0.62	3.2	(0.46)	17.0	(2,470)	1.8	(0.26)	6.69	(970)	0.48	(70)
M	9.7	0.65	3.6	(0.52)	18.9	(2,740)	2.2	(0.32)	8.07	(1,170)	0.69	(100)
N	8.3	0.60	3.1	(0.45)	17.0	(2,470)	3.7	(0.54)	8.00	(1,160)	0.31	(45)

^aFrom McNatt (1973).

tested by an independent laboratory in accordance with product standard ANSI A135.6.

Medium-Density Fiberboard

Minimum property requirements for MDF are specified by the American National Standard for MDF, ANSI A208.2-2002 (CPA 2002), and some of selected properties are given in Table 12–6 from different manufacturers. Medium-density fiberboard is frequently used in furniture applications. It is also used for interior door skins, moldings, flooring

substrate, and interior trim components (Cai and others 2006, Youngquist and others 1993).

Timber Elements/Structural Composite Lumber

Glued-Laminated Timber

Structural glued-laminated timber (glulam) is an engineered, stress-rated product that consists of two or more layers of lumber that are glued together with the grain of all layers,

Table 12–5. Selected properties of hardboard products^a

Mill	Type of hardboard	Moisture content (%)	Specific gravity	Modulus of elasticity		Modulus of rupture		Ultimate tensile stress		Internal bond	
				GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)
A	1/8-in.	4.6	0.9	3.83	(556)	31.44	(4,560)	23.24	(3,370)	1.24	(180)
B	standard	6.5	1.02	4.36	(633)	33.92	(4,920)	23.17	(3,360)	2.76	(400)
C		5.2	0.94	4.20	(609)	45.85	(6,650)	37.58	(5,450)	2.17	(315)
D		5.6	0.9	3.32	(482)	38.75	(5,620)	28.61	(4,150)	1.55	(225)
E		6.5	0.95	3.55	(515)	47.50	(6,890)	32.96	(4,780)	3.52	(510)
F		7.7	0.91	3.23	(468)	37.85	(5,490)	25.72	(3,730)	1.93	(280)
B	1/4-in.	6.4	1.02	4.45	(645)	33.85	(4,910)	22.61	(3,280)	1.86	(270)
E	standard	6.0	0.90	3.88	(563)	38.96	(5,650)	23.65	(3,430)	1.65	(240)
A	1/4-in. tempered	4.9	0.99	5.30	(768)	53.02	(7,690)	31.58	(4,580)	1.79	(260)
F	1/4-in. tempered	6.9	0.98	5.14	(745)	55.57	(8,060)	30.61	(4,440)	1.86	(270)

^aFrom McNatt and Myers (1993).**Table 12–6. Selected properties of medium-density fiberboard products^a**

Mill no.	Density (g cm ⁻³)	Modulus of rupture		Modulus of elasticity		Internal bond		Screw-holding edge		Capacity face	
		MPa	(lb in ⁻²)	GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)	kg	(lb)	kg	(lb)
1	0.73	33.6	(4,873)	3.21	(466)	0.86	(125)	117	(257)	148	(326)
2	0.90	34.0	(4,932)	3.97	(576)	0.94	(136)	147	(325)	185	(407)
3	0.79	23.2	(3,366)	2.98	(432)	1.94	(282)	150	(330)	202	(445)
4	0.82	39.3	(5,703)	4.38	(635)	0.83	(121)	114	(252)	148	(326)
5	0.95	24.6	(3,565)	3.56	(517)	0.92	(133)	184	(405)	231	(509)
6	0.80	36.4	(5,278)	3.99	(578)	0.71	(103)	143	(315)	183	(404)
7	0.77	37.4	(5,421)	3.94	(572)	1.23	(179)	163	(360)	210	(464)
8	0.71	35.2	(5,107)	3.34	(485)	1.09	(158)	147	(324)	189	(416)

^aFrom Suchsland and others (1979).

which are referred to as laminations, parallel to the length. Table 12–7 provides some selected properties of glulam products from different research studies.

Douglas–Fir–Larch, Southern Pine, yellow-cedar, Hem–Fir, and Spruce–Pine–Fir are commonly used for glulam in the United States. Nearly any species can be used for glulam timber, provided its mechanical and physical properties are suitable and it can be properly glued. Industry standards cover many softwoods and hardwoods, and procedures are in place for using other species.

Manufacturers of glulam timber have standardized the target design values in bending for beams. For softwoods, these design values are given in “Standard for Wood Products: Structural Glued-Laminated Timber” (AITC 2007). This specification contains design values and recommended modification of stresses for the design of glulam timber members in the United States. The *National Design Specification for Wood Construction* (NDS) summarizes the design information in ANSI/AITC 190.1 and defines the practice to be

followed in structural design of glulam timbers (AF&PA 2005). APA–The Engineered Wood Association has also developed design values for glulam under National Evaluation Report 486, which is recognized by all the building codes.

Structural Composite Lumber

Structural composite lumber (SCL) products are characterized by smaller pieces of wood glued together into sizes common for solid-sawn lumber. One type of SCL product is manufactured by laminating veneer with all plies parallel to the length. This product is called laminated veneer lumber (LVL) and consists of specially graded veneer. Another type of SCL product consists of strands of wood or strips of veneer glued together under high pressures and temperatures. Depending upon the component material, this product is called laminated strand lumber (LSL), parallel strand lumber (PSL), or oriented strand lumber (OSL).

In contrast with sawn lumber, the strength-reducing characteristics of SCL are dispersed within the veneer or strands and have much less of an effect on strength properties. Thus,

Table 12–7. Selected properties of glulam products

Reference	Species	Moisture content (%)	Number of laminations	Static bending properties			
				Modulus of elasticity		Modulus of rupture	
				GPa	($\times 10^6$ lb in ⁻²)	MPa	(lb in ⁻²)
Manbeck and others (1993)	Red maple	12	8	12.3	(1.78)	62.6	(9,080)
		12	12	12.2	(1.77)	55.0	(7,980)
		12	16	12.3	(1.78)	54.2	(7,860)
Moody and others (1993)	Yellow poplar	8.2	8	13.0	(1.89)	55.6	(8,060)
		7.5	12	13.4	(1.94)	52.1	(7,560)
		8	17	12.3	(1.79)	45.3	(6,570)
Shedlauskus and others (1996)	Red oak	12.8	8	13.0	(1.88)	60.5	(8,770)
		11.1	18	12.8	(1.86)	46.0	(6,670)
Janowiak and others (1995)	Red maple	12.6	12	12.2	(1.77)	55.0	(7,980)
		8.9	5	12.8	(1.86)		
		8.9	5	12.9	(1.87)	45.7	(6,630)
Hernandez and others (2005)	Ponderosa pine	8.8	8	9.44	(1.37)	31.4	(4,560)
		8.8	13	9.07	(1.32)	29.6	(4,290)
Hernandez and Moody (1992)	Southern Pine	—	10	14.1	(2.04)	61.7	(8,950)
		—	17	13.5	(1.96)	49.8	(7,230)
Marx and Moody (1981 a,b)	Southern Pine	10	4, 8, 10	11.2	(1.63)	46.5	(6,740)
		10	4, 8, 11	10.8	(1.56)	33.9	(4,920)
	Douglas-fir–larch	11	4, 8, 12	13.9	(2.02)	47.2	(6,840)
		11	4, 8, 13	13.6	(1.97)	40.7	(5,910)
Moody (1974)	Southern Pine	11.8	17	9.3	(1.35)	28.6	(4,150)
		11.9	17	10.3	(1.49)	31.4	(4,560)

relatively high design values can be assigned to strength properties for both LVL and PSL. Whereas both LSL and OSB have somewhat lower design values, they have the advantage of being produced from a raw material that need not be in a log size large enough for peeling into veneer.

All types of SCL products can be substituted for sawn lumber products in many applications. Laminated veneer lumber is used extensively for scaffold planks and in the flanges of prefabricated I-joists. Both LVL and PSL beams are used as headers and major load-carrying elements in construction. The LSL and OSB products are used for band joists in floor construction and as substitutes for studs and rafters in wall and roof construction. Various types of SCL are also used in a number of nonstructural applications, such as the manufacture of windows and doors. Table 12–8 provides some selected properties of LVL products from different research studies.

Wood–Nonwood Composites

Wood–Plastic Composite

The use of wood–plastic composite lumber in North America has experienced tremendous growth in the past decade, largely because of residential construction applications.

Common applications in North America include decking, railings, window profiles, roof tiles, and siding. These lumber products are generally manufactured using profile extrusion. Some generalizations can be made regarding the performance of wood–plastic composites, but there are exceptions. Flexural and tensile properties of wood–plastic composite lumber generally fall between those of solid wood lumber and unfilled plastics. Most commercial wood–plastic composites are considerably less stiff than solid wood but are stiffer than unfilled plastic (Clemons 2002). Compared with solid wood lumber, wood–plastic composites have better decay resistance and dimensional stability when exposed to moisture. Compared with unfilled plastics, wood–plastic composites are stiffer and have better dimensional stability when exposed to changes in temperature.

Table 12–9 shows mechanical properties of unfilled polypropylene and several wood–polypropylene composites. One of the primary reasons to add wood filler to unfilled plastics is to improve stiffness. Strength of the unfilled plastic can also increase but only if the wood component acts as reinforcement with good bonding between the two components. Table 12–9 illustrates how wood–plastic composite properties can vary with changing variables. For example, adding wood fiber instead of wood flour to polypropylene

Table 12–8. Selected properties of laminated veneer lumber for structural composite lumber products

Reference	Species	Static bending properties						Tensile properties				
		Modulus of elasticity			Modulus of rupture			Modulus of elasticity		Ultimate tensile stress		
		Edge	Flat	Edge	Flat	Edge	Flat	GPa	MPa	($\times 10^6$) lb in ⁻²	MPa	(lb in ⁻²)
		($\times 10^6$) GPa	($\times 10^6$) lb in ⁻²	MPa	(lb in ⁻²)	MPa	(lb in ⁻²)	GPa	MPa	($\times 10^6$) lb in ⁻²	MPa	(lb in ⁻²)
Bohlen (1974)	Douglas-fir	—	—	—	—	—	—	15.2	28.99	(2.20)	28.99	(4,205)
Youngquist and others (1984)	Douglas-fir	—	—	—	—	—	—	14.0–15.0	28.1–39.0	(2.03–2.17)	28.1–39.0	(4,080–5,650)
								11.1–12.4	18.3–38.1	(1.61–1.80)	18.3–38.1	(2,660–5,520)
Jung (1982)	Douglas-fir	15.5–19.2	(2.25–2.79)	15.4–19.3	(2.23–2.80)	58.0–71.7	(8,420–10,400)	15.6–20.3	37.9–46.2	(2.27–2.94)	37.9–46.2	(5,500–6,700)
Kunesh (1978)	Douglas-fir	15.9	(2.31)	16.1	(2.34)	—	—	14.1	44.4	(2.04)	44.4	(6,435)
Koch (1973)	Southern Pine	13.2	(1.91)	0.0	0.00	64.2	(9,310)	—	—	—	—	—
Moody (1972)	Douglas-fir	—	—	—	—	—	—	14.3	37.6	(2.07)	37.6	(5,450)
	Southern Pine	—	—	—	—	—	—	13.5	34.6	(1.96)	34.6	(5,025)
Moody and Peters (1972)	Southern Pine	14.1	(2.04)	14.7	(2.13)	80.8	(11,720)	86.0	—	—	—	—
Wang and others (2003b)	Red maple	10.8	(1.56)	11.3	(1.64)	83.3	(12,081)	—	—	—	—	—
Hindman and others (2006)	Southern Pine	15.8	(2.29)	17.4	(2.54)	—	—	—	—	—	—	—
Kretschmann and others (1993)	Douglas-fir	9.0–12.8	(1.30–1.86)	9.0–13.7	(1.30–1.98)	37.9–67.9	(5,500–9,850)	8.5–12.8	20.8–49.1	(1.24–1.86)	20.8–49.1	(3,020–7,100)
	Southern Pine	9.8–13.7	(1.34–1.98)	8.8–13.0	(1.27–1.89)	51.9–70.3	(7,530–10,190)	9.6–13.6	36.6–51.2	(1.39–1.97)	36.6–51.2	(5,310–7,430)

Table 12–9. Selected properties of wood–plastic products^a

Composite	Specific gravity	Tensile properties				Flexural properties				Izod impact energy (J m ⁻¹)	
		Strength		Modulus		Strength		Modulus		Notched	Unnotched
		MPa	(lb in ⁻²)	GPa	(×10 ⁶ lb in ⁻²)	MPa	(lb in ⁻²)	GPa	(×10 ⁶ lb in ⁻²)		
Polypropylene (PP)	0.90	28.5	(4,134)	1.53	(0.22)	38.30	(5,555)	1.19	(0.17)	20.9	656
PP + 40% wood flour	1.05	25.4	(3,684)	3.87	(0.56)	44.20	(6,411)	3.03	(0.44)	22.2	73
PP + 40% wood flour + 3% coupling agent	1.05	32.3	(4,685)	4.10	(0.59)	53.10	(7,702)	3.08	(0.45)	21.2	78
PP + 40% wood fiber	1.03	28.2	(4,090)	4.20	(0.61)	47.90	(6,947)	3.25	(0.47)	23.2	91
PP + 40% wood fiber + 3% coupling agent	1.03	52.3	(7,585)	4.23	(0.61)	72.40	(10,501)	3.22	(0.47)	21.6	162

^aFrom Stark and Rowlands (2003).

improved the strength and stiffness. Generally, adding a coupling agent to the mix also improved mechanical properties. Adding wood to polypropylene was not without tradeoffs. Impact resistance of such composites decreased compared with that of unfilled polypropylene.

In addition to these commercial deck products, wood–plastic composites are being developed for structural applications such as foundation elements, deck substructures, industrial decking, and shoreline structures (Bender and others 2006). Table 12–10 shows the range of average mechanical properties of extruded wood–plastic composites by polymer type. In general, polyvinylchloride and polyethylene formulations produce higher mechanical properties than those produced from polyethylene alone. Formulations that use coupling agents with either polypropylene or high-density polyethylene result in improved strength, stiffness, and reduced moisture absorption properties.

Properties of wood–plastic composites can vary greatly depending upon such variables as type, form, weight fractions of constituents, type of additives, and processing methods (Stark and Rowlands 2003, Wolcott and others 2006). Because formulations from each commercial manufacture are proprietary, design data should be obtained directly from the manufacturer.

Inorganic-Bonded Composites

Inorganic-bonded wood composites are molded products or boards that contain between 10% and 70% by weight wood particles or fibers and conversely 90% to 30% inorganic binder. Acceptable properties of an inorganic-bonded wood composite can be obtained only when the wood particles are fully encased with the binder to make a coherent material. This differs considerably from the technique used to manufacture thermosetting-resin-bonded boards, where flakes or

particles are “spot welded” by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than that of most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than that of resin-bonded wood composites. The properties of inorganic-bonded wood composites are significantly influenced by the amount and nature of the inorganic binder and the woody material as well as the density of the composites.

Inorganic binders fall into three main categories: gypsum, magnesia cement, and Portland cement. Gypsum and magnesia cement are sensitive to moisture, and their use is generally restricted to interior applications. Composites bonded with Portland cement are more durable than those bonded with gypsum or magnesia cement and are used in both interior and exterior applications. Inorganic-bonded composites are made by blending proportionate amounts of lignocellulosic fiber with inorganic materials in the presence of water and allowing the inorganic material to cure or “set up” to make a rigid composite. All inorganic-bonded composites are very resistant to deterioration, particularly by insects, vermin, and fire. Typical properties of low-density cement-wood composite fabricated using an excelsior-type particle are shown in Table 12–11.

Testing Standards

The physical and mechanical properties of wood-based composite materials are usually determined by standard ASTM test methods. The following are the commonly used methods described in ASTM (2009):

ASTM C 208–08. Standard specification for cellulosic fiber insulating board.

Table 12–10. Selected properties of extruded wood–plastic products

Composite	Tensile strength (MPa (lb in ⁻²))	Compression strength (MPa (lb in ⁻²))	Bending strength (GPa (×10 ⁶ lb in ⁻²))	Bending modulus (MPa (lb in ⁻²))	Shear strength (MPa (lb in ⁻²))	Dowel bearing strength (MPa (lb in ⁻²))
Polypropylene (PP) ^{a, b}	20.0 (2,900)	55.2 (8,000)	3.49–5.97 (0.506–0.866)	22.2–60.8 (3,220–8,820)	22.0 (3,190)	84.8 (12,300)
High-density polyethylene (HDPE) ^c	5.5–15.2 (800–2,200)	11.7–26.9 (1,700–3,900)	1.79–5.17 (0.260–0.750)	10.3–25.5 (1,500–3,700)	7.79–10.3 (1,130–1,500)	35.7 (5,180)
Polyvinylchloride (PVC) ^c	25.1 (3,640)	61.2 (8,880)	4.81–7.58 (0.697–1.100)	35.9–54.5 (5,200–7,900)	20.2 (2,930)	72.4–128.2 (10,500–18,600)

^aFrom Slaughter (2004).^bFrom Kobbe (2005).^cFrom Wolcott (2001).**Table 12–11. General properties of low-density cement–wood composite fabricated using an excelsior-type particle^{a, b}**

Property	Value range (MPa (lb in ⁻²))	
	Low	High
Bending strength	1.7 (250)	5.5 (800)
Modulus of elasticity	621 (90,000)	1,241 (180,000)
Tensile strength	0.69 (100)	4.1 (600)
Compression strength	0.69 (100)	5.5 (800)
Shear ^c	0.69 (100)	1.4 (200)
<i>E/G</i> ratio ^d	40.0	100.0

^aData present compilation of raw data from a variety of sources for range of board properties. Variables include cement–wood mix, particle configuration, density, and forming and curing method.^bSpecific gravity range from 0.5 to 1.0.^cShear strength data are limited to small samples having a specific gravity of 0.5 to 0.65.^d*E/G* is ratio of bending modulus of elasticity to shear modulus. For wood, this ratio is about 16.

ASTM D 1037–06a. Standard test methods for evaluating the properties of wood-based fiber and particle panel materials.

ASTM D 2718–00 (2006). Standard test method for structural panels in planar shear (rolling shear).

ASTM D 2719–89 (2007). Standard test methods for structural panels in shear through-the-thickness.

ASTM D 3043–00 (2006). Standard test methods of testing structural panels in flexure.

ASTM D 3044–94 (2006). Standard test method for shear modulus of wood-based structural plywood.

ASTM D 3500–90 (2003). Standard test methods for structural panels in tension.

ASTM D 3501–05a. Standard test methods of testing plywood in compression.

ASTM D 3737–08. Standard practice for establishing allowable properties for structural glued laminated timber (glulam).

ASTM D 5456–09. Specification for evaluation of structural composite lumber products.

ASTM D 7031–04. Standard guide for evaluating mechanical and physical properties of wood-plastic composite products.

ASTM D 7032–08. Standard specification for establishing performance ratings for wood-plastic composite deck boards and guardrail systems.

ASTM D 7341–09. Standard practice for establishing characteristic values for flexural properties of structural glued laminated timber by full-scale testing.

ASTM E 1333–96 (2002). Test method for determining formaldehyde concentration in air and emission rate from wood products using a large chamber.

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Drying and Control of Moisture Content and Dimensional Changes

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In the living tree, wood contains large quantities of water. As green wood dries, most of the water is removed. The moisture remaining in the wood tends to come to equilibrium with the relative humidity of the surrounding air. Correct drying, handling, and storage of wood will minimize moisture content changes that might occur after drying when the wood is in service. If moisture content is controlled within reasonable limits by such methods, major problems from dimensional changes can usually be avoided.

The discussion in this chapter is concerned with moisture content determination, recommended moisture content values, drying methods, methods of calculating dimensional changes, design factors affecting such changes in structures, and moisture content control during transit, storage, and construction. Data on green moisture content, fiber saturation point, shrinkage, and equilibrium moisture content are given with information on other physical properties in Chapter 4.

Wood in service is always undergoing slight changes in moisture content. These changes that result from daily humidity changes are often small and usually of no consequence. Changes that occur because of seasonal variation, although gradual, tend to be of more concern. Protective coatings can retard dimensional changes in wood but do not prevent them. In general, no significant dimensional changes will occur if wood is fabricated or installed at a moisture content corresponding to the average atmospheric conditions to which it will be exposed. When incompletely dried material is used in construction, some minor dimensional changes can be tolerated if the proper design is used.

Determination of Moisture Content

The amount of moisture in wood is ordinarily expressed as a percentage of wood mass when oven-dried. Four methods of determining moisture content are covered in ASTM D 4442 (ASTM 2007). Two of these—the oven-drying and the electrical methods—are described in this chapter.

The oven-drying method has been the most universally accepted method for determining moisture content, but it is slow and necessitates cutting the wood. In addition, the oven-drying method may give values slightly greater than true moisture content with woods containing volatile extrac-

tives. The electrical method is rapid, does not require cutting the wood, and can be used on wood installed in a structure. However, considerable care must be taken to use and interpret the results correctly. Use of the electrical method is generally limited to moisture content values less than 30%.

Oven-Drying Method

In the oven-drying method, specimens are taken from representative boards or pieces of a quantity of lumber. With lumber, obtain the specimens at least 500 mm (20 in.) from the end of the pieces. They should be free from knots and other irregularities, such as bark and pitch pockets. Specimens from lumber should be full cross sections and 25 mm (1 in.) long. Specimens from larger items may be representative sectors of such sections or subdivided increment borer or auger chip samples. Convenient amounts of chips and particles can be selected at random from larger batches, with care taken to ensure that the sample is representative of the batch. Select veneer samples from four or five locations in a sheet to ensure that the sample average will accurately indicate the average of the sheet.

To prevent drying or uptake of moisture, weigh each specimen immediately. If the specimen cannot be weighed immediately, place it in a plastic bag or tightly wrapped in metal foil to protect it from moisture change until it can be weighed. After weighing, place the specimen in an oven heated to 101 to 105 °C (214 to 221 °F), and keep it there until no appreciable weight change occurs in 4-h weighing intervals. A lumber section 25 mm (1 in.) along the grain will reach a constant weight in 12 to 48 h. Smaller specimens will take less time. The constant or oven-dry mass and the (original) mass of the specimen when cut are used to determine the percentage of moisture content (MC) using the formula

$$MC(\%) = \frac{\text{Mass when cut} - \text{Ovendry mass}}{\text{Ovendry mass}} \times 100 \quad (13-1)$$

Electrical Method

The electrical method of determining the moisture content of wood uses the relationships between moisture content and measurable electrical properties of wood, such as conductivity (or its inverse, resistivity), dielectric constant, or power-loss factor. These properties vary in a definite and predictable way with changing moisture content, but correlations are not perfect. Therefore, moisture determinations using electrical methods are always subject to some uncertainty.

Electric moisture meters are available commercially and are based on each of these properties and identified by the property measured. Conductance-type (or resistance) meters measure moisture content in terms of the direct current conductance of the specimen. Dielectric-type meters are of

two types. Those based principally on dielectric constant are called capacitance or capacitive admittance meters; those based on loss factor are called power-loss meters.

The principal advantages of the electrical method compared with the oven-drying method are speed and convenience. Only a few seconds are required for the determination, and the piece of wood being tested is not cut or damaged, except for driving electrode needle points into the wood when using conductance-type meters. Thus, the electrical method is adaptable to rapid sorting of lumber on the basis of moisture content, measuring the moisture content of wood installed in a building, or establishing the moisture content of a quantity of lumber or other wood items, when used in accordance with ASTM D 4442.

For conductance meters, needle electrodes (pins) of various lengths are driven into the wood. The two general types of electrodes are insulated and uninsulated. Uninsulated electrodes will sense the lowest resistance (highest conductance) along their length, thus highest moisture content level. Moisture gradients between the surface and the interior can lead to confusion; therefore, insulating the electrode except the tip is useful to show moisture gradients. If the wood is wetter near the center than the surface, which is typical for drying wood, the reading will correspond to the depth of the tip of the insulated electrodes. If a meter reading increases as the electrodes are being driven in, then the moisture gradient is typical. In this case, drive the pins about one-fifth to one-fourth the thickness of the wood to reflect the average moisture content of the entire piece. Dried or partially dried wood sometimes regains moisture in the surface fibers from rewetting therefore the surface moisture content is greater than that of the interior. An example of this is when dried wood is rained on. In this case, the meter with the uninsulated pins will read the higher moisture content surface, possibly causing a significant deviation from the average moisture content. To guard against this problem, electrodes with insulated shanks have been developed. They measure moisture content of only the wood at the tips of the electrodes.

Dielectric-type meters are fitted with surface contact electrodes designed for the type of specimen material being tested. The electric field from these electrodes penetrates well into the specimen, but with a strength that decreases rapidly with depth of penetration. For this reason, the surface layers of the specimen influence the readings of dielectric (pinless) meters predominantly, and the meter reading may not adequately represent the material near the core if there is a large moisture content gradient.

To obtain accurate moisture content values, use each instrument in accordance with its manufacturer's instructions. The electrodes should be appropriate for the material being tested and properly oriented according to the meter manufacturer's instructions. Take the readings after inserting

the electrode. Apply a species correction supplied with the instrument when appropriate. Make temperature corrections if the temperature of the wood differs considerably from the temperature of calibration used by the manufacturer. Approximate corrections for conductance-type (resistance) meters are made by adding or subtracting about 0.5% for each 5.6 °C (10 °F) the wood temperature differs from the calibration temperature. Add the correction factors to the readings for temperatures less than the calibration temperature and subtract from the readings for temperatures greater than the calibration temperature. Temperature corrections for older dielectric meters are rather complex and are best made from published charts (James 1988). Newer dielectric meters perform this temperature calibration internally, although newer dielectric meters require a specific gravity adjustment.

Although some meters have scales that go up to 120%, the range of moisture content that can be measured reliably is 4% to about 30% for commercial dielectric meters and about 6% to 30% for resistance meters. The precision of the individual meter readings decreases near the limits of these ranges. Readings greater than 30% must be considered only qualitative. When the meter is properly used on a quantity of lumber dried to a constant moisture content below fiber saturation, the average moisture content from the corrected meter readings should be within 1% of the true average.

Recommended Moisture Content

Install wood at the moisture content levels that the wood will experience in service. This minimizes the seasonal variation in moisture content, thus dimensional changes, after installation, avoiding problems such as floor buckling or cracks in furniture. The in-service moisture content of exterior wood (siding, wood trim) primarily depends on the outdoor relative humidity and exposure to rain or sun. The in-service moisture content of interior wood primarily depends on indoor relative humidity, which in turn is a complex function of moisture sources, ventilation rate, dehumidification (for example, air conditioning), and outdoor humidity conditions.

Recommended values for interior wood presented in this chapter are based on measurements in well-ventilated buildings without unusual moisture sources and without air conditioning. In air-conditioned buildings, moisture conditions depend largely on the proper sizing of the air-conditioning equipment. Installing wood in basements or over a crawl space may experience moisture contents greater than the range given. Wood in insulated walls or roofs and attics may experience moisture contents greater or less than the range. Nevertheless, the recommended values for installation provide a useful guideline.

Timbers

Ideally, dry solid timbers to the average moisture content the material will reach in service. Although this optimum is possible with lumber less than 76 mm (3 in.) thick, it is seldom practical to obtain fully dried timbers, thick joists, and planks. When thick solid members are used, some shrinkage of the assembly should be expected. In the case of built-up assemblies, such as roof trusses, it may be necessary to tighten bolts or other fastenings occasionally to maintain full bearing of the connectors as the members shrink.

Lumber

Match the recommended moisture content of wood as closely as is practical to the equilibrium moisture content (EMC) conditions in service. Table 13–1 shows the EMC conditions in outdoor exposure in various U.S. cities for each month. The EMC data are based on the average relative humidity and temperature data (30 or more years) available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration. The relative humidity data are the averages of the morning and afternoon values. In most cases, these values are representative of the EMC attained by the wood. However, in some locations, early morning relative humidity may occasionally reach 100%. Under these conditions, condensation may occur on the wood surface, therefore surface fibers will exceed the EMC. The moisture content requirements are more exacting for finished lumber and wood products used inside heated and air-conditioned buildings than those for lumber used outdoors or in unheated buildings. For various areas of the United States, the recommended moisture content values for wood used inside heated buildings are shown in Figure 13–1. Values and tolerances for both interior and exterior uses of wood in various forms are given in Table 13–2. If the average moisture content is within 1% of that recommended and all pieces fall within the individual limits, the entire lot is probably satisfactory (Simpson 1998).

General commercial practice is to kiln dry wood for some products, such as flooring and furniture, to a slightly lower moisture content than service conditions demand. This anticipates a moderate increase in moisture content during processing, transportation, and construction. This practice is intended to ensure uniform distribution of moisture among the individual pieces. Common grades of softwood lumber and softwood dimension lumber are not normally dried to the moisture content values indicated in Table 13–2. Dry lumber, as defined in the American Softwood Lumber Standard, has a maximum moisture content of 19%. Some industry grading rules provide for an even lower maximum. For example, to be grade marked KD 15, the maximum moisture content permitted is generally 15%.

Glued Wood Products

When veneers are bonded with cold-setting adhesives to make plywood, they take up comparatively large

Table 13-1. Equilibrium moisture content for outside conditions in several U.S. locations prior to 1997

		Equilibrium moisture content ^a (%)											
State	City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
AK	Juneau	16.5	16.0	15.1	13.9	13.6	13.9	15.1	16.5	18.1	18.0	17.7	18.1
AL	Mobile	13.8	13.1	13.3	13.3	13.4	13.3	14.2	14.4	13.9	13.0	13.7	14.0
AZ	Flagstaff	11.8	11.4	10.8	9.3	8.8	7.5	9.7	11.1	10.3	10.1	10.8	11.8
AZ	Phoenix	9.4	8.4	7.9	6.1	5.1	4.6	6.2	6.9	6.9	7.0	8.2	9.5
AR	Little Rock	13.8	13.2	12.8	13.1	13.7	13.1	13.3	13.5	13.9	13.1	13.5	13.9
CA	Fresno	16.4	14.1	12.6	10.6	9.1	8.2	7.8	8.4	9.2	10.3	13.4	16.6
CA	Los Angeles	12.2	13.0	13.8	13.8	14.4	14.8	15.0	15.1	14.5	13.8	12.4	12.1
CO	Denver	10.7	10.5	10.2	9.6	10.2	9.6	9.4	9.6	9.5	9.5	11.0	11.0
DC	Washington	11.8	11.5	11.3	11.1	11.6	11.7	11.7	12.3	12.6	12.5	12.2	12.2
FL	Miami	13.5	13.1	12.8	12.3	12.7	14.0	13.7	14.1	14.5	13.5	13.9	13.4
GA	Atlanta	13.3	12.3	12.0	11.8	12.5	13.0	13.8	14.2	13.9	13.0	12.9	13.2
HI	Honolulu	13.3	12.8	11.9	11.3	10.8	10.6	10.6	10.7	10.8	11.3	12.1	12.9
ID	Boise	15.2	13.5	11.1	10.0	9.7	9.0	7.3	7.3	8.4	10.0	13.3	15.2
IL	Chicago	14.2	13.7	13.4	12.5	12.2	12.4	12.8	13.3	13.3	12.9	14.0	14.9
IN	Indianapolis	15.1	14.6	13.8	12.8	13.0	12.8	13.9	14.5	14.2	13.7	14.8	15.7
IA	Des Moines	14.0	13.9	13.3	12.6	12.4	12.6	13.1	13.4	13.7	12.7	13.9	14.9
KS	Wichita	13.8	13.4	12.4	12.4	13.2	12.5	11.5	11.8	12.6	12.4	13.2	13.9
KY	Louisville	13.7	13.3	12.6	12.0	12.8	13.0	13.3	13.7	14.1	13.3	13.5	13.9
LA	New Orleans	14.9	14.3	14.0	14.2	14.1	14.6	15.2	15.3	14.8	14.0	14.2	15.0
ME	Portland	13.1	12.7	12.7	12.1	12.6	13.0	13.0	13.4	13.9	13.8	14.0	13.5
MA	Boston	11.8	11.6	11.9	11.7	12.2	12.1	11.9	12.5	13.1	12.8	12.6	12.2
MI	Detroit	14.7	14.1	13.5	12.6	12.3	12.3	12.6	13.3	13.7	13.5	14.4	15.1
MN	Minneapolis-St. Paul	13.7	13.6	13.3	12.0	11.9	12.3	12.5	13.2	13.8	13.3	14.3	14.6
MS	Jackson	15.1	14.4	13.7	13.8	14.1	13.9	14.6	14.6	14.6	14.1	14.3	14.9
MO	St. Louis	14.5	14.1	13.2	12.4	12.8	12.6	12.9	13.3	13.7	13.1	14.0	14.9
MT	Missoula	16.7	15.1	12.8	11.4	11.6	11.7	10.1	9.8	11.3	12.9	16.2	17.6
NE	Omaha	14.0	13.8	13.0	12.1	12.6	12.9	13.3	13.8	14.0	13.0	13.9	14.8
NV	Las Vegas	8.5	7.7	7.0	5.5	5.0	4.0	4.5	5.2	5.3	5.9	7.2	8.4
NV	Reno	12.3	10.7	9.7	8.8	8.8	8.2	7.7	7.9	8.4	9.4	10.9	12.3
NM	Albuquerque	10.4	9.3	8.0	6.9	6.8	6.4	8.0	8.9	8.7	8.6	9.6	10.7
NY	New York	12.2	11.9	11.5	11.0	11.5	11.8	11.8	12.4	12.6	12.3	12.5	12.3
NC	Raleigh	12.8	12.1	12.2	11.7	13.1	13.4	13.8	14.5	14.5	13.7	12.9	12.8
ND	Fargo	14.2	14.6	15.2	12.9	11.9	12.9	13.2	13.2	13.7	13.5	15.2	15.2
OH	Cleveland	14.6	14.2	13.7	12.6	12.7	12.7	12.8	13.7	13.8	13.3	13.8	14.6
OK	Oklahoma City	13.2	12.9	12.2	12.1	13.4	13.1	11.7	11.8	12.9	12.3	12.8	13.2
OR	Pendleton	15.8	14.0	11.6	10.6	9.9	9.1	7.4	7.7	8.8	11.0	14.6	16.5
OR	Portland	16.5	15.3	14.2	13.5	13.1	12.4	11.7	11.9	12.6	15.0	16.8	17.4
PA	Philadelphia	12.6	11.9	11.7	11.2	11.8	11.9	12.1	12.4	13.0	13.0	12.7	12.7
SC	Charleston	13.3	12.6	12.5	12.4	12.8	13.5	14.1	14.6	14.5	13.7	13.2	13.2
SD	Sioux Falls	14.2	14.6	14.2	12.9	12.6	12.8	12.6	13.3	13.6	13.0	14.6	15.3
TN	Memphis	13.8	13.1	12.4	12.2	12.7	12.8	13.0	13.1	13.2	12.5	12.9	13.6
TX	Dallas-Ft. Worth	13.6	13.1	12.9	13.2	13.9	13.0	11.6	11.7	12.9	12.8	13.1	13.5
TX	El Paso	9.6	8.2	7.0	5.8	6.1	6.3	8.3	9.1	9.3	8.8	9.0	9.8
UT	Salt Lake City	14.6	13.2	11.1	10.0	9.4	8.2	7.1	7.4	8.5	10.3	12.8	14.9
VA	Richmond	13.2	12.5	12.0	11.3	12.1	12.4	13.0	13.7	13.8	13.5	12.8	13.0
WA	Seattle-Tacoma	15.6	14.6	15.4	13.7	13.0	12.7	12.2	12.5	13.5	15.3	16.3	16.5
WI	Madison	14.5	14.3	14.1	12.8	12.5	12.8	13.4	14.4	14.9	14.1	15.2	15.7
WV	Charleston	13.7	13.0	12.1	11.4	12.5	13.3	14.1	14.3	14.0	13.6	13.0	13.5
WY	Cheyenne	10.2	10.4	10.7	10.4	10.8	10.5	9.9	9.9	9.7	9.7	10.6	10.6

^aEMC values were determined from the average of 30 or more years of relative humidity and temperature data available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration.

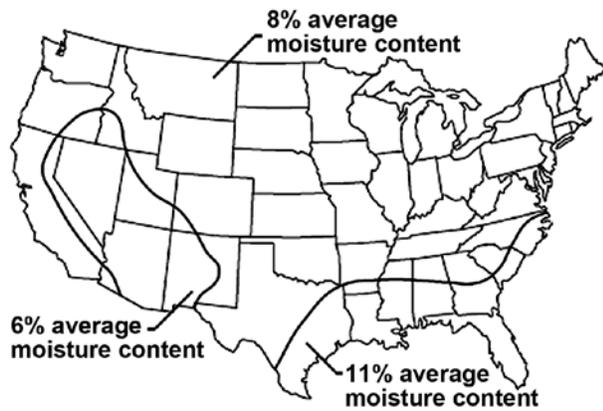


Figure 13–1. Recommended average moisture content for interior use of wood products in various areas of the United States.

quantities of moisture. To keep the final moisture content low and to minimize the need for re-drying the plywood, the initial moisture content of the veneer should be as low as practical. However, dry veneer is brittle and difficult to handle without damage, so the minimum practical moisture content is about 4%. Freshly glued plywood intended for interior service should be dried to the moisture content values given in Table 13–2.

Hot-pressed plywood and other board products, such as particleboard and hardboard, usually do not have the same moisture content as lumber. The high temperatures used in hot presses cause these products to assume a lower moisture content for a given relative humidity. Because this lower equilibrium moisture content varies widely, depending on the specific type of hot-pressed product, it is recommended that such products be conditioned at 30% to 40% relative humidity for interior use and 65% for exterior use.

Lumber used in the manufacture of large laminated members should be dried to a moisture content slightly less than the moisture content expected in service. This is done so

that the moisture adsorbed from the adhesive will not cause the moisture content of the product to exceed the service value. The range of moisture content between laminations assembled into a single member should not exceed 5 percentage points.

Although laminated members are often massive and respond rather slowly to changes in environmental conditions, it is desirable to follow the recommendations in Table 13–2 for moisture content at time of installation.

Drying of Wood

Drying is required for wood to be used in most products. Dried lumber has many advantages over green lumber for producers and consumers. Removal of excess water reduces weight, thus shipping and handling costs. Proper drying reduces shrinking and swelling of wood while in use to manageable amounts under all but extreme conditions of relative humidity or rewetting such as flooding. As wood dries, most of its strength properties increase, as well as its electrical and thermal insulating properties. Properly dried lumber can be cut to precise dimensions and machined more easily and efficiently; wood parts can be more securely fitted and fastened together with nails, screws, bolts, and adhesives; warping, splitting, checking, and other harmful effects of uncontrolled drying are largely eliminated; and paint, varnish, and other finishes are more effectively applied and maintained. Wood must be relatively dry before gluing or treating with decay-preventing and fire-retardant chemicals.

The key to successful and efficient drying is control of the drying process. Timely application of optimum or at least adequate temperature, relative humidity, and air circulation conditions is critical. Uncontrolled drying leads to drying defects that can adversely affect the serviceability and economics of the product. The usual strategy is to dry as fast as the particular species, thickness, and end-product requirements allow without damaging the wood. Slower drying can be uneconomical and can introduce the risk of stain.

Table 13–2. Recommended moisture content values for various wood products at time of installation

Use of wood	Recommended moisture content (%) for areas in the United States					
	Most areas of the United States		Dry southwestern area ^a		Damp, warm coastal area ^a	
	Average ^b	Individual pieces	Average ^b	Individual pieces	Average ^b	Individual pieces
Interior: woodwork, flooring, furniture, wood trim	8	6–10	6	4–9	11	8–13
Exterior: siding, wood trim, sheathing, laminated timbers	12	9–14	9	7–12	12	9–14

^aMajor areas are indicated in Figure 13–1.

^bTo obtain a realistic average, test at least 10% of each item. If the quantity of a given item is small, make several tests. For example, in an ordinary dwelling containing 60 floor joists, at least six tests should be made on joists selected at random.

Softwood lumber intended for framing in construction is usually targeted for drying to an average moisture content of 15%, not to exceed 19%. Softwood lumber for many appearance grade uses is dried to a lower moisture content of 10% to 12% and to 7% to 9% for furniture, cabinets, and millwork. Hardwood lumber for framing in construction, although not in common use, should also be dried to an average moisture content of 15%, not to exceed 19%. Hardwood lumber for furniture, cabinets, and millwork is usually dried to 6% to 8% moisture content.

Lumber drying is usually accomplished by some combination of air drying, accelerated air drying or pre-drying, and kiln drying. Wood species, initial moisture content, lumber thickness, economics, and end use are often the main factors in determining the details of the drying process.

Air Drying

The main purpose of air drying lumber is to evaporate as much of the water as possible before end use or prior to kiln-drying. Air drying lumber down to 20% to 25% moisture content prior to kiln-drying is common. Sometimes, depending on a mill's scheduling, air drying may be cut short at a higher moisture content before the wood is sent to the dry kiln. Air drying saves energy costs and reduces required dry kiln capacity. Limitations of air drying are generally associated with uncontrolled drying. The drying rate is very slow during the cold winter months. At other times, hot, dry winds may increase degrade and volume losses as a result of severe surface checking and end splitting. End coating may alleviate end checking and splitting. Warm, humid periods with little air movement may encourage the growth of fungal stains, as well as aggravate chemical stains. Another limitation of air drying is the high cost of carrying a large inventory of high value lumber for extended periods. Air drying time to 20% to 25% moisture content varies widely, depending on species, thickness, location, and the time of year the lumber is stacked. Some examples of extremes for 25-mm- (1-in.-) thick lumber are 15 to 30 days for some of the low-density species, such as pine, spruce, red alder, and soft maple, stacked in favorable locations and favorable times of the year; 200 to 300 days for slow-drying species, such as sinker hemlock and pine, oak, and birch, in northern locations and stacked at unfavorable times of the year. Details of important air-drying considerations, such as lumber stacking and air drying yard layout, are covered in *Air Drying of Lumber: A Guide to Industry Practices* (Rietz and Page 1971).

Accelerated Air Drying and Pre-Drying

The limitations of air drying have led to increased use of technology that reduces drying time and introduces some control into drying (green) wood. Accelerated air drying involves the use of fans to force air through lumber piles in a shed. This protects the lumber from the elements and improves air circulation compared with air drying, thus

improving quality. Heat is sometimes added to reduce the relative humidity and slightly increase the shed temperature to aid drying. Pre-dryers take this acceleration and control a step further by providing control of both temperature and relative humidity and providing forced air circulation in a completely enclosed compartment. Typical conditions in a pre-dryer are 27 to 38 °C (80 to 100 °F) and 65% to 85% relative humidity.

Kiln Drying

In kiln drying, higher temperatures and faster air circulation are used to significantly increase the drying rate. Specific kiln schedules have been developed to control temperature and relative humidity in accordance with the moisture content and stress situation within the wood, thus minimizing shrinkage-caused defects (Boone and others 1988).

Drying Mechanism

Water in wood normally moves from high to low zones of moisture content, which means that the surface of the wood must be drier than the interior if moisture is to be removed. Drying can be broken down into two phases: movement of water from the interior to the wood surface and evaporation of water from the surface. The surface fibers of most species reach moisture equilibrium with the surrounding air soon after drying begins. This is the beginning of the development of a typical moisture gradient (Fig. 13–2), that is, the difference in moisture content between the inner and outer portions of a board. If air circulation is too slow, a longer time is required for the wood surface to reach moisture equilibrium. This is one reason why air circulation is so important in kiln drying. If air circulation is too slow, the drying rate is also slower than necessary and mold could develop on the surface of lumber. If drying is too fast, electrical energy in running the fans is wasted, and in certain species, surface checking and other drying defects can develop if relative humidity and air velocity are not coordinated.

Water moves through the interior of wood as a liquid or vapor through various air passageways in the cellular structure of the wood, as well as through the wood cell walls. Moisture moves in these passageways in all directions, both across and with the grain. In general, lighter species dry faster than heavier species because the structure of lighter wood contains more openings per unit volume, and moisture moves through air faster than through wood cell walls. Water moves by two main mechanisms: capillary action (liquid) and diffusion of bound water (vapor). Capillary action causes the free water to flow through cell cavities and the small passageways that connect adjacent cell cavities. Diffusion of bound water moves moisture from areas of high concentration to areas of low concentration. Diffusion in the longitudinal direction is about 10 to 15 times faster than radial or tangential diffusion, and radial diffusion is somewhat faster than tangential diffusion. This explains why flatsawn lumber generally dries faster than quartersawn lumber. Al-

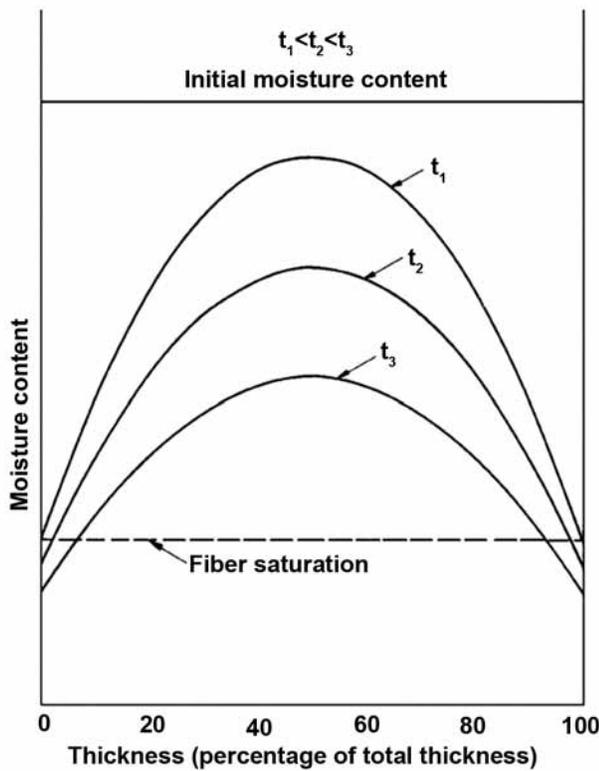


Figure 13-2. Typical moisture gradient in lumber during drying at time increasing from t_1 to t_3 .

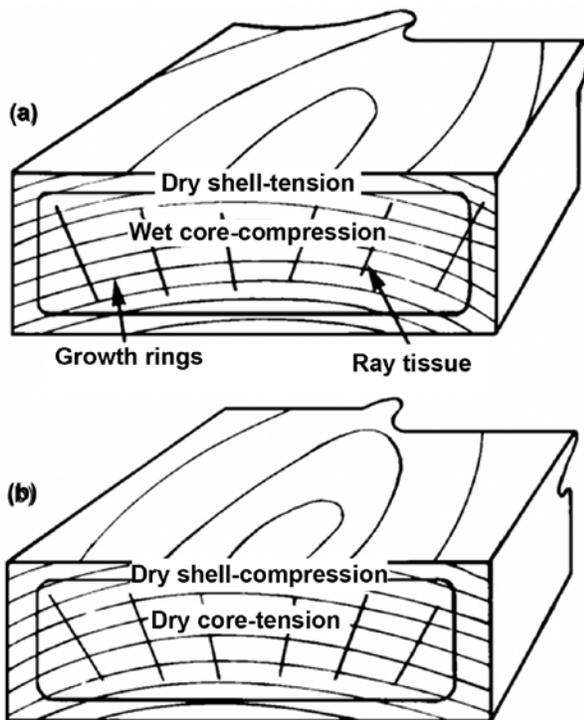


Figure 13-3. End view of board showing development of drying stresses (a) early and (b) later in drying.

though longitudinal diffusion is much faster than diffusion across the grain, it generally is not of practical importance in lumber that is many times longer than it is thick. In addition, a direct result of longitudinal diffusion may be end-checking or splitting without proper care.

Because chemical extractives in heartwood plug up passageways, moisture generally moves more freely in sapwood than in heartwood; thus, sapwood generally dries faster than heartwood. However, the heartwood of many species is lower in moisture content than is the sapwood. Thus heartwood can reach final moisture content as fast as the sapwood.

The rate at which moisture moves in wood depends on the relative humidity of the surrounding air, the steepness of the moisture gradient, and the temperature of the wood. Lower relative humidity increases capillary flow. Low relative humidity also stimulates diffusion by lowering the moisture content at the surface, thereby steepening the moisture gradient and increasing the diffusion rate. The greater the temperature of the wood, the faster moisture will move from the wetter interior to the drier surface, thus the steeper the moisture gradient. If relative humidity is too low in the early stages of drying, excessive shrinkage may occur, resulting in surface and end checking. If the temperature is too high, collapse, honeycomb, or strength reduction can occur.

Drying Stresses

Drying stresses are the main cause of nonstain-related drying defects. Understanding these stresses provides a means for minimizing and recognizing the damage they can cause. The cause of drying stresses is the differential shrinkage between the outer part of a board (the shell) and the interior part (the core) that can result in drying defects. Early in drying, the fibers in the shell dry first and begin to shrink. However, the core has not yet begun to dry and shrink; consequently, the core prevents the shell from shrinking fully. Thus, the shell goes into tension and the core into compression (Fig. 13-3). If the shell dries too rapidly, it is stressed beyond the elastic limit and dries in a permanently stretched (set) condition without attaining full shrinkage. Sometimes surface cracks, or checks, occur from this initial stage of drying and can be a serious defect for many uses. As drying progresses, the core begins to dry and attempts to shrink. However, the shell is set in a permanently expanded condition and prevents normal shrinkage of the core. This causes the stresses to reverse; the core goes into tension and the shell into compression. The change in the shell and core stresses and in the moisture content level during drying is shown in Figure 13-4. These internal tension stresses may be severe enough to cause internal cracks (honeycomb).

Differential shrinkage caused by differences in radial, tangential, and longitudinal shrinkage is a major cause of warp. The distortions shown in Figure 4-3 in Chapter 4 are due to differential shrinkage. When juvenile or reaction wood is present on one edge or face of a board and normal wood is

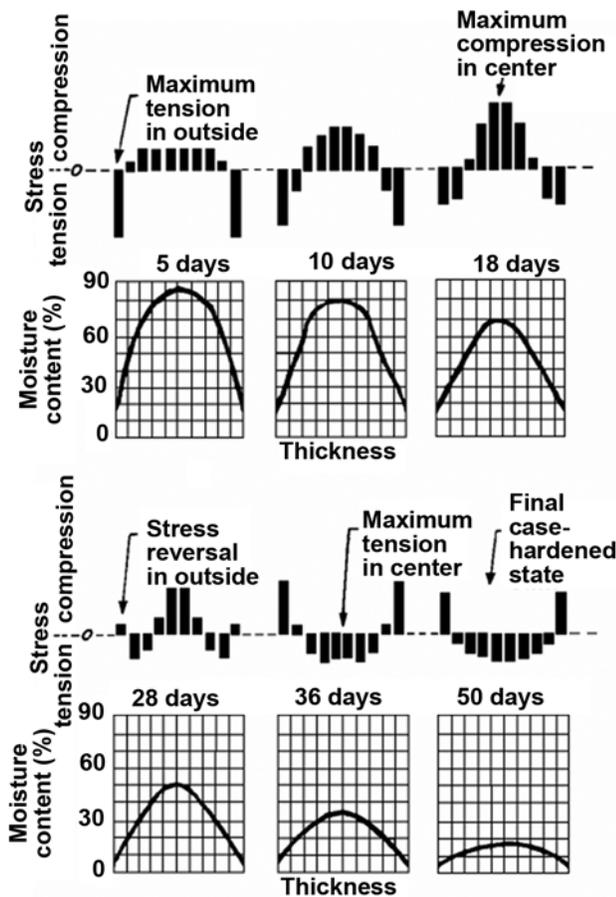


Figure 13-4. Moisture-stress relationship during six stages of kiln drying 50-mm- (2-in.-) thick red oak.

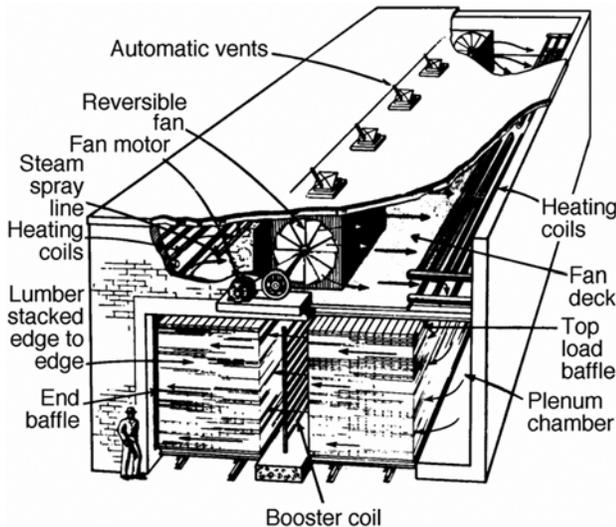


Figure 13-5. Lineshaft, double-track, compartment kiln with alternately opposing fans. Vents are over fan shaft between fans. Vent on high pressure side of fans becomes fresh air inlet when direction of circulation is reversed.

present on the opposite side, the difference in their longitudinal shrinkage can also cause warp.

Dry Kilns

Most dry kilns are thermally insulated compartments designed for a batch process in which the kiln is completely loaded with lumber in one operation and the lumber remains stationary during the entire drying cycle. Temperature and relative humidity are kept as uniform as possible throughout the kiln and can be controlled over a wide range. As the wood dries, kiln temperature and relative humidity change based on a schedule that takes into account the moisture content or the drying rate, or both, of the lumber. All dry kilns use some type of forced-air circulation, with air moving through the lumber perpendicular to the length of the lumber and parallel to the spacers (stickers) that separate each layer of lumber in a stack. This forced-air circulation allows for uniform air flow in the dry kiln.

Three general types of kilns are in common use. One is the track-loaded type (Fig. 13-5), where lumber is stacked on kiln trucks that are rolled in and out of the kiln on tracks. Most softwood lumber in the United States is dried in this kiln type. Another major type is the package-loaded kiln (Fig. 13-6), where individual stacks of lumber are fork-lifted into place in the kiln. Package-loaded kilns are commonly used for drying hardwood lumber. Indirect-steam heat is common for these two types although softwood lumber kilns are sometimes directly heated using combustion gases from burning fuel. A third common type of kiln, usually package loaded, is the dehumidification kiln. Instead of venting humid air to remove water, as the other two types of kilns do, water is removed by condensation on cold dehumidifier coils (Fig. 13-7).

Kiln Schedules

A kiln schedule is a carefully developed compromise between the need to dry lumber as fast as possible for economic efficiency and the need to avoid severe drying conditions that will lead to drying defects. A kiln schedule is a series of temperatures and relative humidities that are applied at various stages of drying. In most schedules, the temperature is gradually increased and the relative humidity decreased, thus lowering the EMC. The schedule for Southern Pine structural lumber is an exception to this general rule. This is lumber usually dried at a constant temperature and relative humidity. Temperatures are chosen to balance the highest drying rate with the avoidance of objectionable drying defects. The stresses that develop during drying are the limiting factor in determining the kiln schedule. The schedule must be developed so that the drying stresses do not exceed the strength of the wood at any given temperature and moisture content. Otherwise, the wood will crack either on the surface or internally or be crushed by forces that collapse the wood cells. Wood generally becomes stronger as the moisture content decreases, and to a lesser

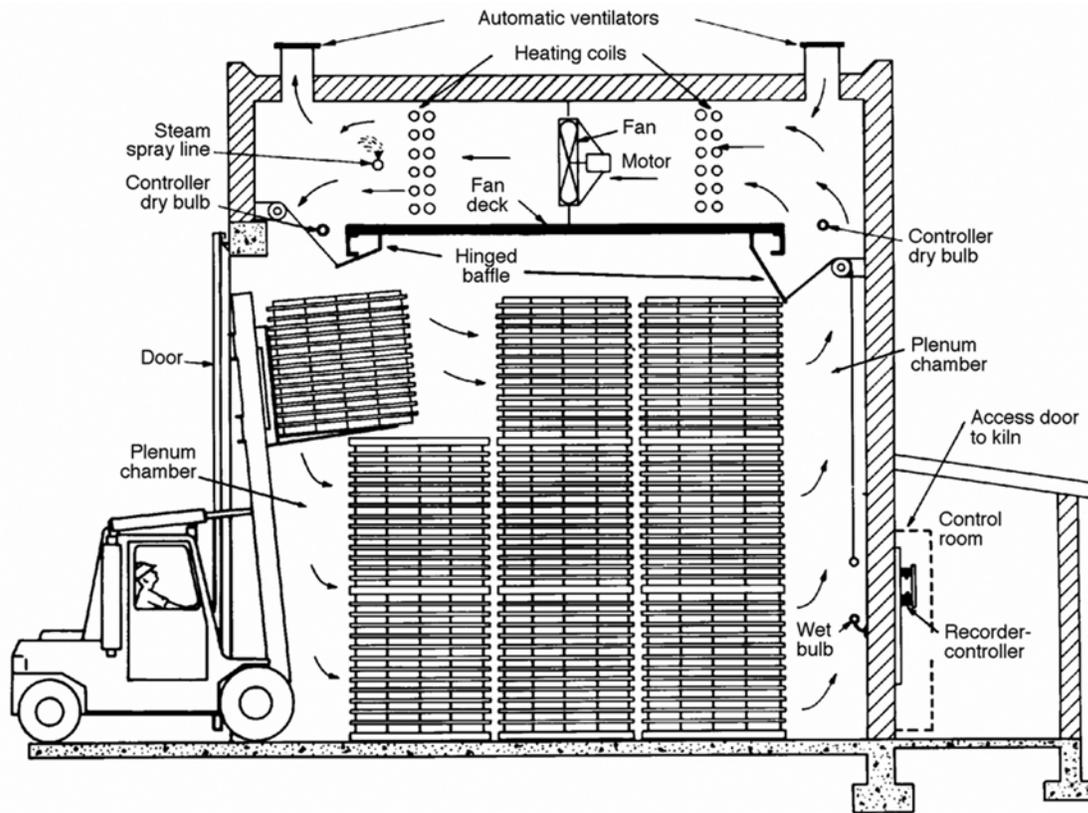


Figure 13–6. Package-loaded kiln with fans connected directly to motors.

extent, it becomes weaker as temperature increases. The net result is that as wood dries it becomes stronger because of the decreasing moisture content and can tolerate higher drying temperatures and lower relative humidities without cracking. This is a fortunate circumstance because as wood dries, its drying rate decreases at any given temperature, and the ability to increase drying temperature helps maintain a reasonably fast drying rate. Thus, rapid drying is achieved in kilns by the use of temperatures as high as possible and relative humidities as low as possible.

Drying schedules vary by species, thickness, grade, moisture content, and end use of lumber. The two general types of kiln schedules are moisture content schedules and time-based schedules. Most hardwood lumber is dried by moisture content schedules. This means that the temperature and relative humidity conditions are changed according to the percentage moisture content of the lumber during drying. A typical hardwood schedule might begin at 49 °C (120 °F) and 80% relative humidity when the lumber is green. By the time the lumber has reached 15% moisture content, the temperature is as high as 82 °C (180 °F). A typical hardwood drying schedule is shown in Table 13–3. Some method of monitoring moisture content during drying is required for schedules based on moisture content. One common method is the use of kiln samples that are periodically weighed, usually manually but potentially remotely with load cells.

Alternatively, imbedded electrodes in sample boards sense the change in electrical conductivity with moisture content. This system is limited to moisture content values less than 30% (Simpson 1991, Denig and others 2000).

Softwood kiln schedules generally differ from hardwood schedules in that changes in kiln temperature and relative humidity are made at predetermined times rather than moisture content levels. Examples of time-based schedules, both conventional temperature (<100 °C (<212 °F)) and high temperature (>110 °C (>230 °F)), are given in Table 13–3. Some hardwoods used as structural lumber also use a time-based schedule as shown in Table 13–3 (Simpson and Wang 2001, Ross and Erickson 2005).

Drying Defects

Most drying defects or problems that develop in wood products during drying can be classified as fracture or distortion, warp, or discoloration. Defects in any one of these categories are caused by an interaction of wood properties with processing factors. Wood shrinkage is mainly responsible for wood ruptures and distortion of shape. Cell structure and chemical extractives in wood contribute to defects associated with uneven moisture content, undesirable color, and undesirable surface texture. Drying temperature is the most important processing factor because it can be responsible for defects in each category.

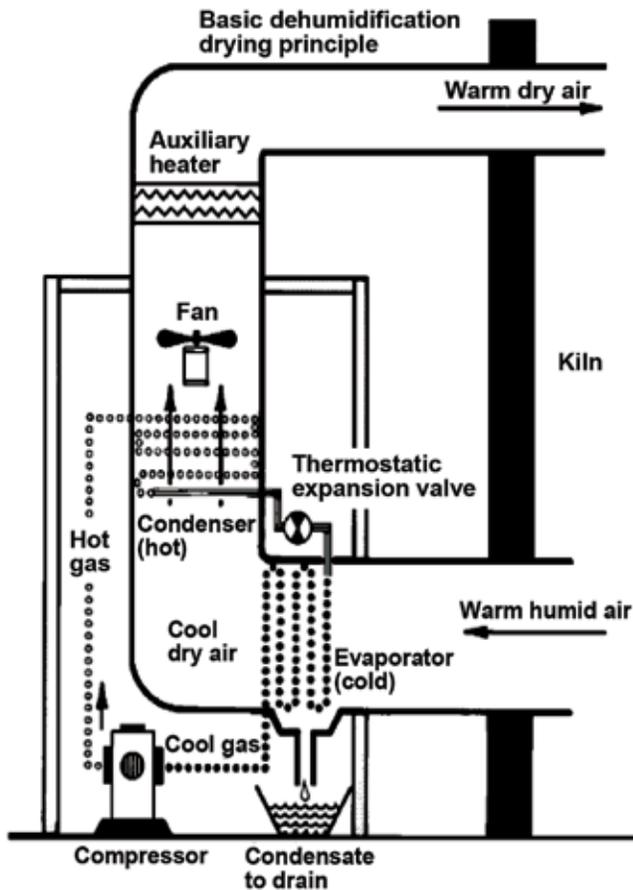
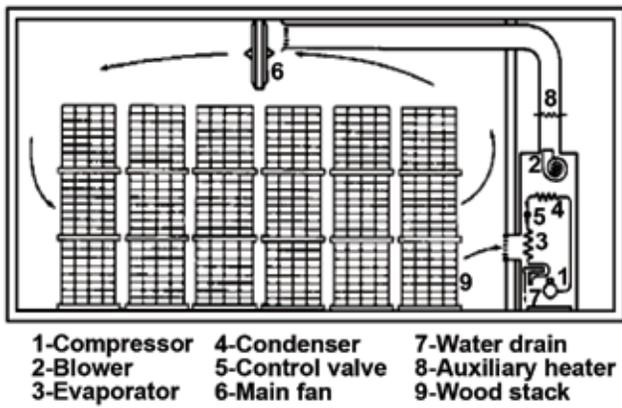


Figure 13-7. A typical dehumidification kiln (top) and dehumidification drying system (bottom).

Fracture or Distortion

Surface checks occur early in drying when the shell of a board is stressed in tension enough to fracture the wood. These checks occur most often on the face of flatsawn boards and are illustrated in Figure 13-8. End checks (Fig. 13-9) are similar to surface checks but appear on the ends of boards and logs. End checks occur because the rapid longitudinal movement of moisture causes the end to dry very quickly and develop high stresses, therefore

fracturing. End coatings, on either the log or freshly sawn (green) lumber, are an effective preventative measure. Collapse is a distortion, flattening, or crushing of wood cells. In severe cases (Fig. 13-10), collapse usually shows up as grooves or corrugations, a washboarding effect. Less severe collapse shows up as excessive thickness shrinkage and may not be a serious problem. Honeycomb (Fig. 13-11) is an internal crack that occurs in the later stages of kiln drying when the core of a board is in tension. This internal defect is caused when the core is still at a relatively high moisture content and drying temperatures are too high for too long during this critical drying period. It may go unnoticed until the lumber is machined. Nondestructive testing methods, using speed of sound, have been found to be effective in detecting the presence of these cracks in dried lumber. Knots may loosen during drying because of the unequal shrinkage between the knot and the surrounding wood (Fig. 13-12).

Warp

Warp in lumber is any deviation of the face or edge of a board from flatness or any edge that is not at right angles to the adjacent face or edge. Warp can be traced to two causes: (a) differences between radial, tangential, and longitudinal shrinkage in the piece as it dries or (b) growth stresses. Warp is aggravated by irregular or distorted grain and the presence of abnormal types of wood, such as juvenile and reaction wood. The six major types of warp are bow, crook, twist, oval, diamond, and cup (Fig. 13-13).

Discoloration

Discoloration impairs the use of dried wood products, particularly when the end use requires a clear, natural finish. Unwanted discoloration can develop in the tree, during storage of logs and green lumber, or during drying. The two general types of discoloration are chemical and fungal.

Chemical discoloration is the result of oxidative and enzymatic reactions with chemical compounds in wood. Discolorations range from pinkish, bluish, and yellowish hues through gray and reddish brown to dark brown shades. Brown stain in pines and darkening in many hardwoods is a common problem when drying temperatures are too high (Fig. 13-14). A deep grayish-brown chemical discoloration can occur in many hardwood species if initial drying is too slow or too high of an initial kiln temperature (Fig. 13-15) (Wiemann and others 2009).

Fungal stains, often referred to as blue or sap stain, are caused by fungi that grow in the sapwood (Fig. 13-16). Blue-stain fungi do not cause decay of the sapwood, and fungi generally do not grow in heartwood. Blue stain can develop if initial drying is too slow.

Another common type of stain develops under stickers (Fig. 13-17). This stain results from contact of the sticker with the board. Sticker stains (sometimes called shadow) are imprints of the sticker that are darker or lighter than the wood between the stickers and can be caused by either chemical or fungal action, or both.

Table 13–3. Typical dry kiln schedules for lumber**Moisture-content-based schedule for 25-mm (1-in.) (4/4) black walnut, dried to 7% moisture content**

Moisture content (%)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
Above 50	49.0 (120)	45.0 (113)	80	14.4
50 to 40	49.0 (120)	43.5 (110)	72	12.1
40 to 35	49.0 (120)	40.5 (105)	60	9.6
35 to 30	49.0 (120)	35.0 (95)	40	6.5
30 to 25	54.5 (130)	32.0 (90)	22	4.0
25 to 20	60.0 (140)	32.0 (90)	15	2.9
20 to 15	65.5 (150)	37.5 (100)	18	3.2
15 to 7	82.2 (180)	54.4 (130)	27	3.7
Equalize	82.2 (180)	58.3 (137)	30	3.8
Condition	82.2 (180)	76.7 (170)	79	11.1

Time-based schedule for 25- to 50-mm (1- to 2-in.) (4/4 to 8/4) Douglas-fir, upper grades, dried to 12% moisture content

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 to 12	76.5 (170)	73.5 (164)	86	14.1
12 to 24	76.5 (170)	71.0 (160)	78	11.4
24 to 48	79.5 (175)	71.0 (160)	69	9.1
48 to 72	82.2 (180)	71.0 (160)	62	7.7
72 to 96	82.2 (180)	60.0 (140)	36	4.5

or until dry

High-temperature schedule for 50- by 100-mm to 50- by 250-mm (2- by 4-in. to 2- by 10-in.) Southern Pine, dried to 15% moisture content

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 until dry	116 (240)	82.2 (180)	29	2.5

Time-based schedule for 50- by 150-mm (2- by 6-in.) sugar maple, dried to 15% moisture content in 5 days

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 to 24	71.0 (160)	67.2 (153)	84	14.1
24 to 48	71.0 (160)	65.6 (150)	78	12.1
48 to 60	71.0 (160)	62.8 (145)	69	10.1
60 to 72	71.0 (160)	57.2 (135)	52	7.4
72 to 84	76.7 (170)	54.4 (130)	35	4.9
84 to 115	82.2 (180)	54.4 (130)	27	3.7

Moisture Content of Dried Lumber

Although widely used, the trade terms “shipping dry,” “air dry,” and “kiln dry” may not have identical meanings as to moisture content in the different producing regions. Despite the wide variations in the use of these terms, they are sometimes used to describe dried lumber. The following statements, which are not exact definitions, outline these categories.

Shipping Dry

Shipping dry means lumber that has been partially dried to prevent stain or mold during brief periods of transit; ideally the outer 3.2 mm (1/8 in.) is dried to 25% or less moisture content (McMillen 1978).

Air Dry

Air dry means lumber dried by exposure to the air outdoors or in a shed or by forced circulation of air that has not been



Figure 13-8. Surface checking on white oak 5/4 lumber.



Figure 13-11. Red cedar timber end shows honey-comb (top). Surface of the timber shows no honey-comb (bottom).



Figure 13-9. End checking in red pine logs.



Figure 13-10. Severe collapse in western redcedar.

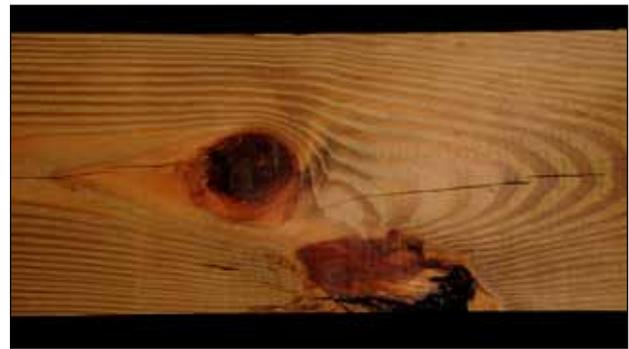


Figure 13-12. Large knot in treated Southern Pine.

heated above 49 °C (120 °F). Commercial air-dry stock generally has an average moisture content low enough for rapid kiln drying or rough construction use. Moisture content is generally in the range of 20% to 25% for dense hardwoods and 15% to 20% for softwoods and low-density hardwoods. Extended exposure can bring standard 19- and 38-mm (nominal 1- and 2-in.) lumber within one or two percentage points of the average exterior equilibrium moisture content of the region. For much of the United States, the minimum moisture content of thoroughly air-dried lumber is 12% to 15%.

Kiln Dry

Kiln dry means lumber that has been dried in a kiln or by some special drying method to an average moisture content

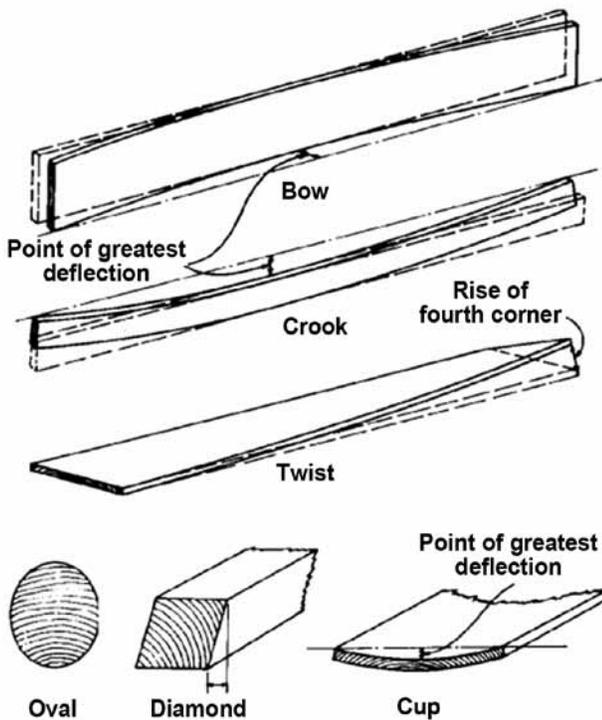


Figure 13-13. Various types of warp that can develop in boards during drying.

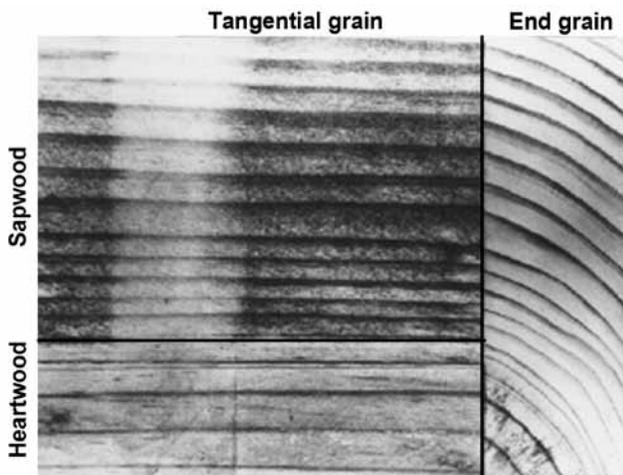


Figure 13-14. Brown sapwood stain in Southern Pine lumber.

specified or understood to be suitable for a certain use. The average moisture content should have upper and lower tolerance limits, and all values should fall within these limits. If the moisture contents fall outside these limits, use the dry kiln to equalize the lumber until the moisture is inside these limits. Kiln-dried softwood dimension lumber generally has an average moisture content of 19% or less; the average moisture content for many other softwood uses is 10% to 20%. Hardwood and softwood lumber for furniture,

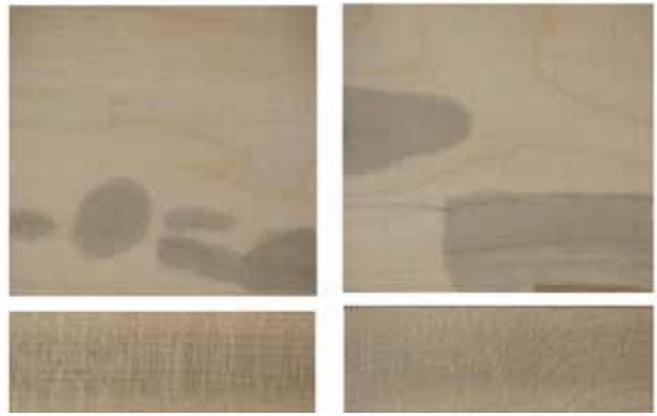


Figure 13-15. Soft maple sapwood boards (surface, end, edge) showing patches of oxidative stain.

cabinetry, and millwork usually has a final moisture content of 6% to 8% and can be specified to be free of drying stresses. Drying stresses built up during the drying cycle are relieved by conditioning inside the dry kiln. The importance of suitable moisture content values is recognized, and provisions covering them are now incorporated in some softwood standards as grading rules. Moisture content values in the general grading rules may or may not be suitable for a specific use; if not, a special moisture content specification should be made (USDC 2005).

Moisture Control during Transit and Storage

Lumber and other wood items may change in moisture content and dimension while awaiting shipment, during fabrication, in transit, and in storage.

When standard 19-mm (nominal 1-in.) dry softwood lumber is shipped in tightly closed boxcars, shipping containers, or trucks or in packages with complete and intact wrappers, average moisture content changes for a package can generally be held to 0.2% or less per month. In holds or between decks of ships, dry material usually adsorbs about 1.5% moisture during normal shipping periods. If green material is included in the cargo, the moisture regain of the dry lumber may be doubled. On the top deck, if unprotected from the elements, the moisture regain can be as much as 7%.

When standard 19-mm (nominal 1-in.) softwood lumber, kiln dried to 8% or less, is piled solid under a good pile roof in a yard in warm, humid weather, average moisture content of a pile can increase at the rate of about 2% per month during the first 45 days. A moisture uptake rate of about 1% per month can then be sustained throughout a humid season. Comparable initial and sustaining moisture uptake rates are about 1% per month in open (roofed) sheds and 0.3% per month in closed sheds. Stock piled for a year in an open



Figure 13–16. Sap stain in Ponderosa Pine. Color ranges from bluish gray to black.

shed in a western location increased 2.7% on the inside of solid piles and 3.5% on the outside of the piles. Protect all manufactured stock from precipitation and spray, because liquid water on a solid pile tends to be absorbed by the wood instead of evaporating. The extent to which additional control of the storage environment is required depends upon the final use of the wood and the corresponding moisture content recommendations. It is important to determine the moisture content of all stock when received. If moisture content is not as specified or required, stickered storage in an appropriate condition could ultimately bring the stock within the desired moisture content range. If a large degree of moisture change is required, the stock must be redried (Rietz 1978).

Plywood and Structural Items

It is good practice to open-pile green or partially dried lumber and timbers using stickers and protect from sunshine and precipitation by a tight roof. Framing lumber and plywood with 20% or less moisture content can be solid-piled (no stickers) in a shed that has good protection against sunshine and direct or wind-driven precipitation. However, a better practice for stock with greater than 12% moisture content is

the use of stickered piling to bring moisture content more in line with the moisture content in use. Dry lumber piled solid in the open for relatively short periods with a minimum pile cover of waterproofed paper whenever possible. Because keeping rain out completely is difficult, storing solid-piled lumber in the open for long periods is not recommended. If framing lumber must be stored in the open for a long time, pile on stickers with good base support and cover the piles. Re-pile using stickers for solid-piled material that has become wet again is good practice.

Finish and Factory Lumber

Keep kiln-dried items such as exterior finish, siding, and exterior millwork in a closed unheated shed. Place material on supports raised above the floor, at least 150 mm (6 in.) high if the floor is paved or 300 mm (12 in.) if not paved. Interior trim, flooring, cabinet work, and lumber for processing into furniture should be stored in a room or closed shed where relative humidity is controlled. In addition, store kiln-dried and machined hardwood dimension or softwood cut stock under controlled humidity conditions.

Dried and machined hardwood dimension or softwood lumber intended for remanufacture should also be stored under controlled humidity conditions. Under uncontrolled conditions, the ends of such stock may attain a higher moisture content than the rest of the stock. Then, when the stock is straight-line ripped or jointed before edge gluing, subsequent shrinkage will cause splitting or open glue joints at the ends of panels. The simplest way to reduce relative humidity in storage areas of all sizes is to heat the closed space to a temperature slightly higher than that of the outside air. Dehumidifiers can be used in small, well-enclosed spaces.

If the heating method is used, and there is no source of moisture except that contained in the air, the equilibrium moisture content can be maintained by increasing the temperature of the storage area greater than the outside temperature by the amounts shown in Table 13–4. When a dehumidifier is used, monitor or control if needed the average temperature in the storage space. Select the proper relative humidity in Table 4–2 in Chapter 4 to give the desired average moisture content. Wood in a factory awaiting or following manufacture can become too dry if the area is heated to 21 °C (70 °F) or greater when the outdoor temperature is low. This often occurs in the northern United States during the winter. Under such circumstances, exposed ends and surfaces of boards or cut pieces will tend to dry to the low equilibrium moisture content condition, causing shrinkage and warp. In addition, an equilibrium moisture content of 4% or more below the moisture content of the core of freshly crosscut boards can cause end checking. Simple remedies are to cover piles of partially manufactured items with plastic film and lower the shop temperature during non-work hours. Increased control can be obtained in critical shop and



Figure 13–17. Sticker stain in sapwood of sugar maple after planing.

storage areas by humidification. In warm weather, cooling can increase relative humidity and dehumidification may be necessary (FPL 1972).

Dimensional Changes in Wood

Dry wood undergoes small changes in dimension with normal changes in relative humidity. More humid air will cause slight swelling, and drier air will cause slight shrinkage. These changes are considerably smaller than those involved with shrinkage from the green condition. Equation (13–2) can be used to approximate dimensional changes caused by shrinking and swelling by using the total shrinkage coefficient from green to oven-dry. However, the equation assumes that the shrinkage–moisture content relationship is linear. Figure 4–4 (Chap. 4) shows that this is not the case, so some error is introduced. The error is in the direction of

underestimating dimensional change, by about 5% of the true change. Many changes of moisture content in use are over the small moisture content range of 6% to 14%, where the shrinkage–moisture content relationship is linear (Chap. 4, Fig. 4–4). Therefore, a set of shrinkage coefficients based on the linear portion of the shrinkage–moisture content curve has been developed (Table 13–5). Estimating approximate changes in dimension using this simple equation utilizes these dimensional change coefficients, from Table 13–5, when moisture content remains within the range of normal use. (Dimensional changes are further discussed in Chaps. 4 and 7.)

Estimation Using Dimensional Change Coefficient

The change in dimension within the moisture content limits of 6% to 14% can be estimated satisfactorily by using a dimensional change coefficient based on the dimension at 10% moisture content:

$$\Delta D = D_1 [C_T (M_F - M_1)] \quad (13-2)$$

where ΔD is change in dimension, D_1 dimension in units of length at start of change, C_T dimensional change coefficient tangential direction (for radial direction, use C_R), M_F moisture content (%) at end of change, and M_1 moisture content (%) at start of change.

Values for C_T and C_R , derived from total shrinkage values, are given in Table 13–5. When $M_F < M_1$, the quantity $(M_F - M_1)$ will be negative, indicating a decrease in dimension; when greater, it will be positive, indicating an increase in dimension.

As an example, assuming the width of a flat-grained white fir board is 232 mm (9.15 in.) at 8% moisture content, its change in width at 11% moisture content is estimated as

$$\begin{aligned} \Delta D &= 232[0.00245(11 - 8)] \\ &= 232(0.00735) \\ &= 1.705 \text{ mm} \end{aligned}$$

$$\begin{aligned} \Delta D &= 9.15[0.00245(11 - 8)] \\ &= 9.15[0.00735] \\ &= 0.06725 \text{ or } 0.067 \text{ in.} \end{aligned}$$

Table 13–4. Increase in storage area temperature above outside temperature to maintain the desired wood moisture content

Outside relative humidity (%)	Temperature differential (°C (°F)) for desired wood moisture content						
	6%	7%	8%	9%	10%	11%	12%
90	18.3 (33)	16.1 (29)	12.8 (23)	10.0 (18)	8.3 (15)	6.1 (11)	5.0 (9)
80	16.7 (30)	13.9 (25)	10.5 (19)	7.8 (14)	6.1 (11)	4.4 (8)	3.3 (6)
70	13.9 (25)	11.1 (20)	8.3 (15)	5.6 (10)	3.9 (7)	2.2 (4)	1.7 (3)
60	11.1 (20)	8.3 (15)	5.0 (9)	3.3 (6)	1.7 (3)	—	—
50	8.3 (15)	5.6 (10)	2.8 (5)	0.6 (1)	—	—	—

Table 13–5. Dimensional change coefficients (C_R , radial; C_T , tangential) for shrinking or swelling within moisture content limits of 6% to 14%

Species	Dimensional change coefficient ^a		Species	Dimensional change coefficient ^a	
	C_R	C_T		C_R	C_T
Hardwoods					
Alder, red	0.00151	0.00256	Honeylocust	0.00144	0.00230
Apple	0.00205	0.00376	Locust, black	0.00158	0.00252
Ash, black	0.00172	0.00274	Madrone, Pacific	0.00194	0.00451
Ash, Oregon	0.00141	0.00285	Magnolia, cucumbertree	0.00180	0.00312
Ash, pumpkin	0.00126	0.00219	Magnolia, southern	0.00187	0.00230
Ash, white	0.00169	0.00274	Magnolia, sweetbay	0.00162	0.00293
Ash, green	0.00169	0.00274	Maple, bigleaf	0.00126	0.00248
Aspen, quaking	0.00119	0.00234	Maple, red	0.00137	0.00289
Basswood, American	0.00230	0.00330	Maple, silver	0.00102	0.00252
Beech, American	0.00190	0.00431	Maple, black	0.00165	0.00353
Birch, paper	0.00219	0.00304	Maple, sugar	0.00165	0.00353
Birch, river	0.00162	0.00327	Oak, black	0.00123	0.00230
Birch, yellow	0.00256	0.00338	Red Oak, commercial	0.00158	0.00369
Birch, sweet	0.00256	0.00338	Red oak, California	0.00123	0.00230
Buckeye, yellow	0.00123	0.00285	Red oak: water, laurel, willow	0.00151	0.00350
Butternut	0.00116	0.00223	White Oak, commercial	0.00180	0.00365
Catalpa, northern	0.00085	0.00169	White oak, live	0.00230	0.00338
Cherry, black	0.00126	0.00248	White oak, Oregon white	0.00144	0.00327
Chestnut, American	0.00116	0.00234	White oak, overcup	0.00183	0.00462
Cottonwood, black	0.00123	0.00304	Persimmon, common	0.00278	0.00403
Cottonwood, eastern	0.00133	0.00327	Sassafras	0.00137	0.00216
Elm, American	0.00144	0.00338	Sweetgum	0.00183	0.00365
Elm, rock	0.00165	0.00285	Sycamore, American	0.00172	0.00296
Elm, slippery	0.00169	0.00315	Tanoak	0.00169	0.00423
Elm, winged	0.00183	0.00419	Tupelo, black	0.00176	0.00308
Elm, cedar	0.00183	0.00419	Tupelo, water	0.00144	0.00267
Hackberry	0.00165	0.00315	Walnut, black	0.00190	0.00274
Hickory, pecan	0.00169	0.00315	Willow, black	0.00112	0.00308
Hickory, true	0.00259	0.00411	Willow, Pacific	0.00099	0.00319
Holly, American	0.00165	0.00353	Yellow-poplar	0.00158	0.00289
Softwoods					
Baldcypress	0.00130	0.00216	Pine, eastern white	0.00071	0.00212
Cedar, yellow-	0.00095	0.00208	Pine, jack	0.00126	0.00230
Cedar, Atlantic white-	0.00099	0.00187	Pine, loblolly	0.00165	0.00259
Cedar, Eastern Red	0.00106	0.00162	Pine, pond	0.00165	0.00259
Cedar, incense	0.00112	0.00180	Pine, lodgepole	0.00148	0.00234
Cedar, northern white- ^b	0.00101	0.00229	Pine, Jeffrey	0.00148	0.00234
Cedar, Port-Orford-	0.00158	0.00241	Pine, longleaf	0.00176	0.00263
Cedar, western red ^b	0.00111	0.00234	Pine, ponderosa	0.00133	0.00216
Douglas-fir, Coast-type	0.00165	0.00267	Pine, red	0.00130	0.00252
Douglas-fir, Interior north	0.00130	0.00241	Pine, shortleaf	0.00158	0.00271
Douglas-fir, Interior west	0.00165	0.00263	Pine, slash	0.00187	0.00267
Fir, balsam	0.00099	0.00241	Pine, sugar	0.00099	0.00194
Fir, California red	0.00155	0.00278	Pine, Virginia	0.00144	0.00252
Fir, noble	0.00148	0.00293	Pine, western white	0.00141	0.00259
Fir, Pacific silver	0.00151	0.00327	Redwood, old-growth ^b	0.00120	0.00205
Fir, subalpine	0.00088	0.00259	Redwood, second-growth ^b	0.00101	0.00229
Fir, grand	0.00112	0.00245	Spruce, black	0.00141	0.00237
Fir, white	0.00112	0.00245	Spruce, Engelmann	0.00130	0.00248

Table 13–5. Dimensional change coefficients (C_R , radial; C_T , tangential) for shrinking or swelling within moisture content limits of 6% to 14%—con.

Species	Dimensional change coefficient ^a			Dimensional change coefficient ^a	
	C_R	C_T		C_R	C_T
Hemlock, eastern	0.00102	0.00237	Spruce, red	0.00130	0.00274
Hemlock, western	0.00144	0.00274	Spruce, white	0.00130	0.00274
Larch, western	0.00155	0.00323	Spruce, Sitka	0.00148	0.00263
			Tamarack	0.00126	0.00259
Imported Woods					
Andiroba, crabwood	0.00137	0.00274	Light red “Philippine mahogany”	0.00126	0.00241
Angelique	0.00180	0.00312	Limba	0.00151	0.00187
Apitong, keruing ^b	0.00243	0.00527	Mahogany ^b	0.00172	0.00238
(all <i>Dipterocarpus</i> spp.)			Meranti	0.00126	0.00289
Avodire	0.00126	0.00226	Obeche	0.00106	0.00183
Balsa	0.00102	0.00267	Okoume	0.00194	0.00212
Banak	0.00158	0.00312	Parana, pine	0.00137	0.00278
Cativo	0.00078	0.00183	Paumarfim	0.00158	0.00312
Cuangare	0.00183	0.00342	Primavera	0.00106	0.00180
Greenheart ^b	0.00390	0.00430	Ramin	0.00133	0.00308
Iroko ^b	0.00153	0.00205	Santa Maria	0.00187	0.00278
Khaya	0.00141	0.00201	Spanish-cedar	0.00141	0.00219
Kokrodua ^b	0.00148	0.00297	Teak ^b	0.00101	0.00186
Lauans: dark red	0.00133	0.00267			
“Philippine mahogany”					

^aPer 1% change in moisture content, based on dimension at 10% moisture content and a straight-line relationship between moisture content at which shrinkage starts and total shrinkage. (Shrinkage assumed to start at 30% for all species except those indicated by footnote b.)

^bShrinkage assumed to start at 22% moisture content.

Then, dimension at end of change

$$D_1 + \Delta D = 232 + 1.7 \quad (= 9.15 + 0.067)$$

$$= 233.7 \text{ mm} \quad (= 9.217 \text{ in.})$$

The thickness of the same board at 11% moisture content can be estimated by using the coefficient $C_R = 0.00112$.

Because commercial lumber is often not perfectly flatsawn or quartersawn, this procedure will probably overestimate width shrinkage and underestimate thickness shrinkage. Note also that if both a size change and percentage moisture content are known, Equation (13–2) can be used to calculate the original moisture content.

Calculation Based on Green Dimensions

Approximate dimensional changes associated with moisture content changes greater than 6% to 14%, or when one moisture content value is outside of those limits, can be calculated by

$$\Delta D = \frac{D_1(M_F - M_1)}{30(100)/S_T - 30 + M_1} \quad (13-3)$$

where S_T is tangential shrinkage (%) from green to oven-dry (Chap. 4 Tables 4–3 and 4–4) (use radial shrinkage S_R when appropriate).

Neither M_1 nor M_F should exceed 30%, the assumed moisture content value when shrinkage starts for most species.

Design Factors Affecting Dimensional Change

Framing Lumber in House Construction

Ideally, house framing lumber should be dried to the moisture content it faces in use to minimize dimensional changes as a result of frame shrinkage. This ideal condition is difficult to achieve, but some drying and shrinkage of the frame may take place without being visible or causing serious defects after the house is completed. If, at the time the wall and ceiling finish is applied, the moisture content of the framing lumber is not more than about 5% above that which it will reach in service, there will be little or no evidence of defects caused by shrinkage of the frame. For heated houses in cold climates, joists over heated basements, studs, and ceiling joists may reach a moisture content as low as 6% to 7% (Table 13–2). In mild climates, the minimum moisture content will be greater.

The most common signs of excessive shrinkage are cracks in plastered walls, truss rise, open joints, and nail pops in dry-wall construction; distortion of door openings; uneven floors; and loosening of joints and fastenings. The extent of vertical shrinkage after the house is completed is proportional to the depth of wood used as supports in a horizontal position, such as girders, floor joists, and plates. After all,

shrinkage occurs primarily in the width and thickness of members, not the length.

Thoroughly consider the type of framing best suited to the whole building structure. Methods should be chosen that will minimize or balance the use of wood across the grain in vertical supports. These involve variations in floor, wall, and ceiling framing. The factors involved and details of construction are covered extensively in *Wood-Frame House Construction* (Sherwood and Stroh 1991).

Heavy Timber Construction

In heavy timber construction, a certain amount of shrinkage is to be expected. A column that bears directly on a wood girder can result in a structure settling as a result of the perpendicular-to-grain shrinkage of the girder. If not provided for in the design, shrinkage may cause weakening of the joints or uneven floors or both. One means of eliminating part of the shrinkage in mill buildings and similar structures is to use metal post caps; the metal in the post cap separates the upper column from the lower column. The same thing is accomplished by bolting wood corbels (tassels or braggers) to the side of the lower column to support the girders.

When joist hangers are installed, the top of the joist should be above the top of the girder; otherwise, when the joist shrinks in the stirrup, the floor over the girder will be higher than that bearing upon the joist. Heavy planking used for flooring should be near 12% moisture content to minimize openings between boards as they approach moisture equilibrium. When standard 38- or 64-mm (nominal 2- or 3-in.) joists are nailed together to provide a laminated floor of greater depth for heavy design loads, the joist material should be somewhat less than 12% moisture content if the building is to be heated.

Interior Finish

Normal seasonal changes in the moisture content of interior finish are not enough to cause serious dimensional change if the woodwork was properly installed. Large members, such as ornamental beams, cornices, newel posts, stair stringers, and handrails, should be built up from comparatively small pieces. Wide door and window trim and base should be hollow-backed. Backband trim, if mitered at the corners, should be glued and splined before erection; otherwise butt joints should be used for the wide faces. Design and install large, solid pieces, such as wood paneling, so that the panels are free to move across the grain. Narrow widths are preferable.

Flooring

Flooring is usually dried to the moisture content expected in service so that shrinking and swelling are minimized and buckling or large gaps between boards do not occur. For basement, large hall, or gymnasium floors, however, leave enough space around the edges to allow for some expansion.

Wood Care and Installation during Construction

Lumber and Trusses

Although it is good housekeeping practice, lumber is often not protected from the weather at construction sites. Lumber is commonly placed on the ground in open areas near the building site as bulked and strapped packages. Place supports under such packages that elevate the packages at least 150 mm (6 in.) off the ground to prevent wetting from mud and ground water. In addition, cover the packages with plastic tarpaulins for protection from rain.

Pile lumber that is green or nearly green on stickers under a roof for additional drying before building into the structure. The same procedure is required for lumber treated with a waterborne preservative but not fully re-dried. Prefabricated building parts, such as roof trusses, sometimes lie unprotected on the ground at the building site. In warm, rainy weather, moisture regain can result in fungal staining. Wetting of the lumber also results in swelling, and subsequent shrinkage of the framing may contribute to structural distortions. Extended storage of lumber at moisture contents greater than 20% without drying can allow decay to develop.

If framing lumber has a greater moisture content when installed than that recommended in Table 13–2, shrinkage can be expected. Framing lumber, even thoroughly air-dried stock, will generally have a moisture content greater than that recommended when it is delivered to the building site. If carelessly handled in storage at the site, the lumber can take up more moisture. Builders can schedule their work so an appreciable amount of drying can take place during the early stages of construction. This minimizes the effects of additional drying and shrinkage after completion. When the house has been framed, sheathed, and roofed, the framing is so exposed that in time it can dry to a lower moisture content than could be found in yard-dried lumber. The application of the wall and ceiling finish is delayed while wiring and plumbing are installed. If this delay is about 30 days in warm, dry weather, the framing lumber should lose enough moisture so that any additional drying in place will be minimal. In cool, damp weather, or if wet lumber is used, the period of exposure should be extended. Checking moisture content of door and window headers and floor and ceiling joists at this time with an electric moisture meter is good practice. When these members approach an average of 12% moisture content, interior finish and trim can normally be installed. Closing the house and using the heating system will hasten the rate of drying.

Before the wall finish is applied, the frame should be examined and defects that may have developed during drying, such as warped or distorted studs, shrinkage of lintels (header) over openings, or loosened joints, should be corrected.

Exterior Trim and Millwork

Exterior trim, such as cornice and rake mouldings, fascia boards, and soffit material, is typically installed before the shingles are laid. Protect trim, siding, and window and door frames on the site by storing in the house or garage until time of installation. Although items such as window frames and sashes are usually treated with some type of water-repellent preservative to resist absorption of water, store in a protected area if they cannot be installed soon after delivery. Wood siding is often received in packaged form and can ordinarily remain in the package until installation.

Finished Flooring

Cracks develop in flooring if the material takes up moisture either before or after installation, then shrinks when the building is heated. Such cracks can be greatly reduced by observing the following practices:

- Specify flooring manufactured according to association rules and sold by dealers that protect the material properly during storage and delivery.
- Measure random pieces of flooring using a non-penetrating meter to ensure moisture content is correct upon arrival and prior to installation.
- Have flooring delivered after masonry and plastering are completed and fully dry, unless a dry storage space is available.
- Install the heating plant before flooring is delivered.
- Break open flooring bundles and expose all sides of flooring to the atmosphere inside the structure.
- Close up the house at night and increase the temperature about 8 °C (15 °F) greater than the outdoor temperature for about 3 days before laying the floor.
- If the house is not occupied immediately after the floor is laid, keep the house closed at night or during damp weather and supply some heat if necessary.

Better and smoother sanding and finishing can be done when the house is warm and the wood has been kept dry (FPL 1961).

Interior Trim

In a building under construction, average relative humidity will be greater than that in an occupied house because of the moisture that evaporates from wet concrete, brickwork, plaster, and even the structural wood members. The average temperature will be lower because workers prefer a lower temperature than is common in an occupied house. Under such conditions, the interior trim tends to have greater moisture content during construction than it will have during occupancy.

Before the interior trim is delivered, the outside doors and windows should be kept closed at night. In this way, interior conditions are held as close as possible to the higher

temperature and lower humidity that ordinarily occurs during the day. Such protection may be sufficient during dry warm weather, but during damp or cool weather, it is highly desirable to heat the house, particularly at night. Whenever possible, the heating plant should be placed in the house before the interior trim is installed, to be available for supplying the necessary heat. Portable heaters can also be used. Keep the inside temperature during the night about 8 °C (15 °F) greater than the outside temperature but not below about 21 °C (70 °F) during the summer or 17 °C (62 °F) when the outside temperature is below freezing.

After buildings have thoroughly dried, less heat is needed, but unoccupied houses, new or old, should have some heat during the winter. A temperature of about 8 °C (15 °F) greater than the outside temperature and above freezing at all times will keep the woodwork, finish, and other parts of the house from being affected by dampness or frost.

Plastering

During a plastering operation in a moderate-sized, six-room house, approximately 450 kg (1,000 lb) of water is used, all of which must dissipate before the house is ready for the interior finish. Adequate ventilation removes the evaporated moisture and keeps it from being adsorbed by the framework. In houses plastered in cold weather, the excess moisture can also cause paint to blister on exterior finish and siding. During warm, dry weather, with the windows wide open, the moisture will be gone within a week after the final coat of plaster is applied. During damp, cold weather, the heating system or portable heaters are used to prevent freezing of plaster and to hasten its drying. Provide adequate ventilation constantly because a large volume of air is required to carry away the amount of water involved. Even in the coldest weather, the windows on the side of the house away from the prevailing winds should be opened 50 to 75 mm (2 to 3 in.), preferably from the top.

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Biodeterioration of Wood

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Under proper conditions, wood will give centuries of service. However, under conditions that permit the development of wood-degrading organisms, protection must be provided during processing, merchandising, and use.

The organisms that can degrade wood are principally fungi, insects, bacteria, and marine borers.

Molds, most sapwood stains, and decay are caused by fungi, which are microscopic, thread-like microorganisms that must have organic material to live. For some of them, wood offers the required food supply. The growth of fungi depends on suitably mild temperatures, moisture, and air (oxygen). Chemical stains, although they are not caused by organisms, are mentioned in this chapter because they resemble stains caused by fungi.

Insects also may damage wood and in many situations must be considered in protective measures. Termites are the major insect enemy of wood, but on a national scale, they are a less serious threat than fungi.

Bacteria in wood ordinarily are of little consequence, but some may make the wood excessively absorptive. In addition, some may cause strength losses over long periods of exposure, particularly in forest soils.

Marine borers can attack susceptible wood rapidly in salt water harbors, where they are the principal cause of damage to piles and other wood marine structures.

Wood degradation by organisms has been studied extensively, and many preventive measures are well known and widely practiced. By taking ordinary precautions with the finished product, the user can contribute substantially to ensuring a long service life.

Fungus Damage and Control

Fungus damage to wood may be traced to three general causes: (a) lack of suitable protective measures when storing logs or bolts; (b) improper seasoning, storing, or handling of the raw material produced from the log; and (c) failure to take ordinary simple precautions in using the final product. The incidence and development of molds, decay, and stains caused by fungi depend heavily on temperature and moisture conditions (Fig. 14–1).

Molds and Fungal Stains

Molds and fungal stains are confined to a great extent to sapwood and are of various colors. The principal fungal

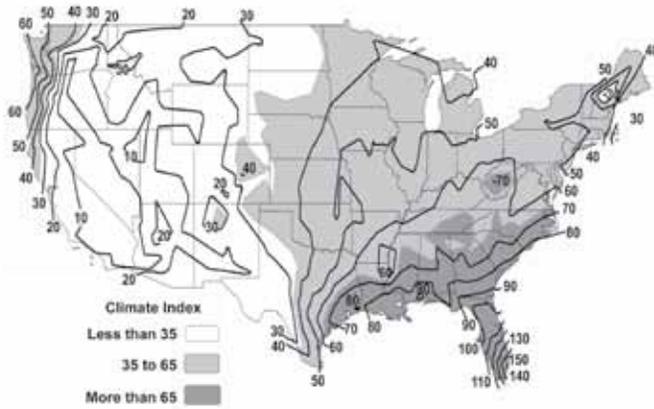


Figure 14–1. Climate index for decay hazard. Higher numbers indicate greater decay hazard.

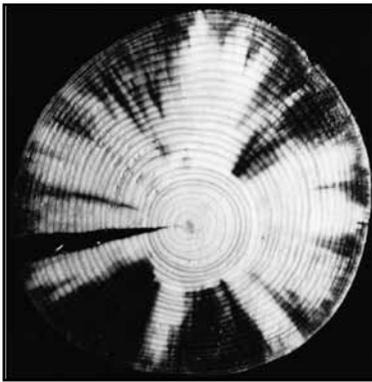


Figure 14–2. Typical radial penetration of log by stain. The pattern is a result of more rapid penetration by the fungus radially (through the ray) than tangentially.

stains are usually referred to as sap stain or blue stain. The distinction between molding and staining is made primarily on the basis of the depth of discoloration. With some molds and the lesser fungal stains, there is no clear-cut differentiation. Typical sap stain or blue stain penetrates into the sapwood and cannot be removed by surfacing. Also, the discoloration as seen on a cross section of the wood often appears as pie-shaped wedges oriented radially, corresponding to the direction of the wood rays (Fig. 14–2). The discoloration may completely cover the sapwood or may occur as specks, spots, streaks, or patches of various intensities of color. The so-called blue stains, which vary from bluish to bluish black and gray to brown, are the most common, although various shades of yellow, orange, purple, and red are sometimes encountered. The exact color of the stain depends on the infecting organisms and the species and moisture condition of the wood. The fungal brown stain mentioned here should not be confused with chemical brown stain.

Mold discolorations usually become noticeable as fuzzy or powdery surface growths, with colors ranging from light shades to black. Among the brighter colors, green and yellowish hues are common. On softwoods, though the fungus may penetrate deeply, the discoloring surface growth often can easily be brushed or surfaced off. However, on large-

pored hardwoods (for example, oaks), the wood beneath the surface growth is commonly stained too deeply to be surfaced off. The staining tends to occur in spots of various concentration and size, depending on the kind and pattern of the superficial growth.

Under favorable moisture and temperature conditions, staining and molding fungi may become established and develop rapidly in the sapwood of logs shortly after they are cut. In addition, lumber and such products as veneer, furniture stock, and millwork may become infected at any stage of manufacture or use if they become sufficiently moist. Freshly cut or unseasoned stock that is piled during warm, humid weather may be noticeably discolored within 5 or 6 days. Recommended moisture control measures are given in Chapter 13.

Ordinarily, stain and mold fungi affect the strength of the wood only slightly; their greatest effect is usually confined to strength properties that determine shock resistance or toughness (Chap. 5). They increase the absorbency of wood, and this can cause over-absorption of glue, paint, or wood preservative during subsequent processing. Increased porosity also makes wood more wettable, which can lead to subsequent colonization by typical wood-decay fungi.

Stain- and mold-infected stock is practically unimpaired for many uses in which appearance is not a limiting factor, and a small amount of stain may be permitted by standard grading rules. Stock with stain and mold may not be entirely satisfactory for siding, trim, and other exterior millwork because of its greater water absorbency. Also, incipient decay may be present, though inconspicuous, in the discolored areas. Both of these factors increase the possibility of decay in wood that is rain-wetted unless the wood has been treated with a suitable preservative.

Chemical Stains

Nonmicrobial or chemical stains are difficult to control and represent substantial loss in wood quality. These stains, which should not be confused with fungal brown stain, include a variety of discolorations in wood that are often promoted by slow drying of lumber and warm to hot temperatures. Such conditions allow naturally occurring chemicals in wood to react with air (enzymatic oxidation) to form a new chemical that is typically dark in color. Common chemical stains include (a) interior sapwood graying, prevalent in oak, hackberry, ash, and maple, (b) brown stain in softwoods, and (c) pinking and browning in the interior of light-colored woods such as maple. Another common discoloration, iron stain, is caused by the interaction of iron with tannins in wood. Iron stain is more prevalent in hardwoods (for example, oak and many tropical hardwoods) and in some softwoods such as Douglas-fir. Control is achieved by eliminating the source of iron.

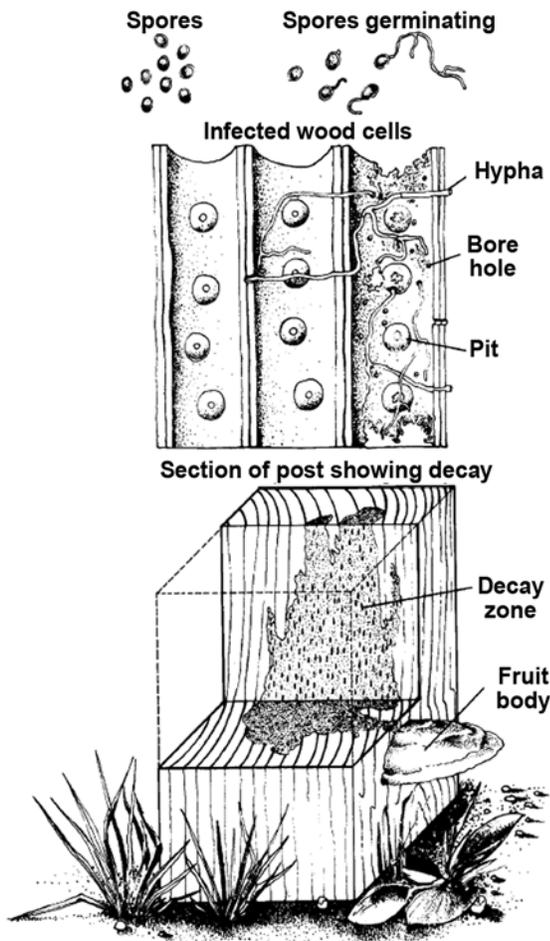


Figure 14-3. The decay cycle (top to bottom). Thousands of spores produced in a fungal fruiting body are distributed by wind or insects. On contacting moist, susceptible wood, spores germinate and fungal hyphae create new infections in the wood cells. In time, serious decay develops that may be accompanied by formation of new fruiting bodies.

Decay

Decay-producing fungi may, under conditions that favor their growth, attack either heartwood or sapwood in most wood species (Fig. 14-3). The result is a condition designated as decay, rot, dote, or doze. Fresh surface growths of decay fungus may appear as fan-shaped patches (Fig. 14-4), strands, or root-like structures that are usually white or brown in color. Sometimes fruiting bodies are produced that take the form of mushrooms, brackets, or crusts. The fungus, in the form of microscopic, threadlike strands called hyphae, permeates the wood and uses parts of it as food. Some fungi live largely on cellulose, whereas others use lignin and cellulose.

Certain decay fungi colonize the heartwood (causing heart rot) and rarely the sapwood of living trees, whereas others confine their activities to logs or manufactured products,



Figure 14-4. Mycelial fans on a wood door.

such as sawn lumber, structural timbers, poles, and ties. Most fungi that attack trees cease their activities after the trees have been cut, as do the fungi causing brown pocket (peck) in baldcypress or white pocket in Douglas-fir and other conifers. Relatively few fungi continue their destruction after the trees have been cut and worked into products and then only if conditions remain favorable for their growth. Although heartwood is more susceptible to decay than is sapwood in living trees, for many species, the sapwood of wood products is more susceptible to decay than is the heartwood.

Most decay can progress rapidly at temperatures that favor growth of plant life in general. For the most part, decay is relatively slow at temperatures below 10 °C (50 °F) and above 35 °C (95 °F). Decay essentially ceases when the temperature drops as low as 2 °C (35 °F) or rises as high as 38 °C (100 °F).

Serious decay occurs only when the moisture content of the wood is above the fiber saturation point (average 30%). Only when previously dried wood is contacted by water in the form of rain or condensation or is in contact with wet ground will the fiber saturation point be reached. By itself, the water vapor in humid air will not wet wood sufficiently to support significant decay, but it will permit development of some mold fungi. Fully air-dried wood usually will have a moisture content not exceeding 20% and should provide a reasonable margin of safety against fungal damage. Thus, wood will not decay if it is kept air dry, and decay already present from prior infection will not progress.

Wood can be too wet for decay as well as too dry. If the wood is water-soaked, the supply of air to the interior of a piece may not be adequate to support development of typical decay fungi. For this reason, foundation piles buried beneath the water table and logs stored in a pond or under a suitable system of water sprays are not subject to decay by typical wood-decay fungi.

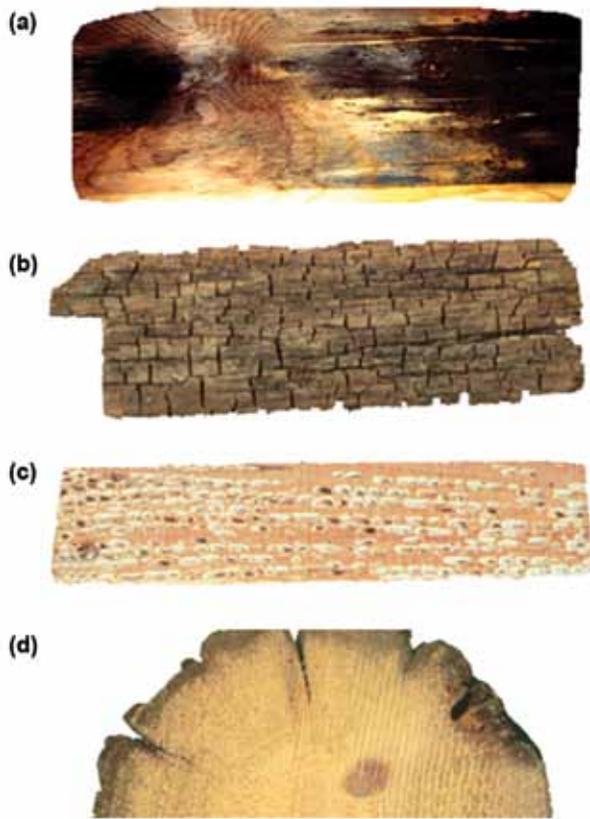


Figure 14–5. Representative samples of four common types of fungal growth on wood: (a) mold discoloration; (b) brown rotted pine (note the dark color and cubical checking in the wood); (c) white rot in maple (note the bleached appearance); (d) soft-rotted preservative-treated pine utility pole (note the shallow depth of decay).

The early or incipient stages of decay are often accompanied by a discoloration of the wood, which can be difficult to recognize but is more evident on freshly exposed surfaces of unseasoned wood than on dry wood. Abnormal mottling of the wood color, with either unnatural brown or bleached areas, is often evidence of decay infection. Many fungi that cause heart rot in the standing tree produce incipient decay that differs only slightly from the normal color of the wood or gives a somewhat water-soaked appearance to the wood.

Typical or late stages of decay are easily recognized, because the wood has undergone definite changes in color and properties, the character of the changes depending on the organism and the substances it removes.

Two kinds of major decay fungi are recognized: brown rot and white rot. With brown-rot fungi, only the cellulose is extensively removed, the wood takes on a browner color, and it can crack across the grain, shrink, collapse, and be crushed into powder (Fig. 14–5). With white-rot fungi, both lignin and cellulose usually are removed, the wood may lose color and appear “whiter” than normal, it does not crack across the grain, and until severely degraded, it retains its

outward dimensions, does not shrink or collapse, and often feels spongy (Fig. 14–5). Brown-rot fungi commonly colonize softwoods, and white-rot fungi commonly occur on hardwoods, but both brown- and white-rot fungi occasionally colonize both types of wood.

Brown, crumbly rot, in the dry condition, is sometimes called dry rot, but the term is incorrect because wood must be damp to decay, although it may become dry later. A few fungi, however, have water-conducting strands; such fungi are capable of carrying water (usually from the soil) into buildings or lumber piles, where they moisten and rot wood that would otherwise be dry. They are sometimes referred to technically as dry-rot fungi or water-conducting fungi. The latter term better describes the true situation because these fungi, like the others, must have water.

A third and generally less important kind of decay is known as soft rot. Soft rot is caused by fungi related to the molds rather than those responsible for brown and white rot. Soft rot typically is relatively shallow, primarily affecting the outer surface of wood; the affected wood is greatly degraded and often soft when wet, but immediately beneath the zone of rot, the wood may be firm (Fig. 14–5). Because soft rot usually is rather shallow, it is most damaging to relatively thin pieces of wood such as slats in cooling towers. It is favored by wet situations but is also prevalent on surfaces that have been alternately wet and dry over a substantial period. Heavily fissured surfaces, familiar to many as weathered wood, generally have been quite degraded by soft-rot fungi.

Decay Resistance of Wood

The heartwood of common native species of wood has various degrees of natural decay resistance. Untreated sapwood of essentially all species has low resistance to decay and usually has a short service life under conditions favoring decay. The natural decay resistance of heartwood is greatly affected by differences in preservative qualities of the wood extractives, the attacking fungus, and the conditions of exposure. Considerable differences in service life can be obtained from pieces of wood cut from the same species, even the same tree, and used under apparently similar conditions. There are further complications because, in a few species, such as the spruces and the true firs (not Douglas-fir), heartwood and sapwood are so similar in color that they cannot be easily distinguished.

Precise ratings of decay resistance of heartwood of different species are not possible because of differences within species and the variety of service conditions to which wood is exposed. However, broad groupings of many native species, based on service records, laboratory tests, and general expertise, are helpful in choosing heartwood for use under conditions favorable to decay. Groupings by natural resistance of some domestic and imported wood species to decay fungi are shown in Table 14–1, which ranks the heartwood of a grouping of species according to decay resistance. The

Table 14–1. Grouping of some domestic and imported woods according to average heartwood decay resistance^a

Very resistant	Resistant	Moderately resistant	Slightly or nonresistant
Domestic			
Black locust	Baldcypress, old growth	Baldcypress, young growth	Alder, red
Mulberry, red	Catalpa	Cherry, black	Ashes
Osage-orange	Cedar	Douglas-fir	Aspens
Yew, Pacific	Atlantic white	Honey locust	Beech
	Eastern redcedar	Larch, western	Birches
	Incense	Pine, eastern white, old growth	Buckeye
	Northern white	Pine, longleaf, old growth	Butternut
	Port-Orford	Pine, slash, old growth	Cottonwood
	Western redcedar	Redwood, young growth	Elms
	Yellow	Tamarack	Basswood
	Chestnut		Firs, true
	Cypress, Arizona		Hackberry
	Junipers		Hemlocks
	Mesquite		Hickories
	Oaks, white ^b		Magnolia
	Redwood, old growth		Maples
	Sassafras		Pines (other than those listed) ^b
	Walnut, black		Spruces
			Sweetgum
			Sycamore
			Tanoak
			Willows
			Yellow-poplar
Imported			
Angelique	Aftotmosia (Kokrodua)	Andiroba	Balsa
Azobe	Apamate (Roble)	Avodire	Banak
Balata	Balau ^b	Benge	Cativo
Goncalo alves	Courbaril	Bubinga	Ceiba
Greenheart	Determa	Ehie	Hura
Ipe (lapacho)	Iroko	Ekop	Jelutong
Jarrah	Kapur	Keruing ^b	Limba
Lignumvitae	Karri	Mahogany, African	Meranti, light red ^b
Purpleheart	Kempas	Meranti, dark red ^b	Meranti, yellow ^b
Teak, old growth	Mahogany, American	Mersawa ^b	Meranti, white ^b
	Manni	Sapele	Obeche
	Spanish-cedar	Teak, young growth	Okoume
	Sucupira	Tornillo	Parana pine
	Wallaba		Ramin
			Sande
			Sepitir
			Seraya, white

^aDecay resistance may be less for members placed in contact with the ground and/or used in warm, humid climates.

Substantial variability in decay resistance is encountered with most species, and limited durability data were available for some species listed. Use caution when using naturally durable woods in structurally critical or ground-contact applications.

^bMore than one species included, some of which may vary in resistance from that indicated.

extent of variations in decay resistance of individual trees or wood samples of a particular species is much greater for most of the more resistant species than for the slightly or nonresistant species.

Natural resistance of wood to fungi is important only where conditions conducive to decay exist or may develop. Where decay hazard exists, heartwood of a species in the resistant category generally gives satisfactory service for wood used above-ground, while those in the very resistant category

generally give satisfactory performance in contact with the ground. Heartwood of species in the other two categories will usually require some form of preservative treatment. For mild decay conditions, a simple preservative treatment—such as a short soak in preservative after all cutting and boring operations are complete—may be adequate for wood low in decay resistance. For more severe decay hazards, pressure treatment is often required. Even the very decay-resistant species may require preservative treatment for important structural uses or other uses where failure would

endanger life or require expensive repairs. When selecting naturally decay-resistant wood species for applications where conditions are conducive to decay, it is important to utilize heartwood. Marketable sizes of some species are primarily second growth and contain a high percentage of sapwood. Consequently, substantial quantities of heartwood lumber of these species are not available. If wood is subjected to severe decay conditions, pressure-treated wood, rather than resistant heartwood, is generally recommended. Preservative treatments and methods are discussed in Chapter 15.

Effect of Decay on Strength of Wood

Decay initially affects toughness, or the ability of wood to withstand impacts. This is generally followed by reductions in strength values related to static bending. Eventually, all strength properties are seriously reduced.

Strength losses during early stages of decay can be considerable, depending to a great extent upon the fungi involved and, to a lesser extent, upon the type of wood undergoing decay. In laboratory tests, losses in toughness ranged from 6% to >50% by the time 1% weight loss had occurred in the wood as a result of fungal attack. By the time weight losses resulting from decay have reached 10%, most strength losses may be expected to exceed 50%. At such weight losses (10% or less), decay is detectable only microscopically. It may be assumed that wood with visually discernible decay has been greatly reduced in all strength values.

Prevention of Mold, Stain, and Decay

Logs, Poles, Piles, and Ties

The wood species, geographic region, and time of year determine what precautions must be taken to avoid serious damage from fungi in logs, poles, piles, ties, and similar thick products during seasoning or storage. In dry climates, rapid surface seasoning of poles and piles will retard development of mold, stain, and decay. The bark is peeled from the pole and the peeled product is decked on high skids or piled on high, well-drained ground in the open to air-dry. In humid regions, such as the Gulf States, these products often do not air-dry fast enough to avoid losses from fungi. Pre-seasoning treatments with approved preservative solutions can be helpful in these circumstances.

For logs, rapid conversion into lumber or storage in water or under a water spray (Fig. 14–6) is the surest way to avoid fungal damage. Preservative sprays promptly applied to the wood will protect most timber species during storage for 2 to 3 months, except in severe decay hazard climates, such as in Mississippi (Fig. 14–1). For longer storage, an end coating is needed to prevent seasoning checks, through which infection can enter the log.

Lumber

Growth of decay fungi can be prevented in lumber and other wood products by rapidly drying them to a moisture content of 20% or less and keeping them dry. Standard air-



Figure 14–6. Spraying logs with water protects them against fungal stain and decay.

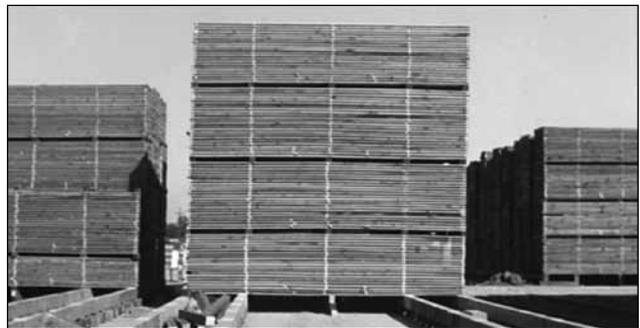


Figure 14–7. A sanitary, well-drained air-drying yard.

drying practices will usually dry the wood fast enough to protect it, particularly if the protection afforded by drying is supplemented by dip or spray treatment of the stock with an EPA-approved fungicidal solution. Successful control by this method depends not only upon immediate and adequate treatment but also upon proper handling of the lumber after treatment. However, kiln drying is the most reliable method of rapidly reducing moisture content.

Air-drying yards should be kept as sanitary and as open as possible to air circulation (Fig. 14–7). Recommended practices include locating yards and sheds on well-drained ground; removing debris (which serves as a source of infection) and weeds (which reduce air circulation); and employing piling methods that permit rapid drying of the lumber and protect against wetting. Storage sheds should be constructed and maintained to prevent significant wetting of the stock. Ample roof overhang on open sheds is desirable. In areas where termites or water-conducting fungi may be troublesome, stock to be held for long periods should be set on foundations high enough so that the wood can be inspected from beneath.

The user's best assurance of receiving lumber free from decay other than light stain is to buy stock marked by a lumber association in a grade that eliminates or limits such

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quality-reducing features. Surface treatment for protection at the drying yard is only temporarily effective. Except for temporary structures, lumber to be used under conditions conducive to decay should be all heartwood of a naturally durable wood species or should be adequately treated with a wood preservative (Chap. 15).

Buildings

The lasting qualities of properly constructed wood buildings are apparent in all parts of the country. Serious decay problems are almost always a sign of faulty design or construction, lack of reasonable care in the handling the wood, or improper maintenance of the structure.

Construction principles that ensure long service and avoid decay in buildings include (a) building with dry lumber, free of incipient decay and not exceeding the amounts of mold and blue stain permitted by standard grading rules; (b) using construction details and building designs that will keep exterior wood and wood-based building components dry and that will promote their drying if they become wet; (c) using wood treated with a preservative or heartwood of a decay-resistant species for parts exposed to aboveground decay hazards; and (d) using pressure-treated wood for the high hazard situation associated with ground contact.

A building site that is dry or for which drainage is provided will reduce the possibility of decay. Grading around the building is an important consideration, as is adequate planning for management of roof runoff (Chap. 17). Stumps, wood debris, stakes, or wood concrete forms are frequently subject to decay if left under or near a building and may become a source for decay infestation for the building.

Wet or infected wood should not be enclosed until it is thoroughly dried. Wet wood includes green (unseasoned) lumber, lumber that has been inadequately dried, or dried lumber that has been rewetted as a result of careless storage and handling. Wood can become infected because of improper handling at the sawmill or retail yard or after delivery to the job site.

Untreated wood parts of substructures should not be permitted to contact the soil. Minimums of 200 mm (8 in.) clearance between soil and framing and 150 mm (6 in.) between soil and siding are recommended. Where frequent hard rains occur, a foundation height above grade of 300 to 460 mm (12 to 18 in.) is advocated. An exception may be made for certain temporary constructions. If contact with soil is unavoidable, the wood should be pressure treated (Chap. 15).

Sill plates and other wood resting on a concrete slab foundation generally should be pressure treated and protected by installing a moisture-resistant membrane, such as polyethylene, beneath the slab. Girder and joist openings in masonry walls should be big enough to ensure an air space around the ends of these wood members. If the members are below the outside soil level, moisture proofing the outer face of the wall is essential.

In buildings without basements but with crawl spaces, wetting of the floor framing and sheathing by condensation may result in serious decay damage. The primary source of condensation is soil moisture. Isolating the crawl space from soil moisture can be achieved by laying a barrier such as polyethylene on the soil. To facilitate inspection of the crawl space, a minimum 460-mm (18-in.) clearance should be left under wood joists.

Wood and wood-based building components should also be protected from rain during construction. Continuous protection from rainwater or condensation in walls and roofs will prevent the development of decay. Thus, design, work quality, and maintenance of wall and roofing systems are critical, particularly at roof edges and points where roofs interface with walls. A fairly wide roof overhang (0.6 m (2 ft)) with gutters and downspouts that are kept free of debris is desirable.

The use of sound, dry lumber is equally important for the interior of buildings. Primary sources for interior moisture are humidity and plumbing leaks. Interior humidity control is discussed in Chapter 17. Plumbing leaks can result in serious decay problems within buildings, particularly if they are undetected for long periods.

Where service conditions in a building are such that the wood cannot be kept dry, the use of preservative-treated wood (Chap. 15) or heartwood of a durable species is advised. Examples include porches, exterior steps, and decking platforms and such places as textile mills, pulp and paper mills, and cold storage plants.

In making repairs necessitated by decay, every effort should be made to correct the moisture condition that led to the damage. If the condition cannot be corrected, all infected parts should be replaced with preservative-treated wood or with all-heartwood lumber of a naturally decay-resistant wood species. If the sources of moisture that caused the decay are entirely eliminated, it is necessary only to replace the weakened wood with dry lumber.

Other Structures and Products

In general, the principles underlying the prevention of mold, stain, or decay damage to veneer, plywood containers, boats, and other wood products and structures are similar to those described for buildings—dry the wood rapidly and keep it dry, or treat it with approved protective and preservative solutions. Interior grades of plywood should not be used where the plywood will be exposed to moisture; the adhesives, as well as the wood, may be damaged by fungi and bacteria and degraded by moisture. With exterior-type panels, joint construction should be carefully designed to prevent the entrance and entrapment of rainwater.

In treated bridge or wharf timbers, checking may occur and may expose untreated wood to fungal attack. Annual in-place treatment of these checks will provide protection from

Table 14–2. Types of damage caused by wood-attacking insects

Type of damage	Description	Causal agent	Damage	
			Begins	Ends
Pin holes	0.25 to 6.4 mm (1/100 to 1/4 in.) in diameter, usually circular Tunnels open:			
	Holes 0.5 to 3 mm (1/50 to 1/8 in.) in diameter, usually centered in dark streak or ring in surrounding wood	Ambrosia beetles	In living trees and unseasoned logs and lumber	During seasoning
	Holes variable sizes; surrounding wood rarely dark stained; tunnels lined with wood-colored substance	Timber worms	In living trees and unseasoned logs and lumber	Before seasoning
	Tunnels usually packed with fine sawdust: Exit holes 0.8 to 1.6 mm (1/32 to 1/16 in.) in diameter; in sapwood of large-pored hardwoods; loose floury sawdust in tunnels	Lyctid powder-post beetles	During or after seasoning	Reinfestation continues until sapwood destroyed
	Exit holes 1.6 to 3 mm (1/16 to 1/8 in.) in diameter; primarily in sapwood, rarely in heartwood; tunnels loosely packed with fine sawdust and elongate pellets	Anobiid powder-post beetles	Usually after wood in use (in buildings)	Reinfestation continues; progress of damage very slow
	Exit holes 2.5 to 7 mm (3/32 to 9/32 in.) in diameter; primarily sapwood of hardwoods, minor in softwoods; sawdust in tunnels fine to coarse and tightly packed	Bostrichid powder-post beetles	Before seasoning or if wood is rewetted	During seasoning or redrying
Grub holes	Exit holes 1.6 to 2 mm (1/16 to 1/12 in.) in diameter; in slightly damp or decayed wood; very fine sawdust or pellets tightly packed in tunnels	Wood-boring weevils	In slightly damp wood in use	Reinfestation continues while wood is damp
	3 to 13 mm (1/8 to 1/2 in.) in diameter, circular or oval			
	Exit holes 3 to 13 mm (1/8 to 1/2 in.) in diameter; circular; mostly in sapwood; tunnels with coarse to fibrous sawdust or it may be absent	Roundheaded borers (beetles)	In living trees and unseasoned logs and lumber	When adults emerge from seasoned wood or when wood is dried
	Exit holes 3 to 13 mm (1/8 to 1/2 in.) in diameter; mostly oval; in sapwood and heartwood; sawdust tightly packed in tunnels	Flatheaded borers (beetles)	In living trees and unseasoned logs and lumber	When adults emerge from seasoned wood or when wood is dried
	Exit holes ~6 mm (~1/4 in.) in diameter; circular; in sapwood of softwoods, primarily pine; tunnels packed with very fine sawdust	Old house borers (a roundheaded borer)	During or after seasoning	Reinfestation continues in seasoned wood in use
	Exit holes perfectly circular, 4 to 6 mm (1/6 to 1/4 in.) in diameter; primarily in softwoods; tunnels tightly packed with coarse sawdust, often in decay softened wood	Woodwasps	In dying trees or fresh logs	When adults emerge from seasoned wood, usually in use, or when kiln-dried
Network of galleries	Nest entry hole and tunnel perfectly circular ~13 mm (~1/2 in.) in diameter; in soft softwoods in structures	Carpenter bees	In structural timbers, siding	Nesting reoccurs annually in spring at same and nearby locations
	Systems of interconnected tunnels and chambers	Social insects with colonies		
	Walls look polished; spaces completely clean of debris	Carpenter ants	Usually in damp partly decayed, or soft-textured wood in use	Colony persists unless prolonged drying of wood occurs
	Walls usually speckled with mud spots; some chambers may be filled with “clay” Chambers contain pellets; areas may be walled off by dark membrane	Subterranean termites Dry-wood termites (occasionally damp wood termites)	In wood structures	Colony persists
Pitch pocket Black check	Openings between growth rings containing pitch	Various insects	In living trees	In tree
	Small packets in outer layer of wood	Grubs of various insects	In living trees	In tree
Pith fleck	Narrow, brownish streaks	Fly maggots or adult weevils	In living trees	In tree
Gum spot	Small patches or streaks of gum-like substances	Grubs of various insects	In living trees	In tree
Ring distortion	Double growth rings or incomplete annual layers of growth	Larvae of defoliating insects or flatheaded cambium borers	In living trees	In tree
	Stained area more than 25.4 mm (1 in.) long introduced by insects in trees or recently felled logs	Staining fungi	With insect wounds	With seasoning

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decay. Similarly, pile tops may be protected by treatment with a wood preservative followed by application of a suitable capping compound or shield.

Wood boats present certain problems that are not encountered in other uses of wood. The parts especially subject to decay are the stem, knighthead, transom, and frameheads, which can be reached by rainwater from above or condensation from below. Frayed surfaces are more likely to decay than are exposed surfaces, and in salt water service, hull members just below the weather deck are more vulnerable than those below the waterline. Recommendations for avoiding decay include (a) using only heartwood of durable species, free of infection, and preferably below 20% moisture content; (b) providing and maintaining ventilation in the hull and all compartments; (c) keeping water out as much as is practicable, especially fresh water; and (d) where it is necessary to use sapwood or nondurable heartwood, impregnating the wood with an approved preservative and treating the fully cut, shaped, and bored wood before installation by soaking it for a short time in preservative solution. Where such mild soaking treatment is used, the wood most subject to decay should also be flooded with an approved preservative at intervals of 2 or 3 years. During subsequent treatment, the wood should be dry so that joints are relatively loose.

Bacteria

Most wood that has been wet for a considerable length of time probably will contain bacteria. The sour smell of logs that have been held under water for several months, or of lumber cut from them, manifests bacterial action. Usually, bacteria have little effect on wood properties, except over long periods, but some may make the wood excessively absorptive. This can result in excessive absorption of moisture, adhesive, paint, or preservative during treatment or use. This effect has been a problem in the sapwood of millwork cut from pine logs that have been stored in ponds. There also is evidence that bacteria developing in pine veneer bolts held under water or sprayed with water may cause noticeable changes in the physical character of the veneer, including some strength loss. Additionally, a mixture of different bacteria and fungi was found capable of accelerating decay of treated cooling tower slats and mine timbers.

Insect Damage and Control

The more common types of damage caused by wood-attacking insects are shown in Table 14-2 and Figure 14-8. Methods of controlling and preventing insect attack of wood are described in the following paragraphs.

Beetles

Bark beetles may damage the surface of the components of logs and other rustic structures from which the bark has not been removed. These beetles are reddish brown to black and

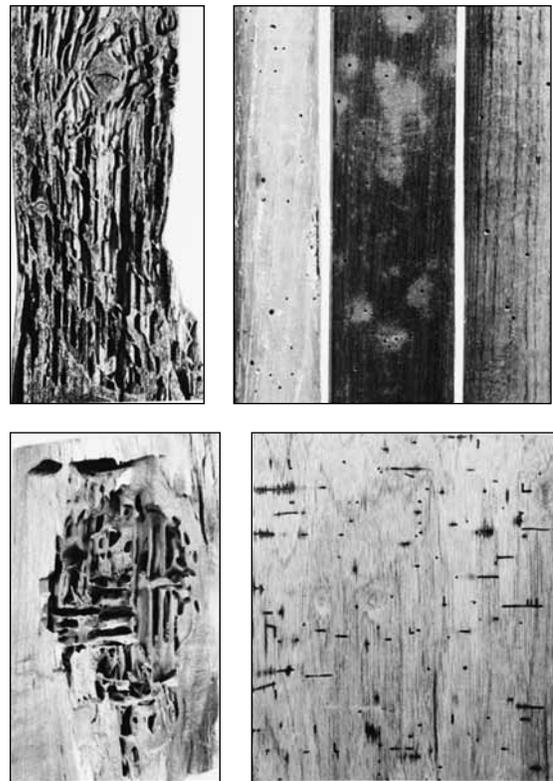


Figure 14-8. Types of insect damage most likely to occur in a building. Upper left—Termite attack; feeding galleries (often parallel to the grain) contain excrement and soil. Upper right—Powder-post beetle attack; exit holes usually filled with wood flour and not associated with discolored wood. Lower left—Carpenter ant attack; nesting galleries usually cut across grain and are free of residue. Lower right—Beetle attack; feeding galleries (made in the wood while green) free of residue and surrounding wood darkly stained.

vary in length from approximately 1.5 to 6.5 mm (1/16 to 1/4 in.) They bore through the outer bark to the soft inner part, where they make tunnels in which they lay their eggs. In making tunnels, bark beetles push out fine brownish-white sawdust-like particles. If many beetles are present, their extensive tunneling will loosen the bark and permit it to fall off in large patches, making the structure unsightly.

To avoid bark beetle damage, logs may be debarked rapidly, sprayed with an approved insecticidal solution, stored in water or under a water spray, or cut during the dormant season (October or November, for instance). If cut during this period, logs should immediately be piled off the ground and arranged for good air movement to promote rapid drying of the inner bark. This should occur before the beetles begin to fly in the spring. Drying the bark will almost always prevent damage by insects that prefer freshly cut wood.

Ambrosia beetles, roundheaded and flatheaded borers, and some powder-post beetles that get into freshly cut timber

can cause considerable damage to wood in rustic structures and some manufactured products. Certain beetles may complete development and emerge several years after the wood is dry, often raising a question as to the origin of the infestation.

Proper cutting practices, rapid debarking, storing under water, and spraying with an approved chemical solution, as recommended for bark beetles, will control these insects. Damage by ambrosia beetles can be prevented in freshly sawn lumber by dipping the product in a chemical solution. The addition of one of the sap-stain preventives approved for controlling molds, stains, and decay will keep the lumber bright. Powder-post beetles attack both hardwoods and softwoods and both freshly cut and seasoned lumber and timber. Powder-post damage is indicated by holes made in the surface of the wood by the winged adults as they emerge and by the fine powder that may fall from the wood. The powder-post beetles that cause most of the damage to dry hardwood lumber belong to the genus *Lyctus*. They attack the sapwood of ash, hickory, oak, and other large-pored hardwoods as it begins to season. Eggs are laid in pores of the wood, and the larvae burrow through the wood, making tunnels from 1.5 to 2 mm (1/16 to 1/12 in.) in diameter, which they leave packed with a fine powder. Species of anobiid beetles colonize coniferous materials.

Susceptible hardwood lumber used for manufacturing purposes should be protected from powder-post beetle attack as soon as it is sawn and when it arrives at the plant. An approved insecticide applied in water emulsion to the green lumber will provide protection. Such treatment may be effective even after the lumber is kiln dried, until it is surfaced. Heat sterilization is another way to kill insects in green lumber. To effectively kill insects in lumber or timbers, heat sterilization requires that the center of the wood be held at 56 °C (133 °F) for 30 min. The time required to reach that temperature is highly variable and depends on thickness of boards, dimension of timbers, and moisture content of the wood (Chap. 20). For example, heating time increases with increasing board thickness or increasing cross-sectional dimension.

Good plant sanitation is extremely important in alleviating the problem of infestation. Proper sanitation measures can often eliminate the necessity for other preventative steps. Damage to manufactured items frequently is traceable to infestation that occurred before the products were placed on the market, particularly if a finish is not applied to the surface of the items until they are sold. Once wood is infested, the larvae will continue to develop, even though the surface is subsequently painted, oiled, waxed, or varnished.

When selecting hardwood lumber for building or manufacturing purposes, any evidence of powder-post infestation should not be overlooked, because the beetles may continue to be active long after the wood is put to use. Heat steriliza-

tion under conditions that ensure the center of the wood will be held at 56 °C (133 °F) for 30 min will effectively kill insects in infested lumber. Those conditions vary with moisture content, size, and dimension of wood—see Chapter 20 for further information on heat sterilization. A 3-min soaking in a petroleum oil solution containing an insecticide is also effective for checking infestation or preventing attack on lumber up to standard 19 mm (nominal 1 in.) thick. Small dimension stock also can be protected by brushing or spraying with approved chemicals. For infested furniture or finished woodwork in a building, the same insecticides may be used, but they should be dissolved in refined petroleum oil, such as mineral spirits. Because *Lyctus* beetles lay their eggs in the open pores of wood, infestation can be prevented by covering the entire surface of each piece of wood with a suitable finish.

Powder-post beetles in the family Anobiidae, depending on the species, infest hardwoods and softwoods. Their life cycle takes 2 to 3 years, and they require wood moisture content around 15% or greater for viable infestation. Therefore, in most modern buildings, the wood moisture content is generally too low for anobiids. When ventilation is inadequate or in more humid regions of the United States, wood components of a building can reach the favorable moisture conditions for anobiids. This is especially a problem in air-conditioned buildings where water condenses on cooled exterior surfaces. Susceptibility to anobiid infestation can be alleviated by lowering the moisture content of wood through improved ventilation and the judicious use of insulation and vapor barriers. Insecticides registered for use against these beetles are generally restricted for exterior applications to avoid potential safety hazards indoors. Wood being reused or recycled from older structures often has lyctid or anobiid larvae in it. Such wood should be fumigated or kiln dried before use in another structure.

Beetles in the family Bostrichidae and weevils in the family Curculionidae are associated with wood moisture contents favorable for wood-infesting fungi because they may benefit nutritionally from the fungi. Thus, protection against these insects consists of the same procedures as for protection against wood-decay fungi.

A roundheaded beetle, commonly known as the old house borer, causes damage to seasoned, coniferous building materials. The larvae reduce the sapwood to a powdery or granular consistency and make a ticking sound while at work. When mature, the beetles make an oval hole approximately 6.5 mm (1/4 in.) in diameter in the surface of the wood and emerge. Anobiid powder-post beetles, which make holes 1.6 to 3.2 mm (1/16 to 1/8 in.) in diameter, also cause damage to pine joists. Infested wood should be drenched with a solution of one of the currently recommended insecticides in a highly penetrating solvent. Beetles nesting in wood behind plastered or paneled walls can be eliminated through fumigation of the building by a licensed operator.



Figure 14–9. A, the northern limit of recorded damage done by subterranean termites in the United States; B, the northern limit of damage done by dry-wood termites.

Termites

Termites superficially resemble ants in size, general appearance, and habit of living in colonies. About 56 species are known in the United States. From the standpoint of their methods of attack on wood, termites can be grouped into two main classes: (a) ground-inhabiting or subterranean termites and (b) wood-inhabiting or nonsubterranean termites.

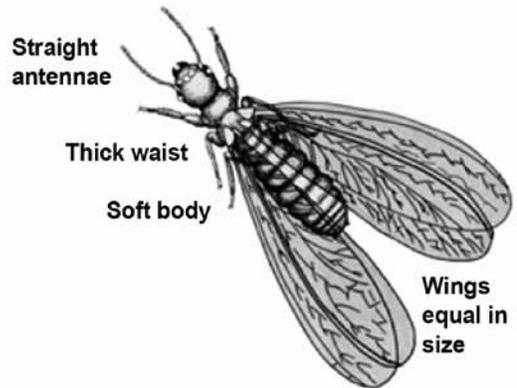
Subterranean Termites

Subterranean termites are responsible for most of the termite damage to wood structures in the United States. This damage can be prevented. Subterranean termites are more prevalent in the southern than in the northern states, where low temperatures do not favor their development (Fig. 14–9). The hazard of infestation is greatest (a) beneath buildings without basements that were erected on a concrete slab foundation or were built over a crawl space that is poorly drained and lacks a moisture barrier (see Chap. 17) and (b) in any substructure wood component close to the ground or an earth fill (for example, an earth-filled porch).

Subterranean termites develop their colonies and maintain their headquarters in the ground. They build their tunnels through earth and around obstructions to reach the wood they need for food. They also must have a constant source of moisture, whether from the wood on which they are feeding or the soil where they nest. The worker members of the colony cause destruction of wood. At certain seasons of the year, usually spring, male and female winged forms swarm from the colony, fly a short time, lose their wings, mate, and if successful in locating a suitable home, start new colonies. The appearance of “flying ants” or their shed wings is an indication that a termite colony may be near and causing serious damage. Not all “flying ants” are termites; therefore, suspicious insects should be identified before investing in eradication (Fig. 14–10).

Subterranean termites normally do not establish themselves in buildings by being carried there in lumber; they primarily

Termites



Ants

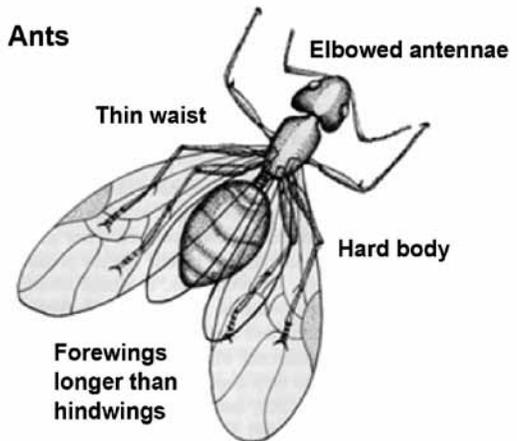


Figure 14–10. A, winged termite; B, winged ant (both greatly enlarged). The wasp waist of the ant and the long wings of the termite are distinguishing characteristics.

enter from ground nests after the building has been constructed. An introduced species, the Formosan termite, is adept at initiating aboveground infestations and nests in structures where wood remains wet for prolonged periods, such as from roof leaks. Telltale signs of subterranean termite presence are the earthen tubes or runways built by these insects over the surfaces of the foundation or other exposed areas to reach the wood above. Another sign is the swarming of winged adults early in the spring or fall. In the wood itself, the termites make galleries that generally follow the grain, leaving a shell of sound wood to conceal their activities. Because the galleries seldom show on the wood surfaces, probing with a pick or knife is advisable if the presence of termites is suspected.

The best protection for wood in areas where subterranean termites are prevalent is to prevent the termites from gaining hidden access to a building. The foundations should be of concrete, pressure-treated wood, or other material through which the termites cannot penetrate. With brick, stone, or concrete block, cement mortar should be used because termites can work through some other kinds of mortar. Also,

it is a good precaution to cap the foundation with 100 mm (4 in.) of reinforced concrete. Posts supporting floor girders should, if they bear directly on the ground, be of concrete. If there is a basement, it should be floored with concrete. Untreated posts in such a basement should rest on concrete piers extending a few inches above the basement floor. However, pressure-treated posts can rest directly on the basement floor. With the crawl-space type of foundation, wood floor joists should be kept at least 460 mm (18 in.) and girders 300 mm (12 in.) from the earth with a polyethylene vapor barrier covering exposed soil and extending partially up the foundation wall. Moisture condensation on the floor joists and subflooring, which may cause conditions favorable to decay and contribute to infestation by termites, can be avoided by covering the soil below with a moisture barrier and assuming proper drainage of rainwater away from all sides of a structure by managing rain and roof runoff with gutters, downspouts, and proper grading around the foundation. All concrete forms, stakes, stumps, and wastewood should be removed from the building site because they are possible sources of infestation. Generally, the precautions effective against subterranean termites are also helpful against decay.

The principal method of protecting buildings in high termite areas is to thoroughly treat the soil adjacent to the foundation walls and piers beneath the building with a soil insecticide. When concrete slab floors are laid directly on the ground, all soil under the slab should be treated with an approved insecticide before the concrete is poured. Furthermore, insulation containing cellulose that is used as a filler in expansion joints should be impregnated with an approved chemical toxic to termites. Sealing the top 13 mm (1/2 in.) of the expansion joint with roofing-grade coal-tar pitch also provides effective protection from ground-nesting termites. Several soil treatments and insecticidal bait control methods are currently available. Information on current control methods is available from national pest control operator associations. These organizations should be consulted to take advantage of the latest technology in termite control.

To control termites already in a building, contact between the termite colony in the soil and the woodwork must be broken. This can be done by blocking the runways from soil to wood, treating the soil, repairing leaks that keep wood within the structure wet (for example, plumbing leaks), or some combination of these techniques. Possible reinfestation can be guarded against by frequent inspections for signs of termites.

Nonsubterranean Termites

In the United States, nonsubterranean termites have been found only in a narrow strip of territory extending from central California around the southern edge of the continental United States to Virginia (Fig. 14–9) and in the West Indies and Hawaii. Their principal damage is confined to an area in southern California, to parts of southern Florida, notably

Key West, and to the islands of Hawaii. They also are a localized problem in Arizona and New Mexico.

The nonsubterranean termites, especially the dry-wood type, do not multiply as rapidly as the subterranean termites and have a somewhat different colony life and habits. The total amount of destruction they cause in the United States is much less than that caused by the subterranean termites. The ability of dry-wood termites to live in dry wood without outside moisture or contact with the ground, however, makes them a definite menace in the regions where they occur. Their destruction is not rapid, but they can thoroughly riddle timbers with their tunneling if allowed to work undisturbed for many years. Nonsubterranean termites are often moved from structure to structure in infested items such as furniture.

In constructing a building in localities where the dry-wood type of nonsubterranean termite is prevalent, it is good practice to inspect the lumber carefully to see that it was not infested before arrival at the building site. If the building is constructed during the swarming season, the lumber should be watched during the course of construction, because infestation by colonizing pairs can easily take place. Because paint is a good protection against the entrance of dry-wood termites, exposed wood (except that which is preservative treated) should be kept covered with a paint film. Fine screen should be placed over any openings to the interior unpainted parts of the building. As in the case of ground-nesting termites, dead trees, old stumps, posts, or wood debris of any kind that could serve as sources of infestation should be removed from the premises.

If a building is infested with dry-wood termites, badly damaged wood should be replaced. If the wood is only slightly damaged or is difficult to replace, further termite activity can be arrested by injecting a small amount of an approved pesticidal dust or liquid formulation into each nest. Current recommendations for such formulations can be found from state pest control associations. Buildings heavily infested with nonsubterranean termites can be successfully fumigated. This method is quicker than the use of poisonous liquids and dusts and does not require finding all of the colonies. However, it does not prevent the termites from returning because no poisonous residue is left in the tunnels. Fumigation is very dangerous and should be conducted only by licensed professional fumigators. Infested pieces of furniture, picture frames, and other small pieces can be individually fumigated, heated, or placed in a freezer for a short time. In localities where dry-wood termites do serious damage to posts and poles, the best protection for these and similar forms of outdoor timbers is full-length pressure treatment with a preservative.

Naturally Termite-Resistant Woods

Only a limited number of woods grown in the United States offer any marked degree of natural resistance to termite

attack. The close-grained heartwood of California redwood has some resistance, especially when used above ground. Very resinous heartwood of Southern Pine is practically immune to attack, but it is not available in large quantities and is seldom used.

Carpenter Ants

Carpenter ants are black or brown. They usually occur in stumps, trees, or logs but sometimes damage poles, structural timbers, or buildings. One form is easily recognized by its giant size relative to other ants. Carpenter ants use wood for shelter rather than for food, usually preferring wood that is naturally soft or has been made soft by decay. They may enter a building directly by crawling or may be carried there in firewood. If left undisturbed, they can, in a few years, enlarge their tunnels to the point where replacement or extensive repairs are necessary. The parts of dwellings they frequent most often are porch columns, porch roofs, window sills, and sometimes the wood plates in foundation walls. They often nest in hollow-core doors. The logs of rustic cabins are also attacked.

Precautions that prevent attack by decay and termites are usually effective against carpenter ants. Decaying or infested wood, such as logs, stumps, or retaining walls, should be removed from the premises, and crevices present in the foundation or woodwork of the building should be sealed. Particularly, leaks in porch roofs should be repaired because the decay that may result makes the wood more desirable to the ants.

When carpenter ants are found in a structure, any badly damaged timbers should be replaced. Because the carpenter ant needs high humidity in its immature stages, alterations in the construction may also be required to eliminate moisture from rain or condensation. In wood not sufficiently damaged to require replacement, the ants can be killed by injection of approved insecticide into the nest galleries. Carpenter ant nests are relatively easy to find because they keep their internal nest sites very clean and free of debris. As particles of wood are removed to create galleries or as pieces of insects that have been fed upon accumulate, the debris is removed from the nest and then accumulates below the nest opening.

Carpenter Bees

Carpenter bees resemble large bumblebees, but the top of their abdomen is hairless, causing their abdomens to shine, unlike bumblebees. The females make large (13-mm- (1/2-in.-) diameter) tunnels into unfinished soft wood for nests. They partition the hole into cells; each cell is provided with pollen and nectar for a single egg. Because carpenter bees reuse nesting sites for many years, a nesting tunnel into a structural timber may be extended several feet and have multiple branches. In thin wood, such as siding, the holes may extend the full thickness of the wood. They nest in wood that has been finished with a stain or thin paint film, or light preservative salt treatments, as well as in bare wood.

A favorite nesting site is in unfinished exterior wood not directly exposed to sunlight (for example, the undersides of porch roofs, and grape arbors).

Control is aimed at discouraging the use of nesting sites in and near buildings. The tunnel may be injected with an insecticide labeled for bee control and plugged with caulk. Treating the surface around the entry hole will discourage reuse of the tunnel during the spring nesting period. A good paint film or pressure preservative treatment protects exterior wood surfaces from nesting damage. Bare interior wood surfaces, such as in garages, can be protected by screens and tight-fitting doors.

Marine Borer Damage and Control

Damage by marine-boring organisms to wood structures in salt or brackish waters is practically a worldwide problem. Evidence of attack is sometimes found in rivers even above the region of brackishness. The rapidity of attack depends upon local conditions and the kinds of borers present. Along the Pacific, Gulf, and South Atlantic Coasts of the United States, attack is rapid, and untreated pilings may be completely destroyed in a year or less. Along the coast of the New England States, the rate of attack is slower because of cold water temperatures but is still sufficiently rapid to require protection of wood where long life is desired. The principal marine borers from the standpoint of wood damage in the United States are described in this section. Control measures discussed in this section are those in use at the time this handbook was revised. Regulations should be reviewed at the time control treatments are being considered so that approved practices will be followed.

Shipworms

Shipworms are the most destructive of the marine borers. They are mollusks of various species that superficially are worm-like in form. The group includes several species of *Teredo* and several species of *Bankia*, which are especially damaging. These mollusks are readily distinguishable on close observation but are all very similar in several respects. In the early stages of their life, they are minute, free-swimming organisms. Upon finding suitable lodgment on wood, they quickly develop into a new form and bury themselves in the wood. A pair of boring shells on the head grows rapidly in size as the boring progresses, while the tail part or siphon remains at the original entrance. Thus, the animal grows in length and diameter within the wood but remains a prisoner in its burrow, which it lines with a shell-like deposit. It lives on the wood borings and the organic matter extracted from the sea water that is continuously being pumped through its system. The entrance holes never grow large, and the interior of wood may be completely honeycombed and ruined while the surface shows only slight perforations. When present in great numbers, shipworms grow only a few centimeters before the wood is so completely occupied that growth is stopped. However, when not



Figure 14-11. *Limnoria* damage to piling.

crowded, they can grow to lengths of 0.3 to 1.2 m (1 to 4 ft) depending on the species.

Pholads

Another group of wood-boring mollusks is the pholads, which clearly resemble clams and therefore are not included with the shipworms. They are entirely encased in their double shells. The *Martesia* are the best-known species, but another well-known group is the *Xylophaga*. Like the shipworms, the *Martesia* enter the wood when they are very small, leaving a small entrance hole, and grow larger as they burrow into the wood. They generally do not exceed 64 mm (2-1/2 in.) long and 25 mm (1 in.) in diameter but are capable of doing considerable damage. Their activities in the United States appear to be confined to the Gulf Coast, San Diego, and Hawaii.

Limnoria and *Sphaeroma*

Another distinct group of marine borers are crustaceans, which are related to lobsters and shrimp. The principal borers in this group are species of *Limnoria* and *Sphaeroma*. Their attack differs from that of the shipworms and the *Martesia* in that the bore hole is quite shallow; the result is that the wood gradually is thinned from the surface inward through erosion by the combined action of the borers and water erosion. Also, the *Limnoria* and *Sphaeroma* do not become imprisoned in the wood but may move freely from place to place.

Limnoria are small, 3 to 4 mm (1/8 to 1/6 in.) long, and bore small burrows in the surface of wood. Although they can change their location, they usually continue to bore in one place. When great numbers of *Limnoria* are present, their burrows are separated by very thin walls of wood that are easily eroded by the motion of the water or damaged by objects floating upon it. This erosion causes the *Limnoria* to burrow continually deeper; otherwise, the burrows would probably not become greater than 51 mm (2 in.) long or 13 mm (1/2 in.) deep. Because erosion is greatest between tide

levels, piles heavily attacked by *Limnoria* characteristically wear within this zone to an hourglass shape (Fig. 14-11). In heavily infested harbors, untreated piling can be destroyed by *Limnoria* within a year.

Sphaeroma are somewhat larger, sometimes reaching a length of 13 mm (1/2 in.) and a width of 6 mm (1/4 in.). In general appearance and size, they resemble the common sow bug or pill bug that inhabits damp places. *Sphaeroma* are widely distributed but are not as plentiful as *Limnoria* and cause much less damage, although damage caused by *Sphaeroma* action resembles that of *Limnoria*. Nevertheless, piles in some structures have been ruined by them. It has been reported that *Sphaeroma* attack salt-treated wood in Florida. Occasionally, they have been found in fresh water.

The average life of well-creosoted structures in areas susceptible to marine borer attack is many times the average life obtained from untreated structures. However, even thorough creosote treatment will not always stop *Martesia*, *Sphaeroma*, and especially *Limnoria*; shallow or erratic creosote penetration affords only slight protection. The spots with poor protection are attacked first, and from there, the borers spread inward and destroy the untreated interior of the pile.

When wood is to be used in salt water, avoidance of cutting or injuring the surface after treatment is even more important than when wood is to be used on land. No cutting or injury of any kind for any purpose should be permitted in the underwater part of the pile. Where piles are cut to grade above the waterline, the exposed surfaces should be protected from decay. This may be accomplished by in-place application of a wood preservative followed by a suitable capping compound.

Protection from Marine Borers

No wood is immune to marine-borer attack, and no commercially important wood of the United States has sufficient marine-borer resistance to justify its use untreated in any important structure in areas where borers are active. The heartwood of several foreign species, such as greenheart, jarrah, azobe, and manbarklak, has shown resistance to marine-borer attack. Service records on these woods, however, do not always show uniform results and are affected by local conditions. Borer damage to wooden marine structures can be prevented, but knowing the type of borer present in the geographic location is important for selection of proper preservative and treatment retention to protect the structure from surface erosion.

Protection of Permanent Structures

The best practical protection for piles in sea water with shipworms and moderate *Limnoria* hazard is heavy treatment with coal-tar creosote or creosote coal-tar solution. Where severe *Limnoria* hazard exists, dual treatment (copper-arsenate-containing waterborne preservatives followed by coal-tar creosote) is recommended. The treatment must be

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thorough, the penetration as deep as possible, and the retention high to give satisfactory results in heavily infested waters. It is best to treat such piles by the full-cell process to refusal; that is, to force in all the preservative the piles can hold without using treatments that cause serious damage to the wood. For highest retentions, it is necessary to air- or kiln-dry the piling before treatment. Details of treatments are discussed in Chapter 15.

The life of treated piles is influenced by the thoroughness of the treatment, the care and diligence used in avoiding damage to the treated shell during handling and installation, and the severity of borer attack. Differences in exposure conditions, such as water temperature, salinity, dissolved oxygen, water depth, and currents, tend to cause wide variations in the severity of borer attack even within limited areas. Service records show average-life figures of 22 to 48 years on well-treated Douglas-fir piles in San Francisco Bay waters. In South Atlantic and Gulf of Mexico waters, creosoted piles are estimated to last 10 to 12 years and frequently much longer. On the North Atlantic Coast, where exposure conditions are less severe, piles can last even longer than the 22- to 48-year life recorded in the San Francisco Bay.

Metal armor and concrete or plastic jacketing have been used with various degrees of success for the protection of marine piles. The metal armor may be in the form of sheets, wire, or nails. Sheathing of piles with copper or muntz metal has been only partially successful, owing to difficulty in maintaining a continuous armor. Theft, mechanical damage from driving, damage by storm or driftwood, and corrosion of sheathing have sooner or later let in the borers, and in only a few cases has long pile life been reported. Attempts during World War II to electroplate wood piles with copper were not successful. Concrete casings are now in greater use than is metal armor, and they appear to provide better protection when high-quality materials are used and carefully applied. Unfortunately, they are readily damaged by ship impact. For this reason, concrete casings are less practical for fender piles than for foundation piles that are protected from mechanical damage.

Jacketing piles by wrapping them with heavy polyvinyl plastic is one form of supplementary protection. If properly applied, the jacketing will kill any borers that may have already become established by creating stagnant water, thereby decreasing oxygen levels in the water that is in contact with the piles. Like other materials, the plastic jacket is subject to mechanical damage.

Protection of Boats

Wood barges have been constructed with planking or sheathing pressure-treated with creosote to protect the hull from marine borers, and the results have been favorable. Although coal-tar creosote is an effective preservative for protecting wood against marine borers in areas of moderate borer hazard, it has disadvantages in many types of boats.

Creosote adds considerably to the weight of the boat hull, and its odor is objectionable to boat crews. In addition, antifouling paints are difficult to apply over creosoted wood.

Antifouling paints that contain copper protect boat hulls against marine-borer attack, but the protection continues only while the coating remains unbroken. Because it is difficult to maintain an unbroken coating of antifouling paint, the U.S. Navy has found it desirable to impregnate the hull planking of some wood boats with certain copper-containing preservatives. Such preservatives, when applied with high retentions (40 kg m^{-3} (2.5 lb ft^{-3})), have some effectiveness against marine borers and should help to protect the hull of a boat during intervals between renewals of the antifouling coating. These copper preservatives do not provide protection equivalent to that furnished by coal-tar creosote; their effectiveness in protecting boats is therefore best assured if the boats are dry docked at regular and frequent intervals and the antifouling coating maintained. The leach-resistant wood preservatives containing copper arsenates have shown superior performance (at a retention of 40 kg m^{-3} (2.5 lb ft^{-3})) to creosote in tests conducted in areas of severe borer hazard.

Plywood as well as plank hulls can be protected against marine borers by preservative treatment. The plywood hull presents a surface that can be covered successfully with a protective membrane of reinforced plastic laminate. Such coverings should not be attempted on wood that has been treated with a preservative carried in oil, because the bond will be unsatisfactory.

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Wood Preservation

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Many commonly used wood species can deteriorate if exposed to conditions that support growth of wood-degrading organisms (see Chap. 14). Wood products can be protected from the attack of decay fungi, harmful insects, or marine borers by applying chemical preservatives. Preservative treatments greatly increase the life of wood structures, thus reducing replacement costs and allowing more efficient use of forest resources. The degree of protection achieved depends on the preservative used and the proper penetration and retention of the chemicals. Some preservatives are more effective than others, and some are more adaptable to certain use requirements. To obtain long-term effectiveness, adequate penetration and retention are needed for each wood species, chemical preservative, and treatment method. Not only are different methods of treating wood available, but treatability varies among wood species—particularly their heartwood, which generally resists preservative treatment more than does sapwood. Although some tree species possess naturally occurring resistance to decay and insects (see Chap. 14), many are in short supply or are not grown in ready proximity to markets.

In considering preservative treatment processes and wood species, the combination must provide the required protection for the conditions of exposure and life of the structure. All these factors are considered by the consensus technical committees in setting reference levels required by the American Wood Protection Association (AWPA, formerly American Wood-Preservers' Association) and ASTM International (formerly American Society for Testing and Materials). Details are discussed later in this chapter. The characteristics, appropriate uses, and availability of preservative formulations may have changed after preparation of this chapter. For the most current information on preservative formulations, the reader is encouraged to contact the appropriate regulatory agencies, standardization organizations, or trade associations. *Note that mention of a chemical in this chapter does not constitute a recommendation.*

Wood Preservatives

Wood preservatives must meet two broad criteria: (1) They must provide the desired wood protection in the intended end use, and (2) they must do so without presenting unreasonable risks to people or the environment. Because wood preservatives are considered to be a type of pesticide, the U.S. Environmental Protection Agency (EPA) is responsible for their regulation. Federal law requires that before selling or distributing a preservative in the United States,

Synopsis of EPA-approved consumer information sheets for wood treated with CCA, ACZA, creosote, or pentachlorophenol

NOTE: This is only a synopsis of information contained in consumer information sheets. For complete consumer information sheets, contact your treated wood supplier or the website of the Environmental Protection Agency.

Handling Precautions

Avoid frequent or prolonged inhalation of sawdust from treated wood. When sawing, sanding, and machining treated wood, wear a dust mask. Whenever possible, these operations should be performed outdoors to avoid indoor accumulations of airborne sawdust from treated wood. When power-sawing and machining, wear goggles to protect eyes from flying particles. Wear gloves when working with the wood. After working with the wood, and before eating, drinking, toileting, and use of tobacco products, wash exposed areas thoroughly. Avoid frequent or prolonged skin contact with creosote- or pentachlorophenol-treated wood. When handling creosote- or pentachlorophenol-treated wood, wear long-sleeved shirts and long pants and use gloves impervious to the chemicals (for example, gloves that are vinyl coated). Because preservatives or sawdust may accumulate on clothes, they should be laundered before reuse. Wash work clothes separately from other household clothing.

Treated wood should not be burned in open fires or in stoves, fireplaces, or residential boilers, because toxic chemicals may be produced as part of the smoke and ashes. Treated wood from commercial or industrial use (such as construction sites) may be burned only in commercial or industrial incinerators or boilers in accordance with state and Federal regulations. CCA-treated wood can be disposed of with regular municipal trash (municipal solid waste, not yard waste) in many areas. However, state or local laws may be stricter than federal requirements. For more information, please contact the waste management agency for your state.

Use Site Precautions

All sawdust and construction debris should be cleaned up and disposed of after construction. Do not use treated wood under circumstances where the preservative may become a component of food or animal feed. Examples of such sites would be use of mulch from recycled arsenic-treated wood, cutting boards, counter tops, animal bedding, and structures or containers for storing animal feed or human food. Only treated wood that is visibly clean and free of surface residue should be used for patios, decks, and walkways. Do not use treated wood for construction of those portions of beehives which may come into contact with honey. Treated wood should not be used where it may come into direct or indirect contact with drinking water, except for uses involving incidental contact such as docks and bridges.

Logs treated with pentachlorophenol should not be used for log homes. Wood treated with creosote or pentachlorophenol should not be used where it will be in frequent or prolonged contact with bare skin (for example, chairs and other outdoor furniture), unless an effective sealer has been applied. Creosote- and pentachlorophenol-treated wood should not be used in residential, industrial, or commercial interiors except for laminated beams or building components that are in ground contact and are subject to decay or insect infestation and where two coats of an appropriate sealer are applied. Do not use creosote- or pentachlorophenol-treated wood for farrowing or brooding facilities. Wood treated with pentachlorophenol or creosote should not be used in the interiors of farm buildings where there may be direct contact with domestic animals or livestock that may crib (bite) or lick the wood. In interiors of farm buildings where domestic animals or livestock are unlikely to crib (bite) or lick the wood, creosote- or pentachlorophenol-treated wood may be used for building components that are in ground contact and are subject to decay or insect infestation and where two coats of an appropriate sealer are applied. Sealers may be applied at the installation site. Urethane, shellac, latex epoxy enamel, and varnish are acceptable sealers for pentachlorophenol-treated wood. Coal-tar pitch and coal-tar pitch emulsion are effective sealers for creosote-treated wood-block flooring. Urethane, epoxy, and shellac are acceptable sealers for all creosote-treated wood.

a company must obtain registration from EPA. Before registering a new pesticide or new use for a registered preservative, EPA must first ensure that the preservative can be used with a reasonable certainty of no harm to human health and without posing unreasonable risks to the environment. To make such determinations, EPA requires more than 100 different scientific studies and tests from applicants. This chapter discusses only wood preservatives registered by the EPA.

Some preservatives are classified as “restricted use” by the EPA and these can be used only in certain applications and can be applied only by certified pesticide applicators. Restricted use refers to the chemical preservative and not to the treated wood product. The general consumer may buy and use wood products treated with restricted-use pesticides; EPA does not consider treated wood a toxic substance nor is it regulated as a pesticide. Although treated wood is not regulated as pesticide, there are limitations on how some types of treated wood should be used. Consumer Information Sheets (EPA-approved) are available from retailers of creosote-, pentachlorophenol-, and inorganic-arsenical-treated wood products. The sheets provide information about the preservative and the use and disposal of treated-wood products (see Synopsis of EPA-Approved Consumer Information Sheets for Wood Treated with CCA, ACZA, Creosote, or Pentachlorophenol). The commercial wood treater is bound by the EPA regulation and can treat wood only for an end use that is allowed for that preservative. Some preservatives that are not classified as restricted by EPA are available to the general consumer for nonpressure treatments. It is the responsibility of the end user to apply these preservatives in a manner that is consistent with the EPA-approved labeling. Registration of preservatives is under constant review by the EPA, and a responsible State or Federal agency should be consulted as to the current status of any preservative.

Before a wood preservative can be approved for pressure treatment of structural members, it must be evaluated to ensure that it provides the necessary durability and that it does not greatly reduce the strength properties of the wood. The EPA typically does not evaluate how well a wood preservative protects the wood. Traditionally this evaluation has been conducted through the standardization process of the AWP. The AWP Book of Standards lists a series of laboratory and field exposure tests that must be conducted when evaluating new wood preservatives. The durability of test products are compared with those of established durable products and nondurable controls. The results of those tests are then presented to the appropriate AWP subcommittees for review. AWP subcommittees are composed of representatives from industry, academia, and government agencies who have familiarity with conducting and interpreting durability evaluations. Preservative standardization by AWP is a two-step process. If the performance of a new preservative is considered appropriate, it is first listed as a potential preservative. Secondary committee action is needed to have the new preservative listed for specific commodities and to set the required treatment level.

More recently the International Code Council–Evaluation Service (ICC–ES) has evolved as an additional route for gaining building code acceptance of new types of pressure-treated wood. In contrast to AWP, the ICC–ES does not standardize preservatives. Instead, it issues Evaluation Reports that provide evidence that a building product complies with building codes. The data and other information needed to obtain an Evaluation Report are first established as Acceptance Criteria (AC). AC326, which sets the performance criteria used by ICC–ES to evaluate proprietary wood preservatives, requires submittal of documentation accredited third party agencies in accordance with AWP, ASTM, and EN standard test methods. The results of those tests are then reviewed by an evaluation committee to determine if the preservative has met the appropriate acceptance criteria.

Wood preservatives have traditionally been divided into two general classes: (1) Oil-type or oil-borne preservatives, such as creosote and petroleum solutions of pentachlorophenol, and (2) waterborne preservatives that are applied as water solutions or with water as the carrier. Many different chemicals are in each of these classes, and each has different effectiveness in various exposure conditions. Some preservatives can be formulated so that they can be delivered with either water or oil-type carriers. In this chapter, both oil-borne and waterborne preservative chemicals are described as to their potential end uses. Tables 15–1 and 15–2 summarize preservatives and their treatment levels for various wood products.

Waterborne Preservatives

Waterborne preservatives are often used when cleanliness and paintability of the treated wood are required. Formulations intended for use outdoors have shown high resistance

to leaching and very good performance in service. Waterborne preservatives are included in specifications for items such as lumber, timber, posts, building foundations, poles, and piling (Table 15–1). Because water is added to the wood in the treatment process, some drying and shrinkage will occur after installation unless the wood is kiln-dried after treatment.

Copper is the primary biocide in many wood preservative formulations used in ground contact because of its excellent fungicidal properties and low mammalian toxicity (Table 15–3). Because some types of fungi are copper tolerant, preservative formulations often include a co-biocide to provide further protection.

Inorganic arsenicals are a restricted-use pesticide. For use and handling precautions of pressure-treated wood containing inorganic arsenicals, refer to the EPA-approved Consumer Information Sheets.

Acid Copper Chromate (ACC)

Acid copper chromate (ACC) contains 31.8% copper oxide and 68.2% chromium trioxide (AWP P5). The solid, paste, liquid concentrate, or treating solution can be made of copper sulfate, potassium dichromate, or sodium dichromate. Tests on stakes and posts exposed to decay and termite attack indicate that wood well impregnated with ACC generally provides acceptable service. However, some specimens placed in ground contact have shown vulnerability to attack by copper-tolerant fungi. ACC has often been used for treatment of wood in cooling towers. Its current uses are restricted to applications similar to those of chromated copper arsenate (CCA) (Table 15–4). ACC and CCA must be used at low treating temperatures (38 to 66 °C (100 to 150 °F)) because they are unstable at higher temperatures. This restriction may involve some difficulty when higher temperatures are needed to obtain good treating results in woods such as Douglas-fir.

Ammoniacal Copper Zinc Arsenate (ACZA)

Ammoniacal copper zinc arsenate (ACZA) is commonly used on the West Coast of North America for the treatment of Douglas-fir. The penetration of Douglas-fir heartwood is improved with ACZA because of the chemical composition and stability of treating at elevated temperatures. Wood treated with ACZA performs and has characteristics similar to those of wood treated with CCA (Table 15–1).

ACZA should contain approximately 50% copper oxide, 25% zinc oxide, and 25% arsenic pentoxide dissolved in a solution of ammonia in water (AWP P5). The weight of ammonia is at least 1.38 times the weight of copper oxide. To aid in solution, ammonium bicarbonate is added (at least equal to 0.92 times the weight of copper oxide).

ACZA replaced an earlier formulation, ammoniacal copper arsenate (ACA) that was used for many years in the United States and Canada.

Table 15–1. Typical use categories and retentions for preservatives used in pressure treatment of Southern Pine species^a

Preservative	Retentions (kg m ⁻³) ^b for each type of exposure and AWPAs use category designation						
	Interior, dry or damp	Exterior above-ground		Soil or fresh water			
		Vertical, coated	Horizontal	General	Severe/ critical	Very severe/ critical	
						1, 2	3A
Waterborne: Listed by the AWPAs							
ACC	NL ^c	NL ^c	4.0	8	—	—	—
ACZA	4.0	4.0	4.0	6.4	9.6	9.6	—
ACQ–B	4.0	4.0	4.0	6.4	9.6	9.6	—
ACQ–C	4.0	4.0	4.0	6.4	9.6	9.6	—
ACQ–D	2.4	2.4	2.4	6.4	9.6	9.6	—
CA–B	1.7	1.7	1.7	3.3	5.0	5.0	—
CA–C	1.0	1.0	1.0	2.4	5.0	5.0	—
CBA–A	3.3	3.3	3.3	6.5	9.8	9.8	—
CCA	NL ^c	NL ^c	4	6.4	9.6	9.6	12.8
CX–A	3.3	3.3	3.3	—	—	—	—
CuN (waterborne)	1.12	1.12	1.12	1.76	—	—	—
EL2	0.30	0.30	0.30	—	—	—	—
KDS	3.0	3.0	3.0	7.5	—	—	—
PTI	0.21	0.21	0.21/0.29 ^d	—	—	—	—
SBX	2.8/4.5 ^e	—	—	—	—	—	—
Oil-type: Listed by the AWPAs							
Creosote	128/NR ^f	128.0	128.0	160	160	192	192
Penta P9 Type A Oil	6.4/NR ^f	6.4	6.4	8.0	8.0	8.0	9.6
Penta P9 Type C Oil	6.4/NR ^f	6.4	6.4	8.0	8.0	8.0	9.6
CuN (oilborne)	0.64/NR ^f	0.64	0.64	0.96	1.2	1.2	1.6
Cu8	0.32	0.32	0.32	—	—	—	—
Waterborne: Evaluation reports from ICC Evaluation Service, Inc.							
ESR–1721	0.8	0.8	0.8	2.2	3.6	5.3	5.3
ESR–1980	2.4	2.4	2.4	5.4	9.6	9.6	—
ESR–2067	0.3	0.3	0.3	—	—	—	—
ESR–2240	1.0	1.0	1.0	2.4	3.7	—	—
ESR–2325	1.1	1.1	1.1	2.6	3.8	—	—
ESR–2711	2.1/2.7 ^g	2.1/2.7 ^g	2.1/2.7 ^g	4.5	6.9	—	—

^aSome exceptions exist for specific applications. See AWPAs Standard U1 or ICC ES Evaluation Reports for details on specific applications. See Table 15–2 for seawater applications.

^bTo convert to retention expressed as lb ft⁻³, divide these values by 16.0.

^cNL, not labeled. EPA labeling does not currently permit use of wood newly treated with these preservatives in most applications within these use categories. See Table 15–4 for more details.

^dHigher retention specified if the preservative is used without a stabilizer in the treatment solution.

^eHigher retention for areas with Formosan subterranean termites.

^fNR, not recommended for interior use in inhabited structures.

^g2.1 kg m⁻³ retention limited to decking and specialty use items.

Chromated Copper Arsenate (CCA)

Wood treated with CCA (commonly called green treated) dominated the treated-wood market from the late 1970s until 2004. However, as the result of the voluntary label changes submitted by the CCA registrants, the EPA labeling of CCA currently permits the product to be used for primarily industrial applications (Table 15–4), and CCA-treated products are generally not available at retail lumber yards. CCA can no longer be used for treatment of lumber intended for use in residential decks or playground equipment. It is important to note that existing structures are not affected by

this labeling change and that the EPA has not recommended removing structures built with CCA-treated lumber. These changes were made as part of the ongoing CCA re-registration process, and in light of the current and anticipated market demand for alternative preservatives for nonindustrial applications. Allowable uses for CCA are based on specific commodity standards listed in the 2001 edition of the AWPAs standards. The most important of these allowable uses are based on the standards for poles, piles, and wood used in highway construction. A list of the most common allowable uses is shown in Table 15–4.

Although several formulations of CCA have been used in the past, CCA Type C has been the primary formulation and is currently the only formulation listed in AWWPA standards. CCA-C was found to have the optimum combination of efficacy and resistance to leaching, but the earlier formulations (CCA-A and CCA-B) have also provided long-term protection for treated stakes exposed in Mississippi (Table 15-5). CCA-C has an actives composition of 47.5% chromium trioxide, 34.0% arsenic pentoxide, and 18.5% copper oxide. AWWPA Standard P5 permits substitution of potassium or sodium dichromate for chromium trioxide; copper sulfate, basic copper carbonate, or copper hydroxide

for copper oxide; and arsenic acid, sodium arsenate, or pyroarsenate for arsenic pentoxide.

High retention levels (40 kg m⁻³ (2.5 lb ft⁻³)) of CCA preservative provide good resistance to attack by the marine borers *Limnoria* and *Teredo* (Table 15-2).

Alkaline Copper Quat (ACQ)

Alkaline copper quat (ACQ) has an actives composition of 67% copper oxide and 33% quaternary ammonium compound (quat). Multiple variations of ACQ have been standardized. ACQ type B (ACQ-B) is an ammoniacal copper formulation, ACQ type D (ACQ-D) is an amine copper formulation, and ACQ type C (ACQ-C) is a combined ammoniacal-amine formulation with a slightly different quat compound. The multiple formulations of ACQ allow some flexibility in achieving compatibility with a specific wood species and application. When ammonia is used as the carrier, ACQ has improved ability to penetrate difficult-to-treat wood species. However, if the wood species is readily treatable, such as Southern Pine sapwood, an amine carrier can be used to provide a more uniform surface appearance. Recently ACQ has been formulated using small particles of copper rather than copper solubilized in ethanolamine. These formulations are discussed in more detail in the Preservatives with ICC-ES Evaluation Reports section. Use of particulate copper formulations of ACQ is currently limited to permeable woods (such as species of pine with a high proportion of sapwood), but efforts continue to adapt the treatment to a broader range of wood species.

Alkaline Copper DCOI (ACD)

Alkaline copper DCOI (ACD) is a recently proposed formulation of alkaline copper ethanolamine that utilizes 4,5-dichloro-2-N-octyl-4-isothiazolin-3-one (DCOI) as co-biocide

Table 15-2. Preservative treatment and retention necessary to protect round timber piles from severe marine borer attack^a

Marine borers and preservatives	Retention (kg m ⁻³) ^b	
	Round piles	Sawn materials
<i>Limnoria tripunctata</i> only		
Ammoniacal copper zinc arsenate	40, 24 ^c	40
Chromated copper arsenate	40, 24 ^c	
Creosote	320, 256 ^c	400
<i>Limnoria tripunctata</i> and Pholads (dual treatment)		
First treatment		
Ammoniacal copper zinc arsenate	16, (1.0)	24
Chromated copper arsenate	16, (1.0)	24
Second treatment		
Creosote	320, (20.0)	320
Creosote solution	320, (20.0)	320

^aSee AWWPA Commodity Specification G for more information.
^bTo convert to retention expressed as lb ft⁻³, divide these values by 16.0.
^cLower retention levels are for marine piling used in areas from New Jersey northward on the East Coast and north of San Francisco on the West Coast in the United States.

Table 15-3. Active ingredients in waterborne preservatives used for pressure treatments

Active ingredient	Preservative
Inorganic actives	
Arsenic	ACZA, CCA
Boron	CBA-A, CX-A, SBX, KDS
Chromium	ACC, CCA
Copper	ACC, ACZA, ACQ-B, ACQ-C, ACQ-D, CA-B, CA-C, CBA-A, CCA, CXA, ESR-1721, ESR-1980, ESR-2240, ESR-2325, KDS, KDS-B, ESR-2711
Zinc	ACZA
Organic actives	
Alkylbenzyl dimethyl ammonium compound	ACQ-C
DCOI	EL2, ESR-2711
Didecyl dimethyl ammonium compound	ACQ-B, ACQ-D
HDO: Bis-(N-cyclohexyldiazoniumdioxo)Cu	CX-A
Imdiacloprid	EL2, PTI, ESR-2067
Propiconazole	CA-C, PTI, ESR-1721
Polymeric betaine	KDS, KDS-B
Tebuconazole	PTI, ESR-1721, ESR-2067, ESR-2325

Table 15–4. Generalized examples of products that may still be treated with CCA under conditions of current label language^a

Type of end use still allowed	2001 AWPA standard
Lumber and timbers used in seawater	C2
Land, fresh-water, and marine piles	C3
Utility poles	C4
Plywood	C9
Wood for highway construction	C14
Round, half-round, and quarter-round fence posts	C16
Poles, piles, and posts used as structural members on farms	C16
Members immersed in or frequently splashed by seawater	C18
Lumber and plywood for permanent wood foundations	C22
Round poles and posts used in building construction	C23
Sawn timbers (at least 5 in. thick) used to support residential and commercial structures	C24
Sawn cross-arms	C25
Structural glued-laminated members	C28
Structural composite lumber (parallel strand or laminated veneer lumber)	C33
Shakes and shingles	C34

^aRefer to the EPA or a treated-wood supplier for the most recent definition of allowable uses.

to provide protection against copper-tolerant fungi. The ratio of alkaline copper to DCOI in the formulation ranges from 20:1 to 25:1. The ACD formulation is listed as a preservative in AWPA standards. It has been proposed for both above-ground and ground-contact applications, but at the time this chapter was finalized it had not yet been standardized for treatment of any commodities.

Copper bis(dimethyldithiocarbamate) (CDDC)

Copper bis(dimethyldithiocarbamate) (CDDC) is a reaction product formed in wood as a result of the dual treatment of two separate treating solutions. The first treating solution contains a maximum of 5% bivalent copper–ethanolamine (2-aminoethanol), and the second treating solution contains a minimum of 2.5% sodium dimethyldithiocarbamate (AWPA P5). Although this preservative is not currently commercially available, CDDC-treated wood products are included in the AWPA Commodity Standards for uses such as residential construction.

Copper Azole (CA–B, CA–C and CBA–A)

Copper azole (CA–B) is a formulation composed of amine copper (96%) and tebuconazole (4%). Copper azole (CA–C) is very similar to CA–B, but half the tebuconazole is replaced with propiconazole. The active ingredients in CA–C are in the ratio of 96% amine copper, 2% tebuconazole, and 2% propiconazole. An earlier formulation (CBA–A) also contained boric acid. Although listed as an amine formulation, copper azole may also be formulated with an amine–ammonia formulation. The ammonia may be included when the copper azole formulations are used to treat refractory species, and the ability of such a formulation to adequately treat Douglas-fir has been demonstrated. Inclusion of ammonia, however, is likely to have slight effects on the surface appearance and initial odor of the treated wood.

Copper HDO (CXA)

Copper HDO (CXA) is an amine copper water-based preservative that has been used in Europe and was recently standardized in the United States. The active ingredients are copper oxide, boric acid, and copper–HDO (bis-(N-cyclohexyldiazoniumdioxo copper). The appearance and handling characteristics of wood treated with copper HDO are similar to those of the other amine copper-based treatments. It is also referred to as copper xyligen. Currently, copper HDO is standardized only for applications that are not in direct contact with soil or water.

Copper Naphthenate (Waterborne)

Waterborne copper naphthenate (CuN–W) has an active composition similar to oil-borne copper naphthenate, but the actives are carried in a solution of ethanolamine and water instead of petroleum solvent. Wood treated with the waterborne formulation has a drier surface and less odor than the oil-borne formulation. The waterborne formulation has been standardized for above-ground and some ground-contact applications (Table 15–1).

Inorganic Boron (Borax–Boric Acid)

Borate preservatives are readily soluble in water and highly leachable and should be used only above ground where the wood is protected from wetting. When used above ground and protected from wetting, this preservative is very effective against decay, termites, beetles, and carpenter ants. Inorganic boron (SBX) is listed in AWPA standards for protected applications such as framing lumber. The solid or treating solution for borate preservatives (borates) should be greater than 98% pure, on an anhydrous basis (AWPA P5). Acceptable borate compounds are sodium octaborate, sodium tetraborate, sodium pentaborate, and boric acid. These compounds are derived from the mineral sodium borate, which is the same material used in laundry additives.

Table 15–5. Results of Forest Products Laboratory studies on 38- by 89- by 457-mm (nominal 2- by 4- by 18-in.) Southern Pine sapwood stakes, pressure-treated with commonly used wood preservatives, installed at Harrison Experimental Forest, Mississippi

Preservative	Average retention (kg m ⁻³ (lb ft ⁻³)) ^a	Average life or condition at last inspection
Controls (untreated stakes)		1.8 to 3.6 years
Acid copper chromate	2.08 (0.13)	11.6 years
	2.24 (0.14)	6.1 years
	4.01 (0.25)	80% failed after 40 years
	4.17 (0.26)	80% failed after 60 years
	4.65 (0.29)	4.6 years
	5.93 (0.37)	60% failed after 60 years
	8.01 (0.50)	50% failed after 40 years
	12.18 (0.76)	22% failed after 40 years
Ammoniacal copper arsenate	2.56 (0.16)	16.6 years
	3.52 (0.22)	80% failed after 30 years
	3.84 (0.24)	38.7 years
	4.01 (0.25)	60% failed after 40 years
	7.37 (0.45)	20% failed after 40 years
	8.17 (0.51)	10% failed after 60 years
	15.54 (0.97)	No failures after 60 years
	20.02 (1.25)	No failures after 60 years
Chromated copper arsenate Type I (Type A)	2.40 (0.15)	28.7 years
	3.52 (0.22)	45% failed after 40 years
Type II (Type B)	4.65 (0.29)	30% failed after 60 years
	7.05 (0.44)	10% failed after 40 years
	7.05 (0.44)	20% failed after 60 years
	3.68 (0.23)	30% failed after 40 years
	4.17 (0.26)	No failures after 46 years
Type III (Type C)	5.93 (0.37)	No failures after 46 years
	8.33 (0.52)	No failures after 46 years
	12.66 (0.79)	No failures after 46 years
	16.66 (1.04)	No failures after 46 years
	2.24 (0.14)	No failures after 25 years
	3.20 (0.20)	No failures after 35 years
	4.00 (0.25)	20% failed after 20 years
	4.33 (0.27)	10% failed after 25 years
6.41 (0.40)	No failures after 35 years	
Oxine copper (Copper-8-quinolinolate)	6.41 (0.40)	No failures after 25 years
	9.61 (0.60)	No failures after 35 years
AWPA P9 heavy petroleum	9.93 (0.62)	No failures after 25 years
	12.66 (0.79)	No failures after 25 years
Copper naphthenate	0.22 (0.014)	26.9 years
	0.48 (0.03)	27.3 years
	0.95 (0.059)	31.3 years
	1.99 (0.124)	No failures after 45 years
0.11% copper in No. 2 fuel oil	0.19 (0.012)	15.9 years
0.29% copper in No. 2 fuel oil	0.46 (0.029)	21.8 years
0.57% copper in No. 2 fuel oil	0.98 (0.061)	27.1 years
0.86% copper in No. 2 fuel oil	1.31 (0.082)	29.6 years
Creosote, coal-tar	52.87 (3.3)	24.9 years
	65.68 (4.1)	14.2 years
	67.28 (4.2)	17.8 years
	73.69 (4.6)	21.3 years
	124.96 (7.8)	70% failed after 54-1/2 years
	128.24 (8.0)	90% failed after 60 years
	132.97 (8.3)	50% failed after 46 years
	160.20 (10.0)	90% failed after 55 years
	189.04 (11.8)	50% failed after 60 years

Table 15–5. Results of Forest Products Laboratory studies on 38- by 89- by 457-mm (nominal 2- by 4- by 18-in.) Southern Pine sapwood stakes, pressure-treated with commonly used wood preservatives, installed at Harrison Experimental Forest, Mississippi—con.

Preservative	Average retention (kg m ⁻³ (lb ft ⁻³)) ^a	Average life or condition at last inspection
Creosote, coal-tar (con.)	211.46 (13.2)	20% failed after 54-1/2 years
	232.29 (14.5)	No failures after 55 years
	264.33 (16.5)	10% failed after 60 years
Pentachlorophenol Stoddard solvent (mineral spirits)	2.24 (0.14)	13.7 years
	2.88 (0.18)	15.9 years
	3.20 (0.20)	9.5 years
	3.20 (0.20)	13.7 years
	6.09 (0.38)	80% failed after 39 years
	6.41 (0.40)	15.5 years
	10.73 (0.67)	No failures after 39 years
Heavy gas oil (Mid-United States)	3.20 (0.20)	89% failed after 50 years
	6.41 (0.40)	80% failed after 50 years
	9.61 (0.60)	20% failed after 50 years
No. 4 aromatic oil (West Coast)	3.36 (0.21)	21.0 years
	6.57 (0.41)	70% failed after 50 years
AWPA P9 (heavy petroleum)	1.76 (0.11)	90% failed after 39 years
	3.04 (0.19)	60% failed after 39 years
	4.65 (0.29)	No failures after 39 years
	8.49 (0.53)	No failures after 35 years
	10.73 (0.67)	No failures after 39 years
Petroleum solvent controls	64.08 (4.0)	7.6 years
	65.68 (4.1)	4.4 years
	75.29 (4.7)	12.9 years
	123.35 (7.7)	14.6 years
	126.56 (7.9)	90% failed after 50 years
	128.16 (8.0)	19.7 years
	128.16 (8.0)	23.3 years
	128.16 (8.0)	14.6 years
	129.76 (8.1)	3.4 years
	136.17 (8.5)	20.9 years
	157.00 (9.8)	6.3 years
	192.24 (12.0)	17.1 years
	193.84 (12.1)	80% failed after 50 years
310.79 (19.4)	9.1 years	

^aRetention of active ingredients for preservatives and total solvent for petroleum solvent controls.

In addition to pressure treatments, borates are commonly sprayed, brushed, or injected to treat wood in existing structures. They will diffuse into wood that is wet, so these preservatives are often used as a remedial treatment. Borates are widely used for log homes, natural wood finishes, and hardwood pallets.

EL2

EL2 is a waterborne preservative composed of the fungicide 4,5-dichloro-2-N-octyl-4-isothiazolin-3-one (DCOI), the insecticide imidacloprid, and a moisture control stabilizer (MCS). The ratio of actives is 98% DCOI and 2% imidacloprid, but the MCS is also considered to be a necessary component to ensure preservative efficacy. EL2 is currently listed in AWPA standards for above-ground applications only (Table 15–1).

KDS

KDS and KDS Type B (KDS–B) utilize copper and polymeric betaine as the primary active ingredients. The KDS formulation also contains boron, and has an actives composition of 41% copper oxide, 33% polymeric betaine, and 26% boric acid. KDS–B does not contain boron and has an actives composition of 56% copper oxide and 44% polymeric betaine. KDS is listed for treatment of commodities used above ground and for general use in contact with soil or fresh water. It is not listed for soil or fresh water contact in severe exposures. The listing includes treatment of common pine species as well as Douglas-fir and western hemlock. KDS–B is currently in the process of obtaining listings for specific commodities. The appearance of KDS-treated wood is similar to that of wood treated with other

alkaline copper formulations (light green–brown). It has some odor initially after treatment, but this odor dissipates as the wood dries.

Oligomeric Alkylphenol Polysulfide (PXTS)

PXTS is a recently developed and somewhat unusual preservative system. It is an oligomer formed by the reaction of cresylic acid and sulfur chlorides in the presence of excess sulfur. PXTS is a solid at room temperature but becomes a liquid when heated to above approximately 58 °C. It can also be dissolved and diluted in some aromatic and organic chlorinated solvents. PXTS is not currently listed for treatment of any commodities and is currently not commercially available.

Propiconazole and Tebuconazole

Propiconazole and tebuconazole are organic triazole biocides that are effective against wood decay fungi but not against insects (AWPA P5, P8). They are soluble in some organic solvents but have low solubility in water and are stable and leach resistant in wood. Propiconazole and tebuconazole are currently components of waterborne preservative treatments used for pressure-treatment of wood in the United States, Europe, and Canada. They are also used as components of formulations used to provide mold and sapstain protection. Propiconazole is also standardized for use with AWPA P9 Type C or Type F organic solvents.

Propiconazole–Tebuconazole–Imidacloprid (PTI)

PTI is a waterborne preservative solution composed of two fungicides (propiconazole and tebuconazole) and the insecticide imidacloprid. It is currently listed in AWPA standards for above-ground applications only. The efficacy of PTI is enhanced by the incorporation of a water-repellent stabilizer in the treatment solutions, and lower retentions are allowed with the stabilizer (Table 15–1).

Preservatives with ICC–ES Evaluation Reports

Some commercially available waterborne wood preservatives are not standardized by the AWPA. Instead, they have obtained ICC–ES evaluation reports. In this chapter we refer to these preservatives by their Evaluation Report number (Table 15–1).

ESR–1721

ESR–1721 recognizes three preservative formulations. Two are the same formulations of copper azole (CA–B and CA–C) also listed in AWPA standards. The other (referred to here as ESR–1721) uses particulate copper that is ground to sub-micron dimensions and dispersed in the treatment solution. Wood treated with ESR–1721 has a lighter green color than the CA–B or CA–C formulations because the copper is not dissolved in the treatment solution. All three formulations are listed for treatment of commodities used in a range of applications, including contact with soil or freshwater.

Use of ESR–1721 (dispersed copper) is currently limited to easily treated pine species.

ESR–1980

ESR–1980 includes a listing for both the AWPA standardized formulation of ACQ–D and a waterborne, micronized copper version of alkaline copper quat (referred to here as ESR–1980). The formulation is similar to ACQ in that the active ingredients are 67% copper oxide and 33% quaternary ammonium compound. However, in ESR–1980 the copper is ground to sub-micron dimensions and suspended in the treatment solution instead of being dissolved in ethanolamine. The treated wood has little green color because the copper is not dissolved in the treatment solution. The use of the particulate form of copper is currently limited to the more easily penetrated pine species, but efforts are underway to adapt the formulation for treatment of a broader range of wood species. ESR–1980 is listed for treatment of commodities used in both above-ground and ground-contact applications.

ESR–2067

ESR–2067 is an organic waterborne preservative with an actives composition of 98% tebuconazole (fungicide) and 2% imidacloprid (insecticide). The treatment does not impart any color to the wood. It is currently listed only for treatment of commodities that are not in direct contact with soil or standing water.

ESR–2240

ESR–2240 is a waterborne formulation that utilizes finely ground (micronized) copper in combination with tebuconazole in an actives ratio of 25:1. It is listed for above-ground and ground-contact applications. In addition to wood products cut from pine species, ESR–2240 can be used for treatment of hem–fir lumber and Douglas–fir plywood.

ESR–2325

ESR–2325 is another waterborne preservative that utilizes finely ground copper particles and tebuconazole as actives. The ratio of copper to tebuconazole in the treatment solution is 25:1. Its use is currently limited to more readily treated species such as the Southern Pine species group, but Douglas–fir plywood is also listed. ESR–2315 is listed for treatment of wood used above-ground and in contact with soil or fresh water.

ESR–2711

ESR–2711 combines copper solubilized in ethanolamine with the fungicide 4,5-dichloro-2-N-octyl-4-isothiazolin-3-one (DCOI). The ratio of copper (as CuO) to DCOIT ranges from 10:1 to 25:1. The ESR listing provides for both above-ground and ground-contact applications. The appearance of the treated wood is similar to that of wood treated with other formulations utilizing soluble copper, such as ACQ. It is currently only listed for treatment of pine species.

Oil-Borne or Oil-Type Preservatives

Oil-type wood preservatives are some of the oldest preservatives, and their use continues in many applications. Wood does not swell from treatment with preservative oils, but it may shrink if it loses moisture during the treating process. Creosote and solutions with heavy, less volatile petroleum oils often help protect wood from weathering but may adversely influence its cleanliness, odor, color, paintability, and fire performance. Volatile oils or solvents with oil-borne preservatives, if removed after treatment, leave the wood cleaner than do the heavy oils but may not provide as much protection. Wood treated with some preservative oils can be glued satisfactorily, although special processing or cleaning may be required to remove surplus oils from surfaces before spreading the adhesive.

Coal-Tar Creosote and Creosote Solutions

Coal-tar creosote (creosote) is a black or brownish oil made by distilling coal tar that is obtained after high-temperature carbonization of coal. Advantages of creosote are (a) high toxicity to wood-destroying organisms; (b) relative insolubility in water and low volatility, which impart to it a great degree of permanence under the most varied use conditions; (c) ease of application; (d) ease with which its depth of penetration can be determined; (e) relative low cost (when purchased in wholesale quantities); and (f) lengthy record of satisfactory use. Creosote is commonly used for heavy timbers, poles, piles, and railroad ties.

AWPA Standard P1/P13 provides specifications for coal-tar creosote used for preservative treatment of piles, poles, and timber for marine, land, and freshwater use. The character of the tar used, the method of distillation, and the temperature range in which the creosote fraction is collected all influence the composition of the creosote, and the composition may vary within the requirements of standard specifications. Under normal conditions, requirements of these standards can be met without difficulty by most creosote producers.

Coal tar or petroleum oil may also be mixed with coal-tar creosote, in various proportions, to lower preservative costs. AWPA Standard P2 provides specifications for coal-tar solutions. AWPA Standard P3 stipulates that creosote–petroleum oil solution shall consist solely of specified proportions of 50% coal-tar creosote by volume (which meets AWPA standard P1/P13) and 50% petroleum oil by volume (which meets AWPA standard P4). However, because no analytical standards exist to verify the compliance of P3 solutions after they have been mixed, the consumer assumes the risk of using these solutions. These creosote solutions have a satisfactory record of performance, particularly for railroad ties and posts where surface appearance of the treated wood is of minor importance. Compared with straight creosote, creosote solutions tend to reduce weathering and checking of the treated wood. These solutions have a greater tendency to accumulate on the surface of the treated wood (bleed) and penetrate the wood with greater difficulty because they are

generally more viscous than is straight creosote. High temperatures and pressures during treatment, when they can be safely used, will often improve penetration of high-viscosity solutions.

Although coal-tar creosote or creosote solutions are well suited for general outdoor service in structural timbers, creosote has properties that are undesirable for some purposes. The color of creosote and the fact that creosote-treated wood usually cannot be painted satisfactorily make this preservative unsuitable where appearance and paintability are important.

The odor of creosote-treated wood is unpleasant to some people. Also, creosote vapors are harmful to growing plants, and foodstuffs that are sensitive to odors should not be stored where creosote odors are present. Workers sometimes object to creosote-treated wood because it soils their clothes, and creosote vapor photosensitizes exposed skin. With precautions to avoid direct skin contact with creosote, there appears to be minimal danger to the health of workers handling or working near the treated wood. The EPA or the wood treater should be contacted for specific information on this subject.

In 1986, creosote became a restricted-use pesticide, and its use is currently restricted to pressure-treatment facilities. For use and handling of creosote-treated wood, refer to the EPA-approved Consumer Information Sheet.

Freshly creosoted timber can be ignited and burns readily, producing a dense smoke. However, after the timber has seasoned for some months, the more volatile parts of the oil disappear from near the surface and the creosoted wood usually is little, if any, easier to ignite than untreated wood. Until this volatile oil has evaporated, ordinary precautions should be taken to prevent fires. Creosote adds fuel value, but it does not sustain ignition.

Other Creosotes

Creosotes distilled from tars other than coal tar have been used to some extent for wood preservation, although they are not included in current AWPA specifications. These include wood-tar creosote, oil-tar creosote, and water–gas-tar creosote. These creosotes provide some protection from decay and insect attack but are generally less effective than coal-tar creosote.

Pentachlorophenol Solutions

Water-repellent solutions containing chlorinated phenols, principally pentachlorophenol (penta), in solvents of the mineral spirits type, were first used in commercial dip treatments of wood by the millwork industry in about 1931. Commercial pressure treatment with pentachlorophenol in heavy petroleum oils on poles started in about 1941, and considerable quantities of various products soon were pressure treated. AWPA Standard P8 defines the properties of pentachlorophenol preservative, stating that pentachlorophenol solutions for wood preservation shall contain not less

than 95% chlorinated phenols, as determined by titration of hydroxyl and calculated as pentachlorophenol.

AWPA standard P9 defines solvents and formulations for organic preservative systems. The performance of pentachlorophenol and the properties of the treated wood are influenced by the properties of the solvent used. A commercial process using pentachlorophenol dissolved in liquid petroleum gas (LPG) was introduced in 1961, but later research showed that field performance of penta-LPG systems was inferior to penta-P9 systems. Thus, penta-LPG systems are no longer used. The heavy petroleum solvent included in AWPA P9 Type A is preferable for maximum protection, particularly when wood treated with pentachlorophenol is used in contact with the ground. The heavy oils remain in the wood for a long time and do not usually provide a clean or paintable surface.

Because of the toxicity of pentachlorophenol, care is necessary when handling and using it to avoid excessive personal contact with the solution or vapor. Do not use indoors or where human, plant, or animal contact is likely. Pentachlorophenol became a restricted-use pesticide in November 1986 and is currently only available for use in pressure treatment. For use and handling precautions, refer to the EPA-approved Consumer Information Sheet.

The results of pole service and field tests on wood treated with 5% pentachlorophenol in a heavy petroleum oil are similar to those with coal-tar creosote. This similarity has been recognized in the preservative retention requirements of treatment specifications. Pentachlorophenol is effective against many organisms, such as decay fungi, molds, stains, and insects. Because pentachlorophenol is ineffective against marine borers, it is not recommended for the treatment of marine piles or timbers used in coastal waters.

Copper Naphthenate

Copper naphthenate is an organometallic compound formed as a reaction product of copper salts and naphthenic acids that are usually obtained as byproducts in petroleum refining. It is a dark green liquid and imparts this color to the wood. Weathering turns the color of the treated wood to light brown after several months of exposure. The wood may vary from light brown to chocolate brown if heat is used in the treating process. AWPA P8 standard defines the properties of copper naphthenate, and AWPA P9 covers the solvents and formulations for organic preservative systems.

Copper naphthenate is effective against wood-destroying fungi and insects. It has been used commercially since the 1940s and is currently standardized for a broad range of applications (Table 15–1). Copper naphthenate is not a restricted-use pesticide but should be handled as an industrial pesticide. It may be used for superficial treatment, such as by brushing with solutions with a copper content of 1% to 2% (approximately 10% to 20% copper naphthenate).

Water-based formulations of copper naphthenate may also be available.

Oxine Copper (copper-8-quinolinolate)

Oxine copper (copper-8-quinolinolate) is an organometallic compound, and the formulation consists of at least 10% copper-8-quinolinolate, 10% nickel-2-ethylhexanoate, and 80% inert ingredients (AWPA P8). It is accepted as a stand-alone preservative for aboveground use for sapstain and mold control and is also used for pressure treating (Table 15–1). A water-soluble form can be made with dodecylbenzene sulfonic acid, but the solution is corrosive to metals.

Oxine copper solutions are greenish brown, odorless, toxic to both wood decay fungi and insects, and have a low toxicity to humans and animals. Because of its low toxicity to humans and animals, oxine copper is the only EPA-registered preservative permitted by the U.S. Food and Drug Administration for treatment of wood used in direct contact with food. Some examples of its uses in wood are commercial refrigeration units, fruit and vegetable baskets and boxes, and water tanks. Oxine copper solutions have also been used on nonwood materials, such as webbing, cordage, cloth, leather, and plastics.

Zinc Naphthenate

Zinc naphthenate is similar to copper naphthenate but is less effective in preventing decay from wood-destroying fungi and mildew. It is light colored and does not impart the characteristic greenish color of copper naphthenate, but it does impart an odor. Waterborne and solventborne formulations are available. Zinc naphthenate is not widely used for pressure treating.

3-Iodo-2-Propynyl Butyl Carbamate

3-Iodo-2-propynyl butyl carbamate (IPBC) is a fungicide that is used as a component of sapstain and millwork preservatives. It is also included as a fungicide in several surface-applied water-repellent-preservative formulations. Waterborne and solvent-borne formulations are available. Some formulations yield an odorless, treated product that can be painted if dried after treatment. It is listed as a pressure-treatment preservative in the AWPA standards but is not currently standardized for pressure treatment of any wood products. IPBC also may be combined with other fungicides, such as didecyltrimethylammonium chloride in formulations used to prevent mold and sapstain.

IPBC/Permethrin

IPBC is not an effective insecticide and has recently been standardized for use in combination with the insecticide permethrin (3-phenoxybenzyl-(1R,S)-cis, trans-2, 2-dimethyl-3-(2,2-dichlorovinyl) cyclopropanecarboxylate) under the designation IPBC/PER. Permethrin is a synthetic pyrethroid widely used for insect control in agricultural and structural applications. The ratio of IPBC to permethrin in the IPBC/PER varies between 1.5:1 and 2.5:1. The formulation is

carried in a light solvent such as mineral spirits, making it compatible with composite wood products that might be negatively affected by the swelling associated with water-based pressure treatments. The IPBC/PER formulation is intended only for use in above-ground applications. The formulation is listed as a preservative in AWP standards, but at the time this chapter was finalized it had not yet been standardized for treatment of any commodities.

Alkyl Ammonium Compounds

Alkyl ammonium compounds such as didecyldimethylammonium chloride (DDAC) or didecyldimethylammonium carbonate (DDAC)/bicarbonate (DDABC) have some efficacy against both wood decay fungi and insects. They are soluble in both organic solvents and water and are stable in wood as a result of chemical fixation reactions. DDAC and DDABC are currently being used as a component of alkaline copper quat (ACQ) (see section on Waterborne Preservatives) for above-ground and ground-contact applications and as a component of formulations used for sapstain and mold control.

4,5-Dichloro-2-N-Octyl-4-Isothiazolin-3-One (DCOI)

4,5-dichloro-2-N-octyl-4-isothiazolin-3-one (DCOI) is a biocide that is primarily effective against wood decay fungi. It is soluble in organic solvents but not in water, and it is stable and leach resistant in wood. The solvent used in the formulation of the preservative is specified in AWP P9 Type C. DCOI can be formulated to be carried in a waterborne system, and it is currently used as a component in the waterborne preservative EL2. It has also recently been proposed for use as co-biocide in a copper ethanolamine formulation referred to as ACD.

Chlorpyrifos

Chlorpyrifos (CPF) is an organophosphate insecticide that has been widely used for agricultural purposes. It has been standardized by the AWP as a preservative but is not currently used as a component of commercial pressure treatments. Chlorpyrifos is not effective in preventing fungal attack and should be combined with an appropriate fungicidal preservative for most applications.

Treatments for Wood Composites

Many structural composite wood products, such as glued-laminated beams, plywood, and parallel strand and laminated veneer lumber, can be pressure-treated with wood preservatives in a manner similar to lumber. However, flake- or fiber-based composites are often protected by adding preservative during manufacture. A commonly used preservative for these types of composites is zinc borate. Zinc borate is a white, odorless powder with low water solubility that is added directly to the furnish or wax during panel manufacture. Zinc borate has greater leach resistance than the more soluble forms of borate used for pressure treatment and thus can be used to treat composite siding products that are exposed outdoors but partially protected from the weather.

Zinc borate is currently listed in AWP Commodity Standard J for nonpressure treatment of laminated strand lumber, oriented strandboard, and engineered wood siding. The standard requires that these products have an exterior coating or laminate when used as siding. Another preservative that has been used to protect composites is ammoniacal copper acetate, which is applied by spraying the preservative onto the OSB flakes before drying.

Water-Repellent and Nonpressure Treatments

Effective water-repellent preservatives will retard the ingress of water when wood is exposed above ground. These preservatives help reduce dimensional changes in the wood as a result of moisture changes when the wood is exposed to rainwater or dampness for short periods. As with any wood preservative, the effectiveness in protecting wood against decay and insects depends upon the retention and penetration obtained in application. These preservatives are most often applied using nonpressure treatments such as vacuum impregnation, brushing, soaking, or dipping. Preservative systems containing water-repellent components are sold under various trade names, principally for the dip or equivalent treatment of window sash and other millwork. The National Wood Window and Door Association (NWWDA) standard, WDMA I.S. 4–07A, *Water Repellent Preservative Treatment for Millwork*, lists preservative formulations that have met certain requirements, including EPA registration and efficacy against decay fungi.

The AWP Commodity Specification I for nonpressure treatment of millwork and other wood products provides requirements for these nonpressure preservatives but does not currently list any formulations. The preservative must also meet the *Guidelines for Evaluating New Wood Preservatives for Consideration by the AWP* for nonpressure treatment.

Water-repellent preservatives containing oxine copper are used in nonpressure treatment of wood containers, pallets, and other products for use in contact with foods. When combined with volatile solvents, oxine copper is used to pressure-treat lumber intended for use in decking of trucks and cars or related uses involving harvesting, storage, and transportation of foods (AWP P8).

Nonpressure preservatives sold to consumers for household and farm use typically contain copper naphthenate, zinc naphthenate, or oxine copper. Their formulations may also incorporate water repellents.

Selecting Preservatives

The type of preservative applied is often dependent on the requirements of the specific application. For example, direct contact with soil or water is considered a severe deterioration hazard, and preservatives used in these applications must have a high degree of leach resistance and efficacy against a broad spectrum of organisms. These same



Figure 15–1. Field stake test plot at Harrison Experimental Forest in southern Mississippi.

preservatives may also be used at lower retentions to protect wood exposed in lower deterioration hazards, such as above the ground. The exposure is less severe for wood that is partially protected from the weather, and preservatives that lack the permanence or toxicity to withstand continued exposure to precipitation may be effective in those applications. Other formulations may be so readily leachable that they can be used only indoors.

To guide selection of the types of preservatives and loadings appropriate to a specific end use, the AWPAs recently developed use category system (UCS) standards. The UCS standards simplify the process of finding appropriate preservatives and preservative retentions for specific end uses. They categorize treated wood applications by the severity of the deterioration hazard (Table 15–6). The lowest category, Use Category 1 (UC1), is for wood that is used in interior construction and kept dry; UC2 is for interior wood completely protected from the weather but occasionally damp. UC3 is for exterior wood used above ground; UC4 is for wood used in ground contact in exterior applications. UC5 includes applications that place treated wood in contact with seawater and marine borers. Individual commodity specifications then list all the preservatives that are standardized for a specific use category along with the appropriate preservative retention.

Although some preservatives are effective in almost all environments, they may not be well-suited for applications involving frequent human contact or for exposures that present only low to moderate biodeterioration hazards. Additional considerations include cost, potential odor, surface dryness, adhesive bonding, and ease of finish application.

Evaluating New Preservatives

Wood preservatives often need to provide protection from a wide range of wood-attacking organisms (fungi, insects, marine borers, and bacteria). Because they must protect wood in so many ways, and protect wood for a long time period,

evaluating wood treatments requires numerous tests. Some of the most important tests are mentioned here, but they should be considered only as a minimum, and other tests are useful as well. Appendix A of the AWPAs Standards provides detailed guidelines on the types of tests that may be needed to evaluate new wood preservatives.

The *laboratory leaching test* helps to evaluate how rapidly the treatment will be depleted. A treatment needs leach resistance to provide long-term protection. In this test small cubes of wood are immersed in water for 2 weeks.

The *laboratory decay test* is used to challenge the treated wood with certain fungal isolates that are known to aggressively degrade wood. It should be conducted with specimens that have been through the leaching test. The extent of decay in wood treated with the test preservative is compared to that of untreated wood and wood treated with an established preservative. This test can help to determine the treatment level needed to prevent decay.

Field stake evaluations are some of the most informative tests because they challenge the treated wood with a wide range of natural organisms under severe conditions (Fig. 15–1). Stakes are placed into the soil in regions with a warm, wet climate (usually either the southeastern United States or Hawaii). At least two different sites are used to account for differences in soil properties and types of organisms present. The extent of deterioration in wood treated with the test preservative is compared to that of untreated wood and wood treated with an established preservative.

Above-ground field exposures are useful for treatments that will be used to protect wood above ground. Although not as severe as field stake tests, above-ground tests do provide useful information on above-ground durability. Specimens are exposed to the weather in an area with a warm, wet climate (usually either the southeastern United States or Hawaii). The specimens are designed to trap moisture and create ideal conditions for above-ground decay. The extent of deterioration in wood treated with the test preservative is compared to that of untreated wood and wood treated with an established preservative.

Corrosion testing is used to determine the compatibility of the treatment with metal fasteners.

Treatability testing is used to evaluate the ability of a treatment to penetrate deeply into the wood. Shallow surface treatments rarely provide long-term protection because degrading organisms can still attack the interior of the wood.

Strength testing compares the mechanical properties of treated wood with matched, untreated specimens. Treatment chemicals or processes have the potential to damage the wood, making it weak or brittle.

Preservative Effectiveness

Preservative effectiveness is influenced not only by the protective value of the preservative chemical, but also by the

Table 15–6. Summary of use category system developed by the American Wood Protection Association

Use category	Service conditions	Use environment	Common agents of deterioration	Typical applications
UC1	Interior construction Above ground Dry	Continuously protected from weather or other sources of moisture	Insects only	Interior construction and furnishings
UC2	Interior construction Above ground Damp	Protected from weather, but may be subject to sources of moisture	Decay fungi and insects	Interior construction
UC3A	Exterior construction Above ground Coated and rapid water runoff	Exposed to all weather cycles, not exposed to prolonged wetting	Decay fungi and insects	Coated millwork, siding, and trim
UC3B	Ground contact or fresh water Non-critical components	Exposed to all weather cycles, normal exposure conditions	Decay fungi and insects	Fence, deck, and guardrail posts, crossties and utility poles (low decay areas)
UC4A	Ground contact or fresh water Non-critical components	Exposed to all weather cycles, normal exposure conditions	Decay fungi and insects	Fence, deck, and guardrail posts, crossties and utility poles (low decay areas)
UC4B	Ground contact or fresh water Critical components or difficult replacement	Exposed to all weather cycles, high decay potential includes salt-water splash	Decay fungi and insects with increased potential for biodeterioration	Permanent wood foundations, building poles, horticultural posts, crossties and utility poles (high decay areas)
UC4C	Ground contact or fresh water Critical structural components	Exposed to all weather cycles, severe environments, extreme decay potential	Decay fungi and insects with extreme potential for biodeterioration	Land and fresh-water piling, foundation piling, crossties and utility poles (severe decay areas)
UC5A	Salt or brackish water and adjacent mud zone Northern waters	Continuous marine exposure (salt water)	Salt-water organisms	Piling, bulkheads, bracing
UC5B	Salt or brackish water and adjacent mud zone NJ to GA, south of San Francisco	Continuous marine exposure (salt water)	Salt-water organisms, including creosote-tolerant <i>Limnoria tripunctata</i>	Piling, bulkheads, bracing
UC5C	Salt or brackish water and adjacent mud zone South of GA, Gulf Coast, Hawaii, and Puerto Rico	Continuous marine exposure (salt water)	Salt-water organisms, including <i>Martesia</i> , <i>Sphaeroma</i>	Piling, bulkheads, bracing

method of application and extent of penetration and retention of the preservative in the treated wood. Even with an effective preservative, good protection cannot be expected with poor penetration or substandard retention levels. The species of wood, proportion of heartwood and sapwood, heartwood penetrability, and moisture content are among the important variables that influence the results of treatment. For various wood products, the preservatives and retention levels listed in the AWPA Commodity Standards or ICC–ES evaluation reports are given in Table 15–1.

Determining whether one preservative is more effective than another within a given use category is often difficult.

Few service tests include a variety of preservatives under comparable conditions of exposure. Furthermore, service tests may not show a good comparison between different preservatives as a result of the difficulty in controlling for differences in treatment quality. Comparative data under similar exposure conditions, with various preservatives and retention levels, are included in the U.S. Forest Service, Forest Products Laboratory, stake test studies. A summary of these test results is included in Table 15–5. Note, however, that because the stakes used in these studies are treated under carefully controlled conditions, their performance may not reflect variability in performance exhibited by a broad range of commercially treated material.



Figure 15–2. During pressure treatment, preservative typically penetrates only the sapwood. Round members have a uniform treated sapwood shell, but sawn members may have less penetration on one or more faces.

Similar comparisons have been conducted for preservative treatments of small wood panels in marine exposure (Key West, Florida). These preservatives and treatments include creosotes with and without supplements, waterborne preservatives, waterborne preservative and creosote dual treatments, chemical modifications of wood, and various chemically modified polymers. In this study, untreated panels were badly damaged by marine borers after 6 to 18 months of exposure, whereas some treated panels have remained free of attack after 19 years in the sea.

Test results based on seawater exposure have shown that dual treatment (waterborne copper-containing preservatives followed by creosote) is possibly the most effective method of protecting wood against all types of marine borers. The AWP standards have recognized this process as well as the treatment of marine piles with high retention levels of ammoniacal copper zinc arsenate (ACZA) or chromated copper arsenate (CCA). The recommended treatment and retention in kilograms per cubic meter (pounds per cubic foot) for round timber piles exposed to severe marine borer hazard are given in Table 15–2. Poorly treated or untreated heartwood faces of wood species containing “high sapwood” that do not require heartwood penetration (for example, southern pines, ponderosa pine, and red pine) have been found to perform inadequately in marine exposure. In marine applications, only sapwood faces should be allowed for waterborne-preservative-treated pine in direct seawater exposure.

Effect of Species on Penetration

The effectiveness of preservative treatment is influenced by the penetration and distribution of the preservative in the wood. For maximum protection, it is desirable to select species for which good penetration is assured.

In general, the sapwood of most softwood species is not difficult to treat under pressure (Fig. 15–2). Examples of species with sapwood that is easily penetrated when it is well dried and pressure treated are the pines, coastal Douglas-fir,

western larch, Sitka spruce, western hemlock, western red-cedar, northern white-cedar, and white fir (*A. concolor*). Examples of species with sapwood and heartwood somewhat resistant to penetration are the red and white spruces and Rocky Mountain Douglas-fir. Cedar poles are commonly incised to obtain satisfactory preservative penetration. With round members, such as poles, posts, and piles, the penetration of the sapwood is important in achieving a protective outer zone around the heartwood.

The proportion of sapwood varies greatly with wood species, and this becomes an important factor in obtaining adequate penetration. Species within the Southern Pine group are characterized by a large sapwood zone that is readily penetrated by most types of preservatives. In part because of their large proportion of treatable sapwood, these pine species are used for the vast majority of treated products in the United States. Other important lumber species, such as Douglas-fir, have a narrower sapwood band in the living tree, and as a result products manufactured from Douglas-fir have a lower proportion of treatable sapwood.

The heartwood of most species is difficult to treat. There may be variations in the resistance to preservative penetration of different wood species. Table 15–7 gives the relative resistance of the heartwood to treatment of various softwood and hardwood species. Although less treatable than sapwood, well-dried white fir, western hemlock, northern red oak, the ashes, and tupelo are examples of species with heartwood that is reasonably easy to penetrate. The southern pines, ponderosa pine, redwood, Sitka spruce, coastal Douglas-fir, beech, maples, and birches are examples of species with heartwood that is moderately resistant to penetration.

Preparation of Wood for Treatment

For satisfactory treatment and good performance, the wood product must be sound and suitably prepared. Except in specialized treating methods involving unpeeled or green material, the wood should be well peeled and either seasoned or conditioned in the cylinder before treatment. It is also highly desirable that all machining be completed before treatment, including incising (to improve the preservative penetration in woods that are resistant to treatment) and the operations of cutting or boring of holes.

Peeling

Peeling round or slabbed products is necessary to enable the wood to dry quickly enough to avoid decay and insect damage and to permit the preservative to penetrate satisfactorily. Even strips of the thin inner bark may prevent penetration. Patches of bark left on during treatment usually fall off in time and expose untreated wood, thus permitting decay to reach the interior of the member.

Careful peeling is especially important for wood that is to be treated by a nonpressure method. In the more thorough

Table 15–7. Penetration of the heartwood of various softwood and hardwood species^a

Ease of treatment	Softwoods	Hardwoods
Least difficult	Bristlecone pine (<i>Pinus aristata</i>)	American basswood (<i>Tilia americana</i>)
	Pinyon (<i>P. edulis</i>)	Beech (white heartwood) (<i>Fagus grandifolia</i>)
	Pondersosa pine (<i>P. ponderosa</i>)	Black tupelo (blackgum) (<i>Nyssa sylvatica</i>)
	Redwood (<i>Sequoia sempervirens</i>)	Green ash (<i>Fraxinus pennsylvanica</i> var. <i>lanceolata</i>)
		Pin cherry (<i>Prunus pennsylvanica</i>)
		River birch (<i>Betula nigra</i>)
		Red oak (<i>Quercus</i> spp.)
		Slippery elm (<i>Ulmus fulva</i>)
		Sweet birch (<i>Betula lenia</i>)
		Water tupelo (<i>Nyssa aquatica</i>)
		White ash (<i>Fraxinus americana</i>)
Moderately difficult	Baldcypress (<i>Taxodium distichum</i>)	Black willow (<i>Salix nigra</i>)
	California red fir (<i>Abies magnifica</i>)	Chestnut oak (<i>Quercus montana</i>)
	Douglas-fir (coast) (<i>Pseudotsuga taxifolia</i>)	Cottonwood (<i>Populus</i> sp.)
	Eastern white pine (<i>Pinus strobus</i>)	Bigtooth aspen (<i>P. grandidentata</i>)
	Jack pine (<i>P. banksiana</i>)	Mockernut hickory (<i>Carya tomentosa</i>)
	Loblolly pine (<i>P. taeda</i>)	Silver maple (<i>Acer saccharinum</i>)
	Longleaf pine (<i>P. palustris</i>)	Sugar maple (<i>A. saccharum</i>)
	Red pine (<i>P. resinosa</i>)	Yellow birch (<i>Betula lutea</i>)
	Shortleaf pine (<i>P. echinata</i>)	
	Sugar pine (<i>P. lambertiana</i>)	
	Western hemlock (<i>Tsuga heterophylla</i>)	
Difficult	Eastern hemlock (<i>Tsuga canadensis</i>)	American sycamore (<i>Platanus occidentalis</i>)
	Engelmann spruce (<i>Picea engelmanni</i>)	Hackberry (<i>Celtis occidentalis</i>)
	Grand fir (<i>Abies grandis</i>)	Rock elm (<i>Ulmus thomasi</i>)
	Lodgepole pine (<i>Pinus contorta</i> var. <i>latifolia</i>)	Yellow-poplar (<i>Liriodendron tulipifera</i>)
	Noble fir (<i>Abies procera</i>)	
	Sitka spruce (<i>Picea sitchensis</i>)	
	Western larch (<i>Larix occidentalis</i>)	
	White fir (<i>Abies concolor</i>)	
White spruce (<i>Picea glauca</i>)		
Very difficult	Alpine fir (<i>Abies lasiocarpa</i>)	American beech (red heartwood) (<i>Fagus grandifolia</i>)
	Corkbark fir (<i>A. lasiocarpa</i> var. <i>arizonica</i>)	American chestnut (<i>Castanea dentata</i>)
	Douglas-fir (Rocky Mountain) (<i>Pseudotsuga taxifolia</i>)	Black locust (<i>Robinia pseudoacacia</i>)
	Northern white-cedar (<i>Thuja occidentalis</i>)	Blackjack oak (<i>Quercus marilandica</i>)
	Tamarack (<i>Larix laricina</i>)	Sweetgum (redgum) (<i>Liquidambar styraciflua</i>)
	Western redcedar (<i>Thuja plicata</i>)	White oak (<i>Quercus</i> spp.)

^aAs covered in MacLean (1952).

processes, some penetration may take place both longitudinally and tangentially in the wood; consequently, small strips of bark are tolerated in some specifications. Processes in which a preservative is forced or permitted to diffuse through green wood lengthwise do not require peeling of the timber. Machines of various types have been developed for peeling round timbers, such as poles, piles, and posts (Fig. 15–3).

Drying

Drying of wood before treatment is necessary to prevent decay and stain and to obtain preservative penetration. However, for treatment with waterborne preservatives by certain diffusion methods, high moisture content levels may be permitted. For treatment by other methods, however, drying before treatment is essential. Drying before treatment opens up the checks before the preservative is applied, thus increasing penetration, and reduces the risk of checks

opening after treatment and exposing unpenetrated wood. Good penetration of heated organic-based preservatives may be possible in wood with a moisture content as high as 40% to 60%, but severe checking while drying after treatment can expose untreated wood.

For large timbers and railroad ties, air drying is a widely used method of conditioning. Despite the increased time, labor, and storage space required, air drying is generally the most inexpensive and effective method, even for pressure treatment. However, wet, warm climatic conditions make it difficult to air dry wood adequately without objectionable infection by stain, mold, and decay fungi. Such infected wood is often highly permeable; in rainy weather, infected wood can absorb a large quantity of water, which prevents satisfactory treatment.

How long the timber must be air dried before treatment depends on the climate, location, and condition of the



Figure 15-3. Machine peeling of poles. The outer bark has been removed by hand, and the inner bark is being peeled by machine. Frequently, all the bark is removed by machine.



Figure 15-4. Deep incising permits better penetration of preservative.

seasoning yard, methods of piling, season of the year, timber size, and species. The most satisfactory seasoning practice for any specific case will depend on the individual drying conditions and the preservative treatment to be used. Therefore, treating specifications are not always specific as to moisture content requirements.

To prevent decay and other forms of fungal infection during air drying, the wood should be cut and dried when conditions are less favorable for fungus development (Chap. 14). If this is impossible, chances for infection can be minimized by prompt conditioning of the green material, careful piling and roofing during air drying, and pretreating the green wood with preservatives to protect it during air drying.

Lumber of all species, including Southern Pine poles, is often kiln dried before treatment, particularly in the southern United States where proper air seasoning is difficult. Kiln drying has the important added advantage of quickly reducing moisture content, thereby reducing transportation charges on poles.

Conditioning of Green Products

Plants that treat wood by pressure processes can condition green material by means other than air and kiln drying. Thus, they avoid a long delay and possible deterioration of the timber before treatment.

When green wood is to be treated under pressure, one of several methods for conditioning may be selected. The steaming-and-vacuum process is used mainly for southern pines, and the Boulton or boiling-under-vacuum process is used for Douglas-fir and sometimes hardwoods.

In the steaming process, the green wood is steamed in the treating cylinder for several hours, usually at a maximum of 118 °C (245 °F). When steaming is completed, a vacuum is immediately applied. During the steaming period, the outer part of the wood is heated to a temperature approaching that of the steam; the subsequent vacuum lowers the boiling point so that part of the water is evaporated or forced out of the wood by the steam produced when the vacuum is applied. The steaming and vacuum periods used depend upon the wood size, species, and moisture content. Steaming and vacuum usually reduce the moisture content of green wood slightly, and the heating assists greatly in getting the preservative to penetrate. A sufficiently long steaming period will also sterilize the wood.

In the Boulton or boiling-under-vacuum method of partial seasoning, the wood is heated in the oil preservative under vacuum, usually at about 82 to 104 °C (180 to 220 °F). This temperature range, lower than that of the steaming process, is a considerable advantage in treating woods that are especially susceptible to injury from high temperatures. The Boulton method removes much less moisture from heartwood than from sapwood.

Incising

Wood that is resistant to penetration by preservatives may be incised before treatment to permit deeper and more uniform penetration. To incise, lumber and timbers are passed through rollers equipped with teeth that sink into the wood to a predetermined depth, usually 13 to 19 mm (1/2 to 3/4 in.). The teeth are spaced to give the desired distribution of preservative with the minimum number of incisions. A machine of different design is required for deeply incising the butts of poles, usually to a depth of 64 mm (2.5 in.) (Fig. 15-4).

Incising is effective because preservatives usually penetrate the wood much farther along the grain than across the grain. The incisions open cell lumens along the grain, which

greatly enhances penetration. Incising is especially effective in improving penetration in the heartwood areas of sawn surfaces.

Incising is practiced primarily on Douglas-fir, western hemlock, and western larch ties and timbers for pressure treatment and on cedar and Douglas-fir poles. Incising can result in significant reductions in strength (Chap. 5).

Cutting and Framing

All cutting and boring of holes should be done prior to preservative treatment. Cutting into the wood in any way after treatment will frequently expose the untreated interior of the timber and permit ready access to decay fungi or insects.

In some cases, wood structures can be designed so that all cutting and framing is done before treatment. Railroad companies have followed this practice and have found it not only practical but economical. Many wood-preserving plants are equipped to carry on such operations as the adzing and boring of crossties; gaging, roofing, and boring of poles; and framing of material for bridges and specialized structures, such as water tanks and barges.

Treatment of the wood with preservative oils results in little or no dimensional change. With waterborne preservatives, however, some change in the size and shape of the wood may occur even though the wood is redried to the moisture content it had before treatment. If precision fitting is necessary, the wood is cut and framed before treatment to its approximate final dimensions to allow for slight surfacing, trimming, and reaming of bolt holes. Grooves and bolt holes for timber connectors are cut before treatment and can be reamed out if necessary after treatment.

Application of Preservatives

Wood-preserving methods are of two general types: (a) pressure processes, in which the wood is impregnated in closed vessels under pressures considerably above atmospheric, and (b) nonpressure processes, which vary widely in the procedures and equipment used.

Pressure Processes

In commercial practice, wood is most often treated by immersing it in a preservative in a high-pressure apparatus and applying pressure to drive the preservative into the wood. Pressure processes differ in details, but the general principle is the same. The wood, on cars or trams, is run into a long steel cylinder, which is then closed and filled with preservative (Fig. 15–5). Pressure forces the preservative into the wood until the desired amount has been absorbed. Considerable preservative is absorbed, with relatively deep penetration. Three pressure processes are commonly used: full cell, modified full cell, and empty cell.

Full Cell

The full-cell (Bethel) process is used when the retention of a maximum quantity of preservative is desired. It is a

standard procedure for timbers to be treated with creosote when protection against marine borers is required. Waterborne preservatives may be applied by the full-cell process if uniformity of penetration and retention is the primary concern. With waterborne preservatives, control over preservative retention is obtained by regulating the concentration of the treating solution.

Steps in the full-cell process are essentially the following:

1. The charge of wood is sealed in the treating cylinder, and a preliminary vacuum is applied for a half-hour or more to remove the air from the cylinder and as much as possible from the wood.
2. The preservative, at ambient or elevated temperature depending on the system, is admitted to the cylinder without breaking the vacuum.
3. After the cylinder is filled, pressure is applied until the wood will take no more preservative or until the required retention of preservative is obtained.
4. When the pressure period is completed, the preservative is withdrawn from the cylinder.
5. A short final vacuum may be applied to free the charge from dripping preservative.

When the wood is steamed before treatment, the preservative is admitted at the end of the vacuum period that follows steaming. When the timber has received preliminary conditioning by the Boulton or boiling-under-vacuum process, the cylinder can be filled and the pressure applied as soon as the conditioning period is completed.

Modified Full Cell

The modified full-cell process is basically the same as the full-cell process except for the amount of initial vacuum and the occasional use of an extended final vacuum. The modified full-cell process uses lower levels of initial vacuum; the actual amount is determined by the wood species, material size, and final retention desired. The modified full-cell process is commonly used for treatment of lumber with waterborne preservatives.

Empty Cell

The objective of the empty-cell process is to obtain deep penetration with a relatively low net retention of preservative. For treatment with oil preservatives, the empty-cell process should always be used if it will provide the desired retention. Two empty-cell processes, the Rueping and the Lowry, are commonly employed; both use the expansive force of compressed air to drive out part of the preservative absorbed during the pressure period.

The Rueping empty-cell process, often called the empty-cell process with initial air, has been widely used for many years in Europe and the United States. The following general procedure is employed:

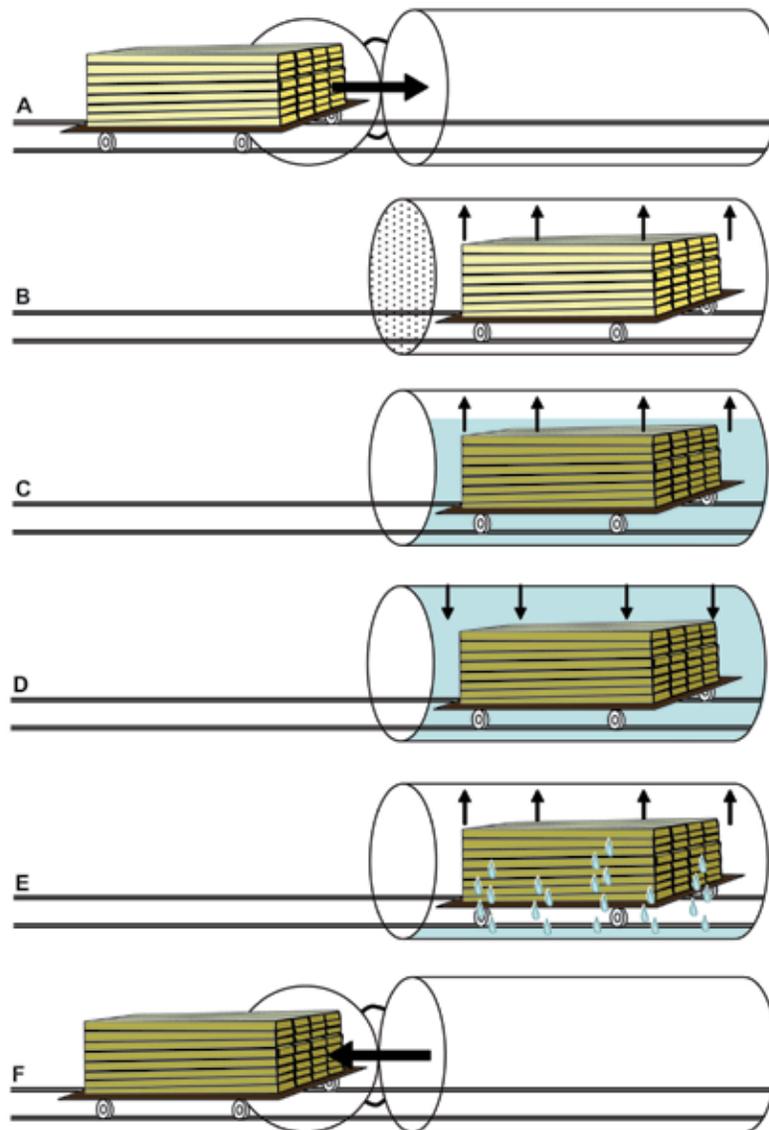


Figure 15-5. Typical steps in pressure treating process: A, untreated wood is placed in cylinder; B, a vacuum is applied to pull air out of the wood; C, the wood is immersed in solution while still under vacuum; D, pressure is applied to force the preservative into the wood; E, preservative is pumped out, and a final vacuum is pulled to remove excess preservative; F, excess preservative is pumped away, and the wood is removed from the cylinder.

1. Air under pressure is forced into the treating cylinder, which contains the charge of wood. The air penetrates some species easily, requiring but a few minutes application of pressure. In treating the more resistant species, common practice is to maintain air pressure from 1/2 to 1 h before admitting the preservative, but the necessity for lengthy air-pressure periods does not seem fully established. The air pressures employed generally range from 172 to 689 kPa (25 to 100 lb in⁻²), depending on the net retention of preservative desired and the resistance of the wood.
2. After the period of preliminary air pressure, preservative is forced into the cylinder. As the preservative is pumped in, the air escapes from the treating cylinder into an equalizing or Rueping tank, at a rate that keeps the pressure constant within the cylinder. When the treating cylinder is filled with preservative, the treating pressure is increased above that of the initial air and is maintained until the wood will absorb no more preservative, or until enough has been absorbed to leave the required retention of preservative in the wood after the treatment.

- At the end of the pressure period, the preservative is drained from the cylinder, and surplus preservative is removed from the wood with a final vacuum. The amount of preservative recovered can be from 20% to 60% of the gross amount injected.

The Lowry is often called the empty-cell process without initial air pressure. Preservative is admitted to the cylinder without either an initial air pressure or a vacuum, and the air originally in the wood at atmospheric pressure is imprisoned during the filling period. After the cylinder is filled with the preservative, pressure is applied, and the remainder of the treatment is the same as described for the Rueping treatment.

The Lowry process has the advantage that equipment for the full-cell process can be used without other accessories that the Rueping process usually requires, such as an air compressor, an extra cylinder or Rueping tank for the preservative, or a suitable pump to force the preservative into the cylinder against the air pressure. However, both processes have advantages and are widely and successfully used.

With poles and other products where bleeding of preservative oil is objectionable, the empty-cell process is followed by either heating in the preservative (expansion bath) at a maximum of 104 °C (220 °F) or a final steaming for a specified time limit at a maximum of 116 °C (240 °F) prior to the final vacuum.

Treating Pressures and Preservative Temperatures

The pressures used in treatments vary from about 345 to 1,723 kPa (50 to 250 lb in⁻²), depending on the species and the ease with which the wood takes the treatment. Most commonly, pressures range from about 862 to 1,207 kPa (125 to 175 lb in⁻²). Many woods are sensitive to high treating pressures, especially when hot. For example, AWPA standards permit a maximum pressure of 1,050 kPa (150 lb in⁻²) in the treatment of redwood, eastern hemlock, and eastern white pine, while the limitation for oak is 1,723 kPa (250 lb in⁻²).

AWPA T1 standard requires that the temperature of creosote and creosote solutions, as well as that of the oil-type preservatives, during the pressure period not be greater than 100 °C (212 °F). For the waterborne preservatives that contain chromium (ACC and CCA), the maximum solution temperature is limited to 50 °C (120 °F) to avoid premature precipitation of the preservative. For most other waterborne preservatives, the maximum solution temperature is 65 °C (150 °F), although a higher limit 93 °C (200 °F) is permitted for inorganic boron solutions.

Effect on Mechanical Properties

Coal-tar creosote, creosote solutions, and pentachlorophenol dissolved in petroleum oils are practically inert to wood and have no chemical influence that would affect its strength.

Chemicals commonly used in waterborne salt preservatives, including chromium, copper, arsenic, and ammonia, are reactive with wood. Thus, these chemicals are potentially damaging to mechanical properties and may also promote corrosion of mechanical fasteners.

Significant reductions in mechanical properties may be observed if the treating and subsequent drying processes are not controlled within acceptable limits. Factors that influence the effect of the treating process on strength include (a) species of wood, (b) size and moisture content of the timbers treated, (c) type and temperature of heating medium, (d) length of the heating period in conditioning the wood for treatment and time the wood is in the hot preservative, (e) post-treatment drying temperatures, and (f) amount of pressure used. Most important of those factors are the severity and duration of the in-retort heating or post-treatment redrying conditions used. The effect of wood preservatives on the mechanical properties of wood is covered in Chapter 5.

Nonpressure Processes

The numerous nonpressure processes differ widely in the penetration and retention levels of preservative attained, and consequently in the degree of protection they provide to the treated wood. When similar retention and penetration levels are achieved, wood treated by a nonpressure method should have a service life comparable to that of wood treated by pressure. Nevertheless, results of nonpressure treatments, particularly those involving surface applications, are not generally as satisfactory as those of pressure treatment. The superficial processes do serve a useful purpose when more thorough treatments are impractical or exposure conditions are such that little preservative protection is required.

Nonpressure methods, in general, consist of (a) surface application of preservatives by brief dipping, (b) soaking in preservative oils or steeping in solutions of waterborne preservatives, (c) diffusion processes with waterborne preservatives, (d) vacuum treatment, and (e) a variety of miscellaneous processes.

Brief Dipping

It is a common practice to treat window sash, frames, and other millwork, either before or after assembly, by dipping the item in a water-repellent preservative.

In some cases, preservative oil penetrates the end surfaces of ponderosa pine sapwood as much as 25 to 76 mm (1 to 3 in.). However, end penetration in such woods as the heartwood of southern pines and Douglas-fir is much less. Transverse penetration of the preservative applied by brief dipping is very shallow, usually less than a millimeter (a few hundredths of an inch). The exposed end surfaces at joints are the most vulnerable to decay in millwork products; therefore, good end penetration is especially advantageous. Dip applications provide very limited protection to wood

used in contact with the ground or under very moist conditions, and they provide very limited protection against attack by termites. However, they do have value for exterior woodwork and millwork that is painted, not in contact with the ground, and exposed to moisture only for brief periods.

Cold Soaking and Steeping

The methods of cold soaking well-seasoned wood for several hours or days in low-viscosity preservative oils or steeping green or seasoned wood for several days in waterborne preservatives have provided a range of success on fence posts, lumber, and timbers.

Pine posts treated by cold soaking for 24 to 48 h or longer in a solution containing 5% of pentachlorophenol in No. 2 fuel oil have shown an average life of 16 to 20 years or longer. The sapwood in these posts was well penetrated, and preservative solution retention levels ranged from 32 to 96 kg m⁻³ (2 to 6 lb in⁻³). Most species do not treat as satisfactorily as do the pines by cold soaking, and test posts of such woods as birch, aspen, and sweetgum treated by this method have failed in much shorter times.

Preservative penetration and retention levels obtained by cold soaking lumber for several hours are considerably better than those obtained by brief dipping of similar species. However, preservative retention levels seldom equal those obtained in pressure treatment except in cases such as sapwood of pines that has become highly absorptive through mold and stain infection.

Steeping with waterborne preservatives has very limited use in the United States but it has been used for many years in Europe. In treating seasoned wood, both the water and the preservative salt in the solution soak into the wood. With green wood, the preservative enters the water-saturated wood by diffusion. Preservative retention and penetration levels vary over a wide range, and the process is not generally recommended when more reliable treatments are practical.

Diffusion Processes

In addition to the steeping process, diffusion processes are used with green or wet wood. These processes employ waterborne preservatives that will diffuse out of the water of the treating solution or paste into the water of the wood.

The double-diffusion process developed by the Forest Products Laboratory has shown very good results in fence post tests and standard 38- by 89-mm (nominal 2- by 4-in.) stake tests, particularly for full-length immersion treatments. This process consists of steeping green or partially seasoned wood first in one chemical solution, then in another. The two chemicals then react in the wood to form a precipitate with low solubility. However, the preservatives evaluated in this process do not currently have EPA registration for use in nonpressure treatments.

Vacuum Process

The vacuum process, or “VAC-VAC” as referred to in Europe, has been used to treat millwork with water-repellent preservatives and construction lumber with waterborne and water-repellent preservatives.

In treating millwork, the objective is to use a limited quantity of water-repellent preservative and obtain retention and penetration levels similar to those obtained by dipping for 3 min. In this treatment, a quick, low initial vacuum is followed by filling the cylinder under vacuum, releasing the vacuum and soaking, followed by a final vacuum. This treatment provides better penetration and retention than the 3-min dip treatment, and the surface of the wood is quickly dried, thus expediting glazing, priming, and painting. The vacuum treatment is also reported to be less likely than dip treatment to leave objectionably high retention levels in bacteria-infected wood referred to as “sinker stock.”

Lumber intended for buildings has been treated by the vacuum process, either with a waterborne preservative or a water-repellent/preservative solution, with preservative retention levels usually less than those required for pressure treatment. The process differs from that used in treating millwork in employing a higher initial vacuum and a longer immersion or soaking period.

In a study by the Forest Products Laboratory, an initial vacuum of -93 kPa (27.5 inHg) was applied for 30 min, followed by a soaking for 8 h, and a final or recovery vacuum of -93 kPa (27.5 inHg) for 2 h. Results of the study showed good penetration of preservative in the sapwood of dry lumber of easily penetrated species such as the pines. However, in heartwood and unseasoned sapwood of pine and heartwood of seasoned and unseasoned coastal Douglas-fir, penetration was much less than that obtained by pressure treatment. Preservative retention was less controllable in vacuum than in empty-cell pressure treatment. Good control over retention levels is possible in vacuum treatment with a waterborne preservative by adjusting concentration of the treating solution.

Miscellaneous Nonpressure Processes

Several other nonpressure methods of various types have been used to a limited extent. Many of these involve the application of waterborne preservatives to living trees. The Boucherie process for the treatment of green, unpeeled poles has been used for many years in Europe. This process involves attaching liquid-tight caps to the butt ends of the poles. Then, through a pipeline or hose leading to the cap, a waterborne preservative is forced under hydrostatic pressure into the pole.

A tire-tube process is a simple adaptation of the Boucherie process used for treating green, unpeeled fence posts. In this treatment, a section of used inner tube is fastened tight around the butt end of the post to make a bag that holds a

solution of waterborne preservative. There are now limitations for application of these processes because of the potential loss of preservative to the soil around the treatment site.

In-Place and Remedial Treatments

In-place treatments may be beneficial both during construction and as part of an inspection and maintenance program. Although cutting or drilling pressure-treated wood during construction is undesirable, it cannot always be avoided. When cutting is necessary, the damage can be partly overcome by a thorough application of copper naphthenate (1% to 2% copper) to the cut surface. This provides a protective coating of preservative on the surface that may slowly migrate into the end grain of the wood. The exposed end-grain in joints, which is more susceptible to moisture absorption, and the immediate area around all fasteners, including drill holes, will require supplemental on-site treatment. A special device is available for pressure-treating bolt holes that are bored after treatment. For treating the end surfaces of piles where they are cut off after driving, at least two generous coats of copper naphthenate should be applied. A coat of asphalt or similar material may be thoroughly applied over the copper naphthenate, followed by some protective sheet material, such as metal, roofing felt, or saturated fabric, fitted over the pile head and brought down the sides far enough to protect against damage to the treatment and against the entrance of storm water. AWPA Standard M4 contains instructions for the care of pressure-treated wood after treatment.

Surface Applications

The simplest treatment is to apply the preservative to the wood with a brush or by spraying. Preservatives that are thoroughly liquid when cold should be selected, unless it is possible to heat the preservative. When practical, the preservative should be flooded over the wood rather than merely painted. Every check and depression in the wood should be thoroughly filled with the preservative, because any untreated wood left exposed provides ready access for fungi. Rough lumber may require as much as 40 L of preservative per 100 m² (10 gallons per 1,000 ft²) of surface, but surfaced lumber requires considerably less. The transverse penetration obtained will usually be less than 2.5 mm (0.1 in.), although in easily penetrated species, end-grain (longitudinal) penetration is considerably greater. The additional life obtained by such treatments over that of untreated wood will be affected greatly by the conditions of service. For wood in contact with the ground, service life may be from 1 to 5 years.

For brush or spray applications, copper naphthenate in oil is the preservative that is most often used. The solution should contain 1% to 2% elemental copper. Copper naphthenate is available as a concentrate or in a ready-to-use solution in gallon and drum containers. Borate solutions can also be sprayed or brushed into checks or splits. However, because they are not fixed to the wood they can be leached during

subsequent precipitation. Borates are sold either as concentrated liquids (typically formulated with glycol) or as powders that can be diluted with water.

Another type of surface treatment is the application of water-soluble pastes containing combinations of copper naphthenate, copper quinolinolate, copper hydroxide, or borates. The theory with these treatments is that the diffusible components (such as boron) will move through the wood, while the copper component remains near the surface of a void or check. These pastes are most commonly used to help protect the ground-line area of poles. After the paste is applied, it is covered with a wrap to hold the paste against the pole and prevent loss into the soil. In bridge piles this type of paste application should be limited to terrestrial piles that will not be continually or frequently exposed to standing water. These pastes may also be effective if used under cap beams or covers to protect exposed end-grain. Reapplication schedules will vary based on the manufacturers recommendations as well as the method and area of application.

Internal Diffusible Treatments

Surface-applied treatments often do not penetrate deeply enough to protect the inner portions of large wooden members. An alternative to surface-applied treatments is installation of internal diffusible chemicals. These diffusible treatments are available in liquid, solid, or paste form and are applied into treatment holes that are drilled deeply into the wood. They are similar (and in some cases identical) to the surface-applied treatments or pastes. Boron is the most common active ingredient, but fluoride and copper have also been used. In timbers, deep holes are drilled perpendicular to the upper face on either side of checks. In round piles, steeply sloping holes are drilled across the grain to maximize the chemical diffusion and minimize the number of holes needed. The treatment holes are plugged with tight fitting treated wooden plugs or removable plastic plugs. Plugs with grease fittings are also available so that the paste can be reapplied without removing the plug.

Solid rod treatments have advantages in environmentally sensitive areas or in applications where the treatment hole can only be drilled at an upward angle. However, the chemical may not diffuse as rapidly or for as great a distance as compared to a liquid form. Solid forms may be less mobile because diffusible treatments require moisture to move through wood. Concentrated liquid borates may also be poured into treatment holes and are sometimes used in conjunction with the rods to provide an initial supply of moisture. When the moisture content falls below 20%, little chemical movement occurs, but fortunately growth of decay fungi is substantially arrested below 30% moisture. Because there is some risk that rods installed in a dry section of a timber would not diffuse to an adjacent wet section, some experience in proper placement of the treatment holes is necessary. The diffusible treatments do not move as far in the wood as do fumigants, and thus the treatment holes must

be spaced more closely. A study of borate diffusion in timbers of several wood species reported that diffusion along the grain was generally less than 12 cm (5 in.), and diffusion across the grain was typically less than 5 cm (2 in.).

Internal Fumigant Treatments

As with diffusibles, fumigants are applied in liquid or solid form in predrilled holes. However, they then volatilize into a gas that moves through the wood. To be most effective, a fumigant should be applied at locations where it will not readily volatilize out of the wood to the atmosphere. When fumigants are applied, the timbers should be inspected thoroughly to determine an optimal drilling pattern that avoids metal fasteners, seasoning checks, and severely rotted wood. In vertical members such as piles, holes to receive liquid fumigant should be drilled at a steep angle (45° to 60°) downward toward the center of the member, avoiding seasoning checks. The holes should be no more than 1.2 m (4 ft) apart and arranged in a spiral pattern. With horizontal timbers, the holes can be drilled straight down or slanted. As a rule, the holes should be extended to within about 5 cm (2 in.) of the bottom of the timber. If strength is not jeopardized, holes can be drilled in a cluster or in pairs to accommodate the required amount of preservative. If large seasoning checks are present, the holes should be drilled on each side of the member to provide better distribution. As soon as the fumigant is injected, the hole should be plugged with a tight-fitting treated wood dowel or removable plastic plug. For liquid fumigants, sufficient room must remain in the treating hole so the plug can be driven without displacing the chemical out of the hole. The amount of fumigant needed and the size and number of treating holes required depends upon the timber size. Fumigants will eventually diffuse out of the wood, allowing decay fungi to recolonize. Fortunately, additional fumigant can be applied to the same treatment hole. Fumigant treatments are generally more toxic and more difficult to handle than are diffusible treatments. Some are classified as restricted-use pesticides by the U.S. EPA.

One of the oldest and most effective fumigants is chloropicrin (trichloronitromethane). Chloropicrin is a liquid and has been found to remain in wood for up to 20 years; however, a 10-year retreatment cycle is recommended, with regular inspection. Chloropicrin is a strong eye irritant and has high volatility. Due to chloropicrin's hazardous nature, it should be used in areas away from buildings permanently inhabited by humans or animals. During application, workers must wear protective gear, including a full face respirator. Methylisothiocyanate (MITC) is the active ingredient in several fumigants, but is also available in a solid-melt form that is 97% active. The solid-melt MITC is supplied in aluminum tubes. After the treatment hole is drilled the cap is removed from the tube, and the entire tube is placed into the whole. This formulation provides ease of handling and application to upward drilled sloping treatment holes. Metham sodium (sodium N-methyldithiocarbamate) is a widely used

liquid fumigant that decomposes in the wood to form the active ingredient MITC. Granular dazomet (tetrahydro-3,5-dimethyl-2-H-1,3,5, thiazine-6-thione) is applied in a solid granular form that decomposes to a MITC content of approximately 45%. Dazomet is easy to handle but slower to decompose and release MITC than the solid-melt MITC or liquid fumigants. Some suppliers recommend the addition of a catalyst such as copper naphthenate to accelerate the breakdown process.

Best Management Practices

The active ingredients of various waterborne wood preservatives (copper, chromium, arsenic, and zinc) are water soluble in the treating solution but resist leaching when placed into the wood. This resistance to leaching is a result of chemical stabilization (or fixation) reactions that render the toxic ingredients insoluble in water. The mechanism and requirements for the stabilization reactions differ, depending on the type of wood preservative.

For each type of preservative, some reactions occur very rapidly during pressure treatment, while others may take days or even weeks, depending on storage and processing after treatment. If the treated wood is placed in service before these fixation reactions have been completed, the initial release of preservative into the environment may be much greater than if the wood has been conditioned properly.

With oil-type preservatives, preservative bleeding or oozing out of the treated wood is a particular concern. This problem may be apparent immediately after treatment. Such members should not be used in bridges over water or other aquatic applications. In other cases, the problem may not become obvious until after the product has been exposed to heating by direct sunlight. This problem can be minimized by using treatment practices that remove excess preservative from the wood.

Best management practice (BMP) standards have been developed to ensure that treated wood is produced in a way that will minimize environmental concerns. The Western Wood Preservers Institute (WWPI) has developed guidelines for treated wood used in aquatic environments. Although these practices have not yet been adopted by the industry in all areas of the United States, purchasers can require that these practices be followed. Commercial wood treatment firms are responsible for meeting conditions that ensure stabilization and minimize bleeding of preservatives, but persons buying treated wood should make sure that the firms have done so.

Consumers can take steps to ensure that wood will be treated according to the BMPs. Proper stabilization may take time, and material should be ordered well before it is needed so that the treater can hold the wood while it stabilizes. If consumers order wood in advance, they may also be able to store it under cover, allowing further drying and fixation. In general, allowing the material to air dry before it is used is

a good practice for ensuring fixation, minimizing leaching, and reducing risk to construction personnel. With all preservatives, the wood should be inspected for surface residue, and wood with excessive residue should not be placed in service.

CCA

The risk of chemical exposure from wood treated with CCA is minimized after chemical fixation reactions lock the chemical in the wood. The treating solution contains hexavalent chromium, but the chromium reduces to the less toxic trivalent state within the wood. This process of chromium reduction also is critical in fixing the arsenic and copper in the wood. Wood treated with CCA should not be immersed or exposed to prolonged wetting until the fixation process is complete or nearly complete. The rate of fixation depends on temperature, taking only a few hours at 66 °C (150 °F) but weeks or even months at temperatures below 16 °C (60 °F). Some treatment facilities use kilns, steam, or hot-water baths to accelerate fixation.

The BMP guideline for CCA stipulates that the wood should be air seasoned, kiln dried, steamed, or subjected to a hot-water bath after treatment. It can be evaluated with the AWPA chromotropic acid test to determine whether fixation is complete.

ACZA and ACQ–B

The key to achieving stabilization with ACZA and ACQ–B is to allow ammonia to volatilize. This can be accomplished by air or kiln drying. The BMPs require a minimum of 3 weeks of air drying at temperatures higher than 16 °C (60 °F). Drying time can be reduced to 1 week if the material is conditioned in the treatment cylinder. At lower temperatures, kiln drying or heat is required to complete fixation. There is no commonly used method to determine the degree of stabilization in wood treated with ACZA or ACQ–B, although wood that has been thoroughly dried is acceptable. If the wood has a strong ammonia odor, fixation is not complete.

ACQ–C, ACQ–D, and Copper Azole

Proper handling and conditioning of the wood after treatment helps minimize leaching and potential environmental impacts for these preservatives. Amine (and ammonia in some cases) keeps copper soluble in these treatment solutions. The mechanism of copper's reaction in the wood is not completely understood but appears to be strongly influenced by time, temperature, and retention levels. As a general rule, wood that has been thoroughly dried after treatment is properly stabilized.

Copper stabilization in the copper azole CA–B formulation is extremely rapid (within 24 h) at the UC3B retention of 1.7 kg m⁻³ (0.10 lb ft⁻³) but slows considerably at higher retentions unless the material is heated to accelerate fixation.

Pentachlorophenol, Creosote, and Copper Naphthenate

For creosote, the BMPs stipulate use of an expansion bath and final steaming period at the end of the charge.

Expansion Bath—Following the pressure period, the creosote should be heated to a temperature 6 to 12 °C (10 to 20 °F) above the press temperatures for at least 1 h. Creosote should be pumped back to storage and a minimum gauge vacuum of –81 kPa (24 inHg) should be applied for at least 2 h.

Steaming—After the pressure period and once the creosote has been pumped back to the storage tank, a vacuum of not less than –74 kPa (22 inHg) is applied for at least 2 h to recover excess preservative. The vacuum is then released back to atmospheric pressure and the charge is steamed for 2 to 3 h. The maximum temperature during this process should not exceed 116 °C (240 °F). A second vacuum of not less than –74 kPa (22 inHg) is then applied for a minimum of 4 h.

The BMPs for copper naphthenate are similar to those for creosote and pentachlorophenol. The recommended treatment practices for treatment in heavy oil include using an expansion bath, or final steaming, or both, similar to that described for creosote. When No. 2 fuel oil is used as the solvent, the BMPs recommend using a final vacuum for at least 1 h.

Handling and Seasoning of Timber after Treatment

Treated timber should be handled with sufficient care to avoid breaking through the treated shell. The use of pikes, cant hooks, picks, tongs, or other pointed tools that dig deeply into the wood should be prohibited. Handling heavy loads of lumber or sawn timber in rope or cable slings can crush the corners or edges of the outside pieces. Breakage or deep abrasions can also result from throwing or dropping the lumber. If damage results, the exposed areas should be retreated, if possible.

Wood treated with preservative oils should generally be installed as soon as practicable after treatment to minimize lateral movement of the preservative, but sometimes cleanliness of the surface can be improved by exposing the treated wood to the weather for a limited time before installation. Lengthy, unsheltered exterior storage of treated wood before installation should be avoided. Treated wood that must be stored before use should be covered for protection from the sun and weather.

With waterborne preservatives, seasoning after treatment is important for wood that will be used in buildings or other places where shrinkage after placement in the structure would be undesirable. Injecting waterborne preservatives puts large amounts of water into the wood, and considerable shrinkage is to be expected as subsequent seasoning takes place. For best results, the wood should be dried to

approximately the moisture content it will ultimately reach in service. During drying, the wood should be carefully piled and, whenever possible, restrained by sufficient weight on the top of the pile to prevent warping.

Quality Assurance for Treated Wood

Treating Conditions and Specifications

Specifications on the treatment of various wood products by pressure processes have been developed by AWWA. These specifications limit pressures, temperatures, and time of conditioning and treatment to avoid conditions that will cause serious injury to the wood. The specifications also contain minimum requirements for preservative penetration and retention levels and recommendations for handling wood after treatment to provide a quality product. Specifications are broad in some respects, allowing the purchaser some latitude in specifying the details of individual requirements. However, the purchaser should exercise great care so as not to hinder the treating plant operator from doing a good treating job and not to require treating conditions so severe that they will damage the wood.

Penetration and Retention

Penetration and retention requirements are equally important in determining the quality of preservative treatment. Penetration levels vary widely, even in pressure-treated material. In most species, heartwood is more difficult to penetrate than sapwood. In addition, species differ greatly in the degree to which their heartwood may be penetrated. Incising tends to improve penetration of preservative in many refractory species, but those highly resistant to penetration will not have deep or uniform penetration even when incised. Penetration in unincised heartwood faces of these species may occasionally be as deep as 6 mm (1/4 in.) but is often not more than 1.6 mm (1/16 in.).

Experience has shown that even slight penetration has some value, although deeper penetration is highly desirable to avoid exposing untreated wood when checks occur, particularly for important members that are costly to replace. The heartwood of coastal Douglas-fir, southern pines, and various hardwoods, although resistant, will frequently show transverse penetrations of 6 to 12 mm (1/4 to 1/2 in.) and sometimes considerably more.

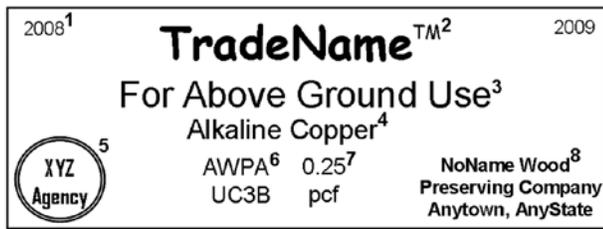
Complete penetration of the sapwood should be the goal in all pressure treatments. It can often be accomplished in small-size timbers of various commercial woods, and with skillful treatment, it may often be obtained in piles, ties, and structural timbers. Practically, however, the operator cannot always ensure complete penetration of sapwood in every piece when treating large pieces of round material with thick sapwood (such as poles and piles). Therefore, specifications permit some tolerance. For instance, AWWA Processing and Treatment Standard T1 for Southern Pine poles requires that 89 mm (3.5 in.) or 90% of the sapwood thickness be

penetrated for waterborne preservatives. The requirements vary, depending on the species, size, class, and specified retention levels.

Preservative retentions are typically expressed on the basis of the mass of preservative per unit volume of wood within a prescribed assay zone. The retention calculation is not based on the volume of the entire pole or piece of lumber. For example, the assay zone for Southern Pine poles is between 13 and 51 mm (0.5 and 2.0 in.) from the surface. To determine the retention, a boring is removed from the assay zone and analyzed for preservative concentration. The preservatives and retention levels listed in the AWWA Commodity Standards and ICC-ES evaluation reports are shown in Table 15-1. The current issues of these specifications should be referenced for up-to-date recommendations and other details. In many cases, the retention level is different depending on species and assay zone. Higher preservative retention levels are specified for products to be installed under severe climatic or exposure conditions. Heavy-duty transmission poles and items with a high replacement cost, such as structural timbers and house foundations, are required to be treated to higher retention levels. Correspondingly, deeper penetration or heartwood limitations are also necessary for the same reasons. It may be necessary to increase retention levels to ensure satisfactory penetration, particularly when the sapwood is either unusually thick or is somewhat resistant to treatment. To reduce bleeding of the preservative, however, it may be desirable to use preservative-oil retention levels less than the stipulated minimum. Older specifications based on treatment to refusal do not ensure adequate penetration or retention of preservative, should be avoided, and must not be considered as a substitute for results-type specification in treatment.

Inspection of Treatment Quality

AWWA standards specify how charges of treated wood should be inspected to ensure conformance to treatment standards. Inspections are conducted by the treating company and also should be routinely conducted by independent third-party inspection agencies. These third-party agencies verify for customers that the wood was properly treated in accordance with AWWA standards. The U.S. Department of Commerce American Lumber Standard Committee (ALSC) accredits third-party inspection agencies for treated-wood products. Quality control overview by ALSC-accredited agencies is preferable to simple treating plant certificates or other claims of conformance made by the producer without inspection by an independent agency. Updated lists of accredited agencies can be obtained from the ALSC website at www.alsc.org. Each piece of treated wood should be marked with brand, ink stamp, or end-tag that shows the logo of an accredited inspection agency and other information required by AWWA standards (Fig. 15-6). Other important information that should be shown includes the type of preservative, preservative retention, and the intended use category



¹ Year(s) of treatment

² Tradename of preservative treatment

³ Intended end-use

⁴ Standard name of preservative

⁵ Third party inspection agency

⁶ AWPA Use Category

⁷ Retention of Preservative in wood

⁸ Treating company

Figure 15–6. Typical end tag for preservative-treated lumber conforming to the ALSC accreditation program.

(exposure condition). Purchasers may also elect to have an independent inspector inspect and analyze treated products to ensure compliance with the specifications—recommended for treated-wood products used for critical structures. Railroad companies, utilities, and other entities that purchase large quantities of treated timber usually maintain their own inspection services.

Effects on the Environment

Preservatives intended for use outdoors have mechanisms that are intended to keep the active ingredients in the wood and minimize leaching. Past studies indicate that a small percentage of the active ingredients of all types of wood preservatives leach out of the wood. The amount of leaching depends on factors such as fixation conditions, preservative retention in the wood, product size and shape, type of exposure, and years in service. Ingredients in all preservatives are potentially toxic to a variety of organisms at high concentrations, but laboratory studies indicate that the levels of preservatives leached from treated wood generally are too low to create a biological hazard.

In recent years, several studies have been conducted on preservative releases from structures and on the environmental consequences of those releases. These recent studies of the environmental impact of treated wood reveal several key points. All types of treated wood evaluated release small amounts of preservative components into the environment. These components can sometimes be detected in soil or sediment samples. Shortly after construction, elevated levels of preservative components can sometimes be detected in the water column. Detectable increases in soil and sediment concentrations of preservative components generally are limited to areas close to the structure. Leached preservative components either have low water solubility or react with components of the soil or sediment, limiting their

mobility and limiting the range of environmental contamination. Levels of these components in the soil immediately adjacent to treated structures can increase gradually over the years, whereas levels in sediments tended to decline over time. Research indicates that environmental releases from treated wood do not cause measurable impacts on the abundance or diversity of aquatic invertebrates adjacent to the structures. In most cases, levels of preservative components were below concentrations that might be expected to affect aquatic life. Samples with elevated levels of preservative components tended to be limited to fine sediments beneath stagnant or slow-moving water where the invertebrate community is not particularly intolerant to pollutants.

Conditions with a high potential for leaching and a high potential for metals to accumulate are the most likely to affect the environment (Fig. 15–7). These conditions are most likely to be found in boggy or marshy areas with little water exchange. Water at these sites has low pH and high organic acid content, increasing the likelihood that preservatives will be leached from the wood. In addition, the stagnant water prevents dispersal of any leached components of preservatives, allowing them to accumulate in soil, sediments, and organisms near the treated wood. Note that all construction materials, including alternatives to treated wood, have some type of environmental impact. In addition to environmental releases from leaching and maintenance activities, the alternatives may have greater impacts and require greater energy consumption during production.

Recycling and Disposal of Treated Wood

Treated wood is not listed as a hazardous waste under Federal law, and it can be disposed of in any waste management facility authorized under State and local law to manage such material. State and local jurisdictions may have additional regulations that impact the use, reuse, and disposal of treated wood and treated-wood construction waste, and users should check with State and local authorities for any special regulations relating to treated wood. Treated wood must not be burned in open fires or in stoves, fireplaces, or residential boilers, because the smoke and ashes may contain toxic chemicals.

Treated wood from commercial and industrial uses (construction sites, for example) may be burned only in commercial or industrial incinerators or boilers in accordance with State and Federal regulations. Spent railroad ties treated with creosote and utility poles treated with pentachlorophenol can be burned in properly equipped facilities to generate electricity (cogeneration). As fuel costs and energy demands increase, disposal of treated wood in this manner becomes more attractive. Cogeneration poses more challenges for wood treated with heavy metals, and particularly for wood treated with arsenic. In addition to concerns with emissions, the concentration of metals in the ash requires further processing.



Figure 15–7. Wood preservative leaching, environmental mobility, and effects on aquatic insects were evaluated at this wetland boardwalk in western Oregon.

As with many materials, reuse of treated wood may be a viable alternative to disposal. In many situations treated wood removed from its original application retains sufficient durability and structural integrity to be reused in a similar application. Generally, regulatory agencies also recognize that treated wood can be reused in a manner that is consistent with its original intended end use.

The potential for recycling preservative-treated wood depends on several factors, including the type of preservative treatment and the original use. Researchers have demonstrated that wood treated with heavy metals can be chipped or flaked and reused to form durable panel products or wood–cement composites. However, this type of reuse has not yet gained commercial acceptance. Techniques for extraction and reuse of the metals from treated wood have also been proposed. These include acid extraction, fungal degradation, bacterial degradation, digestion, steam explosion, or some combination of these techniques. All these approaches show some potential, but none is currently economical. In most situations landfill disposal remains the least expensive option. For treated wood used in residential construction, one of the greatest obstacles is the lack of an efficient process for collecting and sorting treated wood. This is less of a problem for products such as railroad ties and utility poles.

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Finishing of Wood

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Wood finishes (paint, varnish, and stain, for example) give a desired appearance, protect wood surfaces, and provide a cleanable surface. Many people consider *appearance* most important when choosing finishes for wood (lumber and wood composites). However, from a technical aspect, *protection* is most important for wood used outdoors, and providing a *cleanable surface* is most important for wood used indoors. When selecting a finish, one should consider appearance, protection, and cleanability and also how bulk and surface properties of wood affect finish application and performance (how long a finish lasts—its service life).

Wood properties such as density (specific gravity), growth rate, heartwood–sapwood, earlywood–latewood, grain angle, vessels, and texture vary within and across wood species. Wood composites, such as plywood, fiberboard, and oriented strandboard (OSB), have different properties. Of the 18,000 to 25,000 known wood species (exact number varies depending on the grouping of species), approximately 50 are commercial species used in the United States and Canada. Chapters 2–4 give their properties. Of these commercial species, researchers report finishing characteristics for only a few species common to North America, Europe, Japan, and the tropics. However, if one understands how wood properties, finish, and environmental conditions interact, it should be possible to estimate finish performance for most wood species.

Performance depends on choosing an appropriate finish for wood, considering the use conditions, and applying finishes correctly in sufficient amount. For long service life, choose wood products and finishes appropriate for environments where they are used. Indoor use places less stress on finishes than outdoor use. A climate having severe seasonal changes (U.S. Upper Midwest, for example) places greater stress on finishes than does a mild climate (such as the Pacific Northwest).

Guidelines in this chapter explain how to obtain long service life for contemporary finishes on lumber and wood composites used in the United States and Canada. The chapter begins with a review of wood properties important for wood finishing and describes effects of water and weathering on wood and finishes. This background establishes a basis for describing finishes for wood, their application, and common types of finish failures (and ways to avoid them). Publications listed at the end of this chapter provide additional information.

Factors Affecting Finish Performance

Wood surface properties, type of wood product, and weather affect finish performance.

Wood Surface Properties

Wood anatomy, manufacturing processes, moisture content (MC), dimensional change, extractives, and changes as wood ages determine wood surface properties.

Anatomy

Wood species (thus its anatomy) is the primary factor that determines surface properties of wood—properties that affect adhesion and performance of finishes. Wood anatomy determines whether a wood species is a hardwood or softwood, not the density (specific gravity) or its hardness. Finish performance is affected by

- density (overall density, earlywood (EW)–latewood (LW) density difference, and how abruptly density changes at the EW–LW boundary),
- thickness of LW bands,
- ray cells (number and placement),
- vessels (size and location),
- extractives content, and
- growth rate (some species grow faster than others, and environment affects growth rate within a specific species).

Most wood cells (called tracheids in softwoods, fibers in hardwoods) align parallel (axial) to the stem or branch. Softwood tracheids support the tree and transport water and nutrients. Hardwood fibers just support the tree; hardwoods have special cells (vessels) for transporting water and nutrients. Vessel cells are open at each end and stacked to form “pipes.” Axial tracheids and fibers are hollow tubes closed at each end. In softwoods, liquids move in the axial direction by flowing from one tracheid to another through openings called pits. Liquid transport between the bark and center of the stem or branch in hardwoods and softwoods is by ray cells. Figures 16–1 to 16–3 are micrographs showing the orientation of axial and ray cells for white spruce, red oak, and red maple, respectively. Note that the softwood (Fig. 16–1) has no vessels. The large openings are resin canal complexes (common to spruce, pine, larch, and Douglas-fir). Figure 16–2 shows red oak, a ring-porous hardwood. Large-diameter vessels in ring-porous species form along with EW; later in the growing season, the vessels have smaller diameters. Figure 16–3 shows red maple, a diffuse-porous hardwood; small vessels having similar size form throughout the EW and LW. Hardwoods can also be semi-ring porous.

Axial and ray cells form in the cambium, a layer of cells just under the bark. In the early part of the growing season

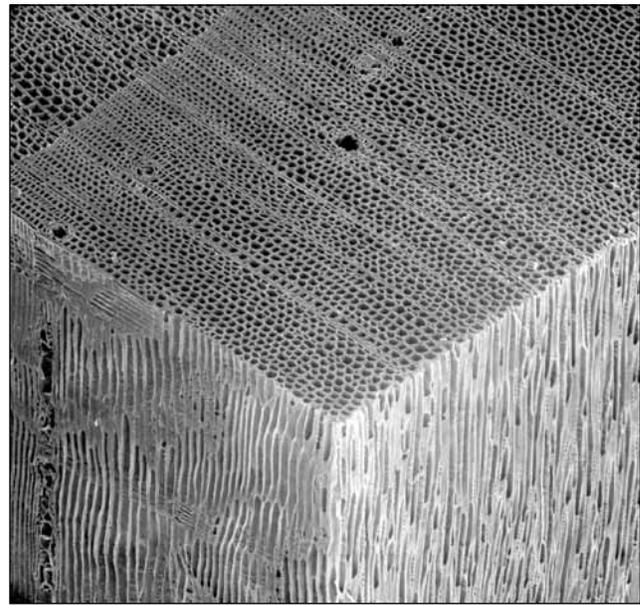


Figure 16–1. Micrograph of white spruce showing gradual transition of cell wall thickness and resin canal complexes. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

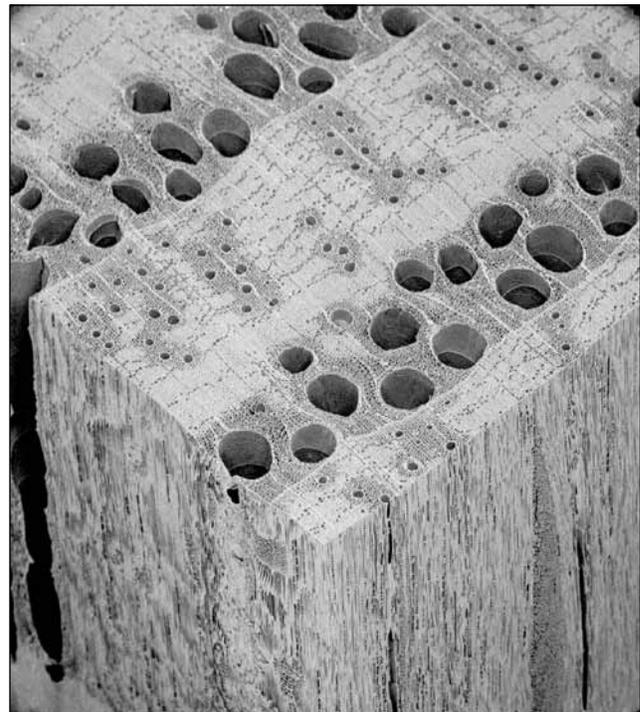


Figure 16–2. Micrograph of red oak showing ring-porous vessels. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

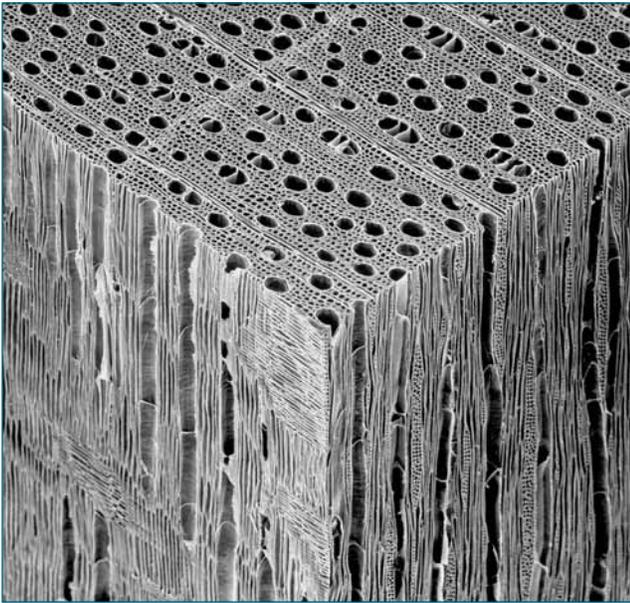


Figure 16–3. Micrograph of red maple showing diffuse-porous vessels. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

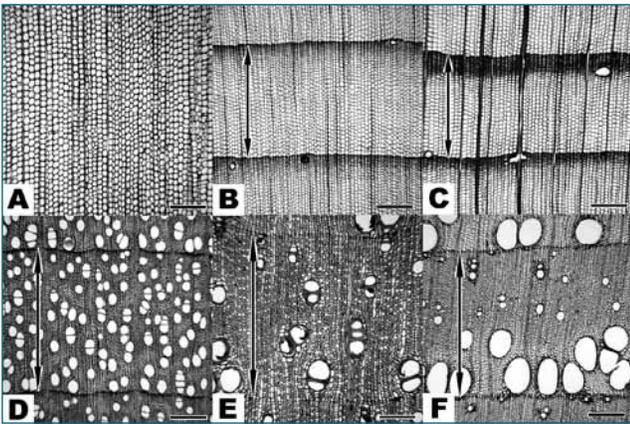


Figure 16–4. Cross-section micrographs of (A) a tropical softwood (*Podocarpus imbricate*), (B) white spruce (*Picea glauca*), (C) Douglas-fir, *Pseudotsuga menziesii* (D) sugar maple (*Acer saccharum*), (E) persimmon (*Diospyros virginiana*), and (F) white ash (*Fraxinus americana*). The arrows show a single growth year for the temperate species.

(temperate species), the cells have large open centers (lumens) and thin cell walls. This is earlywood (also called springwood). As the growing season progresses, cell walls become thicker, forming latewood (also called summerwood). The combination of EW–LW (and vessels in hardwoods) gives annual growth rings. The properties of these growth rings affect the ease with which finishes can be applied (paintability) and how long finishes last (service life).

Cross-section micrographs of three softwoods and hardwoods (Fig. 16–4) show three types of growth characteristics. Softwoods may show “no transition” (no EW–LW boundary, Fig. 16–4a), gradual transition (Fig. 16–4b), or abrupt transition (Fig. 16–4c). Note: the “no transition” softwood is a tropical species (that is, no seasons, therefore no EW–LW transition). Hardwoods may be diffuse porous (Fig. 16–4d), semi-ring porous (Fig. 16–4e), or ring porous (Fig. 16–4f). As a first approximation for explaining finishing characteristics of wood, the various wood species can be grouped into three categories:

- Easy to finish (“no transition” or gradual-transition softwoods and diffuse-porous hardwoods)
- Moderately easy to finish (abrupt-transition softwoods having narrow LW bands and semi-ring-porous hardwoods)
- Difficult to finish (abrupt-transition softwoods having wide LW bands and ring-porous hardwoods)

The important message from wood anatomy is to look at the wood. The six micrographs showing end-grain wood-cell structure do not include all possible combinations of growth rate, grain, and surface texture. When determining paintability, look at grain angles. Look at the width of the LW bands and the transition between them (Fig. 16–5). The blocks show radial and tangential surfaces (that is, vertical- and flat-grain surfaces for six softwoods and quarter-sawn and flat-sawn for two hardwoods). Note the abrupt transitions on the southern yellow pine and Douglas-fir and the gradual transitions on the western redcedar and white pine. Also, note the growth rate and width of the LW bands. Surfaces having abrupt transition, rapid growth rate, and wide LW bands are difficult to finish, particularly on flat-grain wood. Moisture-induced dimensional change increases as wood density increases. Changes are greater for LW than EW. Different dimensional change for abrupt-transition (or ring-porous) species at the EW–LW boundary places stress on coatings.

Shrinkage values given in Table 16–1 were obtained from drying wood from its green state (fiber saturation) to oven-dry (0% MC); swelling rates would be approximately the same. Some species have wide bands of EW and LW. These distinct bands often lead to early paint failure. Wide, prominent bands of LW are characteristic of the southern yellow pines, radiata pine, and Douglas-fir (Fig. 16–5a,b,c), and getting good paint performance is more difficult on these species. In contrast, white pine, redwood, and western redcedar (Fig. 16–5d,e,f) do not have wide LW bands, and these species give excellent paint performance. Diffuse-porous hardwoods such as aspen (Fig. 16–5g) have a fine surface texture and are easy to finish, whereas red oak (Fig. 16–5h) has a highly textured surface and requires surface preparation prior to finishing.

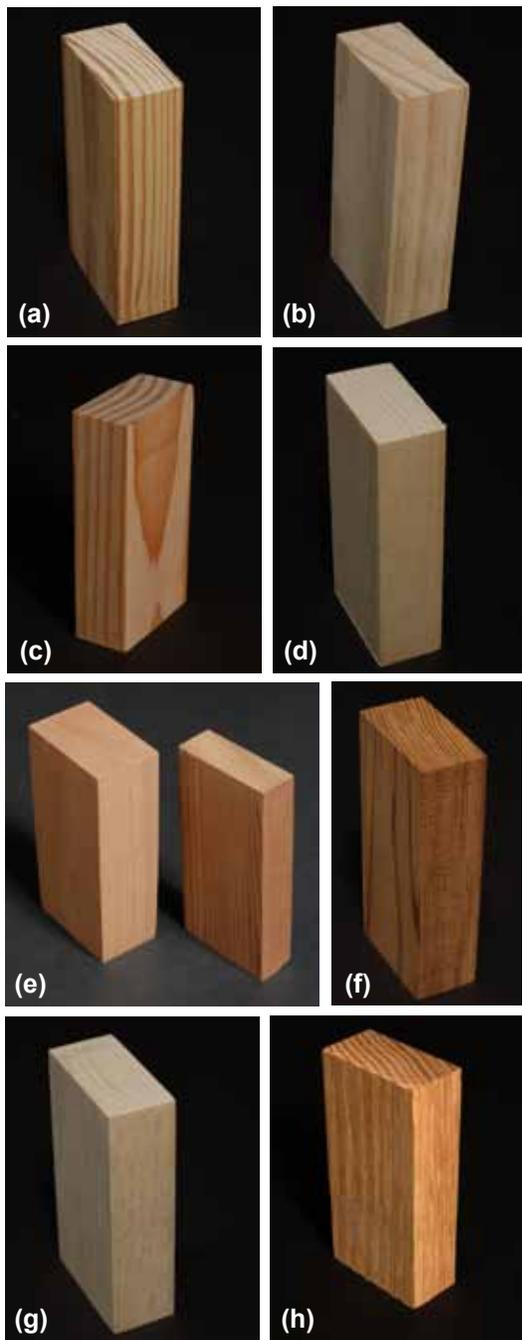


Figure 16–5. Wide LW bands characteristic of (a) the southern yellow pines, (b) radiata pine, and (c) Douglas-fir and narrow LW bands characteristic of (d) white pine, (e) redwood, and (f) western redcedar; (g) and (h) are examples of the difference in surface texture between diffuse-porous and ring porous hardwoods, respectively; (e) shows examples of second or third growth (left) and old-growth (right) redwood.

Fifty years ago, most exterior siding and trim were vertical-grain heartwood of western redcedar or redwood. All-heartwood vertical-grain grades of these species are still available as resawn bevel siding and lumber and are excellent wood substrates for painting (Table 16–1). Other species are generally available only as flat-grain or a mix of flat- and vertical-grain lumber (for example, western hemlock, eastern white pine, lodgepole pine, eastern white cedar, radiata pine, and southern yellow pine). Finishing characteristics of flat-grain western redcedar and redwood are similar to other low-density wood species having moderate EW–LW transition (such as eastern white pine, eastern white cedar, and yellow poplar) Sawing to yield vertical grain is only practical with fairly large-diameter logs. Species available in small-diameter logs yield mostly flat-grain lumber.

Other wood properties, such as knots, juvenile wood, and extractives, affect wood finishing. Extractives include many chemicals with different solubilities in water, organic solvents, and paint resins (also called binders).

Manufacturing

The axial EW and LW cells in a log yield lumber of various grain angles (Fig. 16–6). At one extreme (board a), the growth rings are perpendicular to the plane of the board; at the other extreme (board c), growth rings are parallel to the plane of the board (although they have an arc). Grain varies between these two extremes. Vertical-grain lumber has a grain angle from 90° (growth rings perpendicular to surface) to approximately 45°. From 45° to the other extreme (board c), lumber is considered flat grain. Board b is different. Lumber cut close to the pith (the center of the log) contains abnormal wood cells. These abnormal cells are juvenile wood and have extremely high longitudinal dimensional change (2%) compared with normal wood (0.1–0.2%). The values are the change from green to oven-dry (see Chap. 4). A 10-ft (3-m) board could shrink 2.4 in. (61 mm). This dimensional instability leads to severe warping and cross-grain checking in lumber containing juvenile wood (see Chap. 5).

The bark side and pith side of flat-grain or flat-sawn lumber have slightly different properties. The pith side is more prone to have raised grain than the bark side, particularly with abrupt-transition wood species (southern yellow pine, Douglas-fir, and oak (Table 16–1)). The bark side tends to check more, and the checking is more pronounced in the LW bands.

Table 16–1. Painting characteristics of common wood species

Wood species	Specific gravity ^a (green/dry)	Shrinkage (%) ^b		Paintability ^c (latex paint)	EW/LW transition ^d	Is LW greater than about 1/3 of GR ^e	Color of heartwood
		Tangential	Radial				
Softwoods							
Baldcypress	0.42/0.46	6.2	3.8	II	A	No	Light brown
Cedars				I			
Incense	0.35/0.37	5.2	3.3	I	G	No	Brown
Northern white	0.29/0.31	4.9	2.2	I	G	No	Light brown
Port-Orford	0.39/0.43	6.9	4.6	I	G	No	Cream
Western red	0.31/0.32	5	2.4	I	G	No	Brown
Alaska yellow	0.42/0.44	6	2.8	I	G	No	Yellow
Douglas-fir ^{f,g}	0.45/0.48	7.6	4.8	III	A	Yes	Pale red
Pines							
Eastern white	0.34/0.35	6.1	2.1	I	G	No	Cream
Ponderosa	0.38/0.42	6.2	3.9	II	A	Yes/No	Cream
Southern ^h	0.47/0.51 ^h	8	5	III	A	Yes	Light brown
Western white	0.36/0.38	7.4	4.1	I	G	No	Cream
Radiata	0.45/0.53	7.0	4.2	III	A	Yes/No	Cream
Redwood ⁱ	0.38/0.40	4.4	2.6	I	A	No	Dark brown
Spruce ^j	0.33/0.35	7.1	3.8	I	G	No	White
Tamarack/larch	0.49/0.53	7.4–9.1	3.7–4.5	II	A	Yes/No	Brown
True fir	0.37/0.39	7.0	3.3	I	G	No	White
Western hemlock	0.42/0.45	7.8	4.2	II	G/A	Yes/No	Pale brown
Hardwoods							
Red alder	0.37/0.41	7.3	4.4	I	D	NA	Pale brown
Ash	0.55/0.60	8	5	III	R	Yes	Light brown
Aspen/cottonwood	0.36/0.40	7.0–9.2	3.5–3.9	I	D	NA	Pale brown
Basswood	0.32/0.37	7.8	5.9	I	D	NA	Cream
Beech	0.56/0.64	11.9	5.5	I	D	NA	Pale brown
Birch	0.55/0.62	9.5	7.3	I	D	NA	Light brown
Butternut	0.36/0.38	6.4	3.4	II	SR	Yes	Light brown
Cherry	0.47/0.50	7.1	3.7	I	D	NA	Brown
Chestnut	0.40/0.43	6.7	3.4	III	R	Yes	Light brown
Elm, American	0.46/0.50	9.5	4.2	III	R	Yes	Brown
Hickory	0.64/0.72	11	7	III	R	Yes	Light brown
Maple, sugar	0.56/0.63	9.9	4.8	I	D	NA	Light brown
Oaks							
White oak group	0.60/0.68	8.8	4.4	III	R	Yes	Brown
Red oak group	0.56/0.63	8.6	4.0	III	R	Yes	Brown
Sweetgum	0.46/0.52	10.2	5.3	I	D	NA	Brown
Sycamore	0.46/0.49	8.4	5	I	D	NA	Pale brown
Walnut	0.51/0.55	7.8	5.5	II	SR	Yes	Dark brown
Yellow-poplar	0.40/0.42	8.2	4.6	I	D	NA	Pale brown

^aSpecific gravity based on weight oven-dry and volume at green or 12% moisture content.

^bDimensional change obtained by drying from green to oven-dry. Values reported here are averages from a variety of sources and are provided for comparative purposes. For more specific values, see Chapter 4.

^cI, easy to finish; III, difficult to finish.

^dA, abrupt-transition softwood; G, gradual-transition softwood; R, ring-porous hardwood; D, diffuse-porous hardwood; SR, semi-ring-porous hardwood.

^eGR, growth ring; NA, not applicable; yes/no, depends on the specimen. In ring-porous hardwoods, the growth rate (number of rings per centimeter or inch) will determine the relative proportions of earlywood and latewood.

^fLumber and plywood.

^gCoastal Douglas-fir.

^hLoblolly, shortleaf; specific gravity of 0.54/0.59 for longleaf and slash.

ⁱRedwood is listed as paintability “I” because its LW band is very narrow.

^jSpruce. Values are for Engelmann spruce; other species are similar.

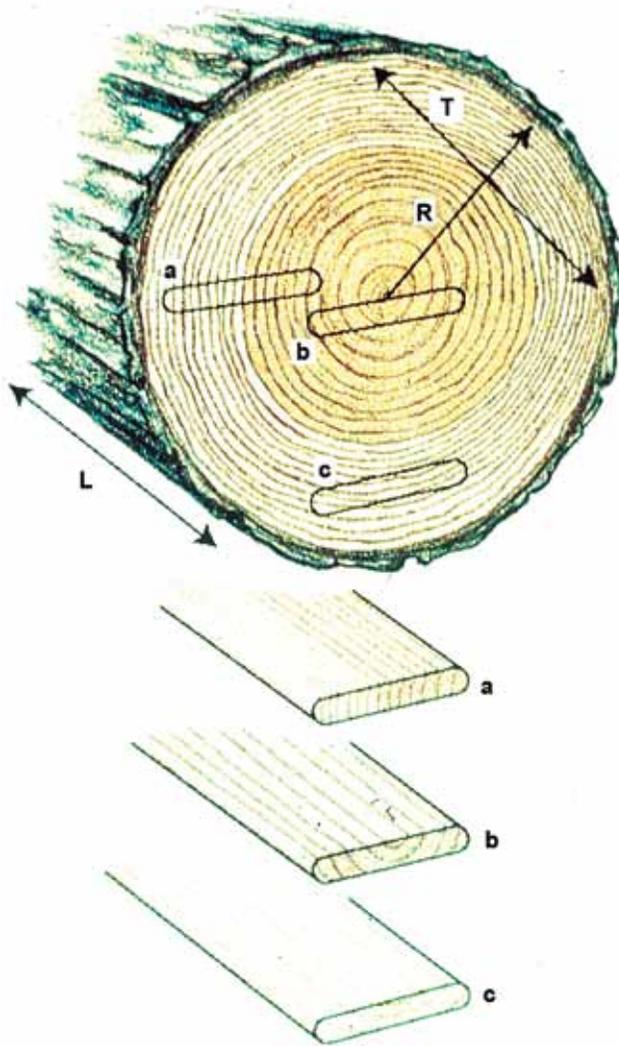


Figure 16-6. Lumber grain affects finish performance: (a) edge-grain (vertical-grain or quarter-sawn) board; (b) edge-grain board containing pith; (c) flat-grain (slash-grain or plain-sawn) board. Arrows show radial (R), tangential (T), and longitudinal (L) orientation of wood grain.

Moisture content

Moisture content (MC) is the amount of water (in any of its forms) contained in wood (see Chap. 4). MC includes water or water vapor absorbed into cell walls and free water within the hollow center of the cells (lumina); it is expressed as weight percentage. The amount of water vapor wood can absorb, depends on wood species; most species can absorb water vapor to increase their mass approximately 30% above an oven-dry MC condition. This water is hydrogen bound within the cell wall matrix of hemicelluloses and, to some extent, cellulose. The limit to the amount of water bound in the wood cell wall is the fiber saturation point.

The amount of water vapor wood absorbs depends on the relative humidity (RH) of the surrounding air. If wood is stored at 0% RH, the MC will eventually approach 0%. If

Moisture

The chemical commonly called water (H_2O) has three states according to temperature and pressure conditions: gas (water vapor or steam), liquid (water), or solid (ice). When water interacts with wood, it can occur in a fourth state (bound water). Moisture is not one of the states of water; it is a term with the power to indicate uncertainty about the water's state, or to refer collectively to water in all its states in wood. For example, some of the moisture in a board at 50% moisture content will occur as liquid water (or ice, depending on the temperature) within cell cavities of the wood, some will occur as water vapor, and some will be bound water (bound within cell walls). Moisture thus accounts for any or all of these states in a single word. In this chapter, the term water designates water in its liquid state.

wood is stored at 100% RH, the MC will eventually reach fiber saturation (approximately 30% moisture). Of course, if kept at a constant RH between these two extremes, wood will stabilize at a MC between 0% and 30%. The RH controls the MC, and when the MC is in balance with the RH, the wood is at its equilibrium moisture content (EMC). This rarely happens because as the RH changes, so does the MC of the wood, and atmospheric RH is continually changing. It varies through daily and seasonal cycles, thus driving the MC of wood through daily and seasonal cycles. See Chapter 4 for more information on MC and EMC.

Finishes cannot change EMC; they affect only the rate at which absorption and desorption occur (see Moisture-Excluding Effectiveness).

Wood outdoors in most areas of the United States cycles around a MC of approximately 12% to 14%. In the Pacific Northwest, average MC can be slightly higher (12% to 16%), and in the Southwest, slightly lower (6% to 9%) (Chap. 13, Tables 13-1 and 13-2). Daily and annual MC may vary from these averages. In general, wood outdoors decreases MC during the summer and increases MC during the winter. (Wood indoors in northern climates increases MC during the summer and decreases MC during the winter. In the south, this distinction is not clear because air conditioning affects indoor RH and thus MC.) Even in humid areas, RH is rarely high enough for a long enough period to bring the MC of wood above 20%. Wood warmed by the sun experiences a virtual RH far below the ambient RH. The surface dries faster than the rest of the lumber. This is why cupping and checking often occur on decking boards; the top surface is much drier than the rest of the board. Shrinkage of the top surface commensurate with this dryness causes cupping and checking parallel to the grain. (Juvenile wood often checks perpendicular to the grain.)

As mentioned, fiber saturation is the limit to the amount of *water vapor* that wood absorbs. *Water vapor* absorbs slowly compared with *liquid water*. *Liquid water* can quickly bring

wood to fiber saturation, and it is the only way to bring the MC of wood above fiber saturation. As wood continues to absorb *liquid water* above its fiber saturation point, the water is stored in the lumen; when water replaces all the air in the lumen, the wood is waterlogged and its MC can be as high as 200%.

Wood can get wet many ways (such as windblown rain, leaks, condensation, dew, and melting ice and snow). The result is always the same—poor performance of wood and finish. Water is usually involved if finishes perform poorly on wood. Even if other factors initially cause poor performance, water accelerates degradation. Fortunately, the MC of lumber can be controlled. However, all too often, this critical factor is neglected during construction and finishing.

Paint wood when its average MC is about that expected to prevail during its service life (approximately 12% for most of the United States and Canada). Painting wood after it acclimates to a MC commensurate with the environment minimizes stress on film-forming finishes. The MC and thus the dimensions of the piece will still fluctuate somewhat, depending on the cyclic changes in atmospheric RH, but the dimensional change should not be excessive. Therefore, film-forming finishes (such as paints) are not stressed and should not fail by cracking.

Most siding and trim is kiln dried to less than 20% MC before shipment, and if it has been kept dry during shipment and storage at the construction site, it should be close to EMC by the time it is finished. If wood gets wet during shipping or storage or at the construction site, a MC of less than 20% is not likely. If wet wood is used, it will dry in service and shrinkage may cause warping, twisting, and checking. If the MC of wood exceeds 20% when the wood is painted, the risk of blistering and peeling is increased. Moreover, water-soluble extractives in species such as redwood and western redcedar may discolor paint.

Plywood, particleboard, hardboard, and other wood composites change MC during manufacture. Frequently, the MC of these materials is not known and may vary depending on the manufacturing process. As with other wood products, condition wood composites prior to finishing.

Dimensional Change

Dimensional change depends on wood species and varies within a particular species. Average shrinkage values obtained by drying wood from its green state to oven dry vary from 2.4% for radial western redcedar to 11.9% for tangential beech (Table 16–1). Dimension in service does not vary to this extent because the MC seldom goes below 6% (Chap. 13, Table 13–1). A film-forming finish would likely decrease this range, but only if the end grain is sealed; unsealed end grain increases MC of painted wood (see Moisture Excluding Effectiveness).

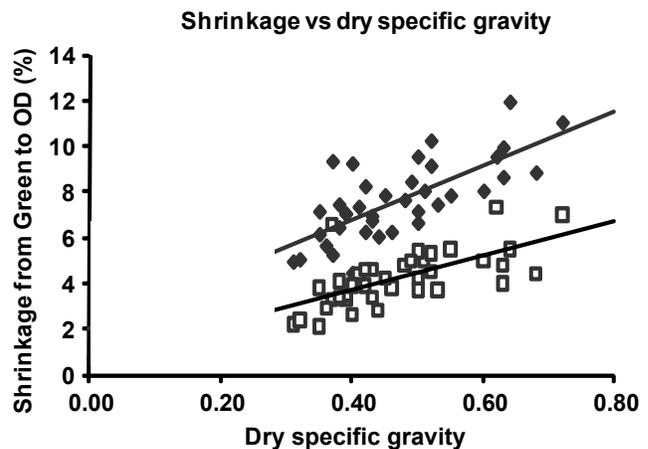


Figure 16–7. Plots of radial (□) and tangential (♦) shrinkage from green to oven dry (OD) as a function of specific gravity for various hardwoods and softwoods from Table 16–1. Lines show least-squares fit.

Wood having little tendency to shrink and swell gives a stable surface for painting. Vertical-grain surfaces are more stable than flat-grain surfaces (Table 16–1, Fig. 16–6), especially outdoors where periodic wetting may produce rapid dimensional change. Wood species having low specific gravity tend to be more dimensionally stable than those having high specific gravity (Fig. 16–7). Low-specific-gravity wood species (that is, those that are more dimensionally stable) hold paint better than high-specific-gravity wood species; however, other factors, such as wood anatomy and manufacturing, also affect paint adhesion.

Wood Extractives

Highly colored extractives occur in heartwood of softwoods such as western redcedar and redwood and hardwoods such as walnut and mahogany. Extractives give heartwood its color, and many extractives are soluble in water. Discoloration of painted or unpainted wood may occur when rain leaches water-soluble extractives from wood. (If indoors, plumbing leaks or high RH can also cause it.) The water carries extractives to wood or paint surfaces and evaporates, leaving extractives as a yellow to reddish brown stain on the surface. Some paints, such as oil-alkyd stain-blocking primers, block leaching of water-soluble extractives.

Wood also contains compounds (resins and oils) that are insoluble in water. Species and growing conditions determine the type and amount of these compounds. For example, many pines contain pitch, and knots of almost all species contain sufficient oils and resins to discolor light-colored paint. These oils and resins are similar chemically to oil-alkyd paints; therefore, oil-alkyd stain-blocking primers cannot block them. Latex-based formulations are also ineffective (see Knots and Pitch).

Shellac (a natural product made from the secretion of lac-producing insects such as *Kerria lacca*) and specially formulated synthetic finishes block extractives bleed from knots. Use shellac or synthetic knot sealers only over knots and paint over them to protect them from water. Blocking diffusion of extractives from knots is difficult, and no easy fix is available other than the extra step of sealing knots before priming. By doing this extra step, you can minimize discoloration of white paint on knotty pine—but it is not easy. If you want white, use knot-free wood. Difficulty sealing knots is the main reason manufacturers cut out the knots to make fingerjointed/edge-glued lumber.

Another option for knots is to use them to accentuate the wood. Use a stain to bring out the color and make the knots a part of the desired appearance.

Wood Products

Six types of wood products are commonly used on the exterior of structures: (1) lumber, (2) plywood, (3) fingerjointed wood, (4) reconstituted wood products (such as hardboard and oriented strandboard (OSB)), (5) wood–plastic composites, and (6) preservative- or fire-retardant-treated wood. Each product has unique characteristics that affect application and performance of finishes.

Lumber

Lumber (such as siding, trim, and decking) for exterior use is available in many species and products, and several publications describe grades:

- “Standard Grading Rules for West Coast Lumber,” West Coast Lumber Inspection Bureau, Portland, Oregon
- “Standard Grading Rules for Canadian Lumber,” National Lumber Grades Authority, New Westminster, British Columbia
- “Western Lumber Grading Rules,” Western Wood Products Association, Portland Oregon
- “Standard Grading Rules for Northeastern Lumber,” Northeastern Lumber Manufacturers Association, Cumberland Maine
- “Standard Grading Rules,” Northern Softwood Lumber Bureau, Cumberland Maine
- “Standard Specifications for Grades of California Redwood Lumber,” Redwood Inspection Service, Pleasant Hill, California
- “Standard Grading Rules for Southern Pine Lumber,” Southern Pine Inspection Bureau, Pensacola Florida

These publications are the basis for selecting wood to meet codes. They give specifications for appearance grades (such as siding and trim) and for structural lumber (such as framing and decking). Western redcedar and redwood are the only species available in vertical-grain grades and saw-textured surfaces (Table 16–1). Southern yellow pine and Douglas-fir plywood are available in saw-textured surfaces.

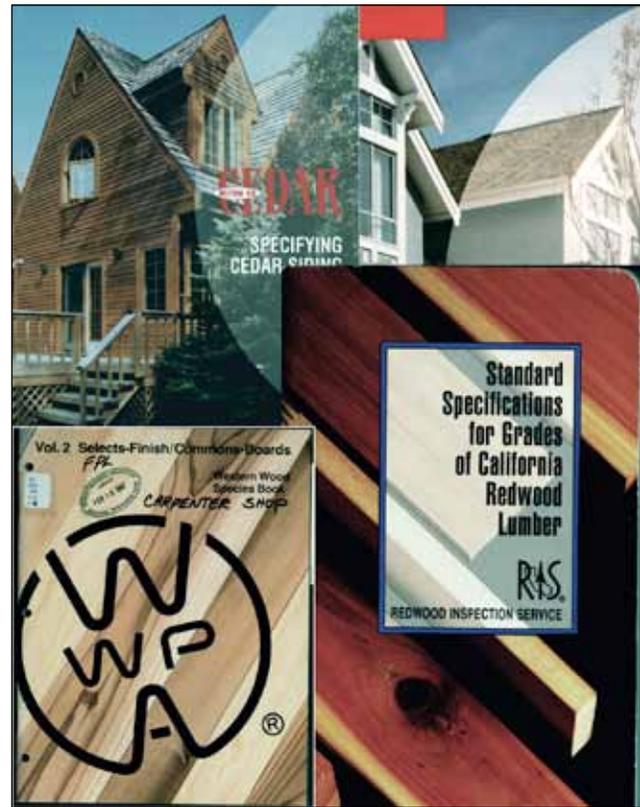


Figure 16–8. Examples of trade association brochures describing wood products.

Unless specified as vertical grain, the grade contains mostly flat-grain lumber. Lumber used for board and batten, drop, or shiplap siding is frequently flat grain. Bevel siding is commonly produced in several grades. The highest grade of redwood and western redcedar bevel siding is vertical grain and all heartwood. Other grades of redwood and western redcedar may be flat, vertical, or mixed grain and may not be all heartwood. Grade is important because species, grain orientation, and surface texture affect paint-holding characteristics.

Descriptions of grades and pictures of many wood species are contained in brochures published by trade associations (such as Western Red Cedar Lumber Association, California Redwood Association, Western Wood Products Association, Southern Forest Products Association, and Northeast Lumber Manufacturing Association) (Fig. 16–8), and these brochures reference the grade rules. When specifying lumber, refer to the grade rules for the product to ensure that the product meets code requirements and use the association brochures to get an idea of appearance.

Textures (roughness or smoothness) of wood surfaces affect selection, application, and service life of finishes. Until recently, a general rule of thumb for matching substrates to finishes was to paint smooth wood and stain saw-textured wood. This easy rule of thumb no longer applies. Although



Figure 16-9. Early paint failure on plywood caused by penetration of moisture into surface face-checks.

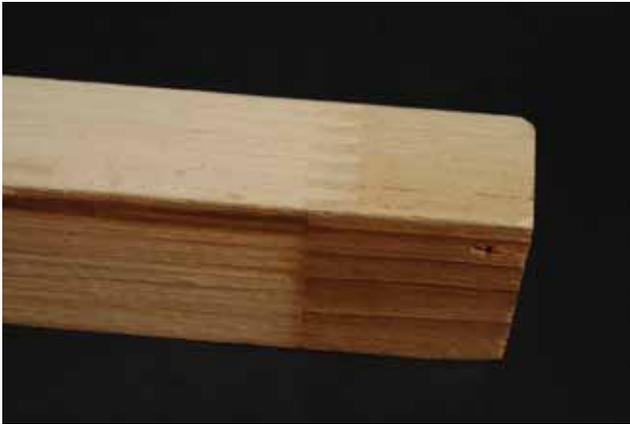


Figure 16-10. Differences in stain from extractives on fingerjointed wood from the white pine group (either eastern or western species) painted with acrylic solid-color stain.

penetrating finishes such as solvent-borne oil-based semi-transparent stains last longer on saw-textured wood than on smooth-planed wood, many film-forming finishes such as opaque stains and paints also last longer on saw-textured wood than on smooth-planed wood. Finishes adhere better, film buildup is thicker, and service life of the finish is longer on saw-textured surfaces than smooth-planed surfaces, particularly for flat-grain lumber.

Plywood

As with lumber, species, grain orientation, and surface texture affect finishing of plywood. Manufacturers of softwood plywood use a lathe to peel logs to give flat-grain veneer. Peeling causes small checks parallel to grain. When the face veneer is laid up to form the plywood panel, the side of the veneer having lathe checks is placed interior to give a surface free of checks. However, after plywood is placed

outdoors, wet-dry cycles (swelling and shrinking) cause the checks to propagate to the surface (face checking). Face checking sometimes extends through paint coatings to detract from the appearance and durability of the paint (Fig. 16-9).

Veneer produced by peeling gives flat-grain plywood and it is commonly available with a saw-textured, abrasively planed (smooth), or paper overlay surface. Douglas-fir and southern yellow pine are available saw-textured (Table 16-1). Saw-textured plywood holds paint much better than does smooth plywood. If smooth plywood is to be painted, scuff-sand it with 50-grit sandpaper and use high-quality latex paint. Latex primer and top-coat generally perform better than oil-alkyd paint. Paint performs poorly on smooth plywood if used as siding but reasonably well on smooth plywood in protected areas such as soffits. Resin-treated paper bonded to plywood forms a medium-density overlay (MDO); MDO eliminates cracks caused by lathe checking and provides plywood with excellent paintability, but the edges are still vulnerable to water. Seal the edges with oil-alkyd primer or an edge sealer formulated for this use. Paper over-laid products should not be finished with semitransparent stain or other penetrating finishes. Use film-forming finishes such as paints or solid-color stains and ensure sufficient film thickness (0.004–0.005 in. (0.10–0.13 mm), or 4–5 mils).

APA—The Engineered Wood Association (Tacoma, Washington) provides information on plywood grades and standards (see Chap. 11).

Fingerjointed Lumber

To obtain “knot free” lumber, mills produce lumber that consists of many small pieces of wood edge-glued and fingerjointed at the end-grain (see Chaps. 10 and 12). Although fingerjointed lumber contains no knots or other obvious defects, most mills do not sort wood pieces prior to gluing to give lumber with similar grain orientation and heartwood-sapwood content. A particular board may contain pieces from different trees, and each piece may have different finishing characteristics; therefore, finishing requirements are determined by the most difficult-to-paint component in a fingerjointed board. Fingerjointed lumber is commonly used for fascia boards, interior and exterior trim, siding, windows, and doors. Paint often fails in a “patchwork” manner according to the paintability of various pieces. The board pictured in Figure 16-10 shows extractive bleed on the component to the right, but not on the component to the left.

Some manufacturers decrease variability in fingerjointed lumber. For example, fingerjointed redwood siding is available in clear all-heart vertical grain and clear flat grain.

Finishing fingerjointed lumber requires care to ensure consistent finish performance on the whole board. To hide color



Figure 16–11. Absorption of water causes differential dimensional change of surface flakes to give an uneven surface (telegraphing).

differences of the various pieces, use opaque finishes rather than natural finishes (such as semitransparent stain). As with other wood products, planed surfaces should be scuff-sanded with 50-grit sandpaper prior to priming. Saw-textured lumber should hold paint better than planed lumber.

Particleboard and Similar Reconstituted Wood Products

Reconstituted wood products are made by forming small pieces of wood into large sheets; sheets are cut into 1.2- by 2.4-m (4- by 8-ft) panel products or other sizes such as siding. These products are classified as particleboard or fiberboard, depending upon the nature of the wood component (see Chap. 11).

Particleboard is made from splinters, chips, flakes, strands, or shavings. Flakeboard is a type of particleboard made from large flakes or shavings. Oriented strandboard (OSB) is a refinement of flakeboard; the flakes have a large length-to-width aspect ratio and are laid down in three layers, with the flakes in each layer oriented 90° to each other as are veneers in plywood (see Chap. 11). Most OSB is used inside the external envelope of structures for sheathing and underlayment, however it contains “exterior” adhesives and water repellent. The water repellent gives OSB water resistance while in transit and storage prior to construction. The water repellent does not decrease paint adhesion.

Lumber characteristics, such as grain orientation, specific gravity, grain boundary transition, warping, and splitting, are not considerations with particleboard, but paint applied directly to particleboard performs poorly. Differential dimensional change of surface flakes causes telegraphing, and paint usually cracks and peels (Fig. 16–11). Telegraphing is the formation of an uneven paint surface caused by swelling of flakes and particles under the paint. Telegraphing occurs on all types of particleboard, but not on fiberboard. Adhesive failure leads to loss of flakes from the surface. Figure 16–11 shows painted flakeboard after 3 years outdoors. The area on the left has one coat of acrylic-latex top-coat and

the area on the right has one coat of oil-alkyd primer and acrylic-latex top-coat. The single coat (top-coat only) has failed, and the area having two-coats (primer and top-coat) is starting to fail, particularly over large flakes. Products intended for outdoor use, such as siding, are overlaid with MDO or wood veneer to improve paint performance. Products having MDO can be finished in the same way as other paper-overlaid products. Seal edges with a product specifically formulated for this use, and apply an oil-alkyd primer to give additional water resistance (see Plywood).

When finishing particleboard that does not have a paper overlay, use a three-coat latex paint system on the surface and seal edges as described above. However, do not expect long-term paint performance.

When particleboard or OSB, without an overlay, is used outdoors, it requires a rigorous maintenance schedule (often every 6 to 12 months).

Mechanical pulping produces wood fibers that are dry- or wet-formed into fiberboard (Chap. 11). Hardboard is a dense fiberboard often used for exterior siding. Hardboard is available in 152- to 203-mm (6- to 8-in.) widths as a substitute for solid-wood beveled siding. The surface of fiberboard accepts and holds paint well, and MDO improves paintability. As with particleboard, seal edges with oil-alkyd primer or other suitable sealer.

Wood–Plastic Composites

Wood-plastic composites (WPCs) account for approximately one-fourth of wood decking. Manufacturers combine wood flour, fibers, particles, or a combination, with polyethylene, polyvinyl chloride, or polypropylene and extrude “boards” in various profiles. Wood content and particle size in the boards vary and thus their ability to accept a finish varies. Boards high in wood content with large particle size may accept a finish; boards high in plastic content may not. Finish a small area to ensure the finish will wet the surface. After the finish cures, check adhesion using the tape pull-off test (see Chalking). Plastics are routinely finished in industrial applications, such as car parts, by activating the plastic surface using flame or plasma. This technology is not used on WPCs for the construction industry, because most manufacturers do not expect their products to be finished.

Treated Wood

Wood used in structures fully exposed to the weather, such as in decks and fences (particularly those portions of the structure in ground contact), needs preservative treatment to protect it from decay (rot) and termites. Wood used in marine exposure also requires preservative treatment to protect it from decay and marine borers. For some uses, building codes may require treatment of wood with either preservative or fire-retardant, or both.

Wood is pressure-impregnated with three types of preservatives: (a) preservative oils (such as coal-tar creosote), (b) organic solvent solution (such as pentachlorophenol), and

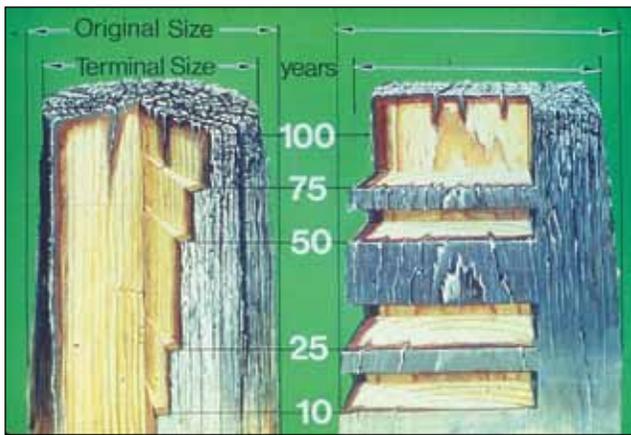


Figure 16–12. Artist's rendition of weathering process of round and square timbers. As cutaway shows, interior wood below surface is relatively unchanged.

(c) waterborne salts (such as copper quaternary ammonium complexes, copper azole, and chromated copper arsenate (CCA)) (Chap. 15). Note: Except for the all-wood foundation, CCA-treated wood is not used in residential construction.

Components for doors and windows are usually dip-treated with a water-repellent preservative (WRP). The American Wood Protection Association sets standards for pressure-impregnated and dip-preservative treatment of wood (AWPA 2008).

Wood treated with waterborne preservatives, such as copper-based systems, can be painted or stained if the wood is clean and dry. Bleed of preservative through finishes, particularly latex-based paints and solid-color stains, can occur if wood is still wet from the preservative treatment. Allow wood to dry before painting; 1 week should be sufficient. Wood treated with coal-tar creosote or other dark oily preservatives is not paintable, except with specially formulated finishes such as two-component epoxy paints; even if the paint adheres to the treated wood, the dark oils tend to discolor paint, especially light-colored paint. Wood treated with a water-repellent preservative, by vacuum-pressure or dipping, is paintable.

Fire-retardant- (FR-) treated wood is generally painted rather than left unfinished because the FR treatment may darken or discolor wood. FR treatment does not generally interfere with adhesion of finishes; however, you should contact the paint manufacturer, the FR manufacturer, and the treating company to ensure that the products are compatible. Some fire retardants may be hygroscopic and cause wood to have high MC. FRs for wood used outdoors are formulated to resist leaching.

Weathering

Weathering is the general term describing outdoor degradation of materials and manifests itself physically and

chemically (for example, cracking and exfoliation of rock, corrosion of metals, and photodegradation of organic materials). Ultraviolet (UV) radiation in sunlight catalyzes photodegradation of organic materials exacerbated by moisture, temperature change, freeze–thaw cycles, abrasion by windblown particles, and growth of microorganisms. Degradation occurs near the surface of wood, wood products, and finishes.

Effect on Wood

Weathering takes many forms depending on the material; wood and wood products initially show color change and slight checking. Leaching of water-soluble extractives, chemical changes, and discoloration of the surface by microorganisms cause color change. As weathering continues, wood develops checks on lateral surfaces and checks and cracks near the ends of boards, and wood fibers slowly erode from the surface. Wood consists of three types of organic components: carbohydrates (cellulose and hemicelluloses), lignin, and extractives. Weathering affects each of these components differently, and physical and chemical changes affect paintability.

Carbohydrates

Carbohydrates (cellulose and hemicelluloses) are polymers of sugars and make up 55% to 65% of wood (Chap. 3). Carbohydrates do not absorb UV radiation and are therefore resistant to UV degradation. However, hemicelluloses and amorphous cellulose readily absorb–desorb moisture; this cyclic wetting and drying may cause different dimensional change for EW/LW bands. Differential dimensional change roughens wood, raises grain, and causes checks, cracks, warping, and cupping. Fewer checks develop in woods with moderate to low specific gravity than in those with high specific gravity; vertical-grain boards develop fewer checks than do flat-grain boards; and vertical-grain boards warp and cup less than do flat-grain boards. To minimize cupping, the width of a board should not exceed eight times its thickness. The tendency to cup increases with the specific gravity and width/thickness ratio.

Lignin

Approximately 20% to 30% of wood is composed of lignin, a polymer that helps bond cellulose and hemicelluloses within cell walls and bonds cells together. The volume between adjacent wood cells (middle lamella) is rich in lignin. If exposed to UV radiation, lignin in the middle lamella, at the surface of wood, begins to degrade within a few hours. The changes are not obvious visually, but they affect the surface chemistry of wood and thus adhesion of finishes. Lignin photodegrades, leaving cellulose fibers loosely attached to the surface. Further weathering causes fibers to be lost from the surface (a process called erosion), but this process is slow. Approximately 6 mm (1/4 in.) of wood is lost in a century (Fig. 16–12). Erosion is slower for most hardwoods and faster for low-density softwoods. Other factors such as

Table 16–2. Erosion of earlywood and latewood on smooth planed surfaces of various wood species after outdoor exposure^a

Wood species	Avg. SG ^b	Erosion (µm) after various exposure times ^c											
		4 years		8 years		10 years		12 years		14 years		16 years	
		LW	EW	LW	EW	LW	EW	LW	EW	LW	EW	LW	EW
Western redcedar plywood	—	170	580	290	920	455	1,095	615	1,165	805	1,355	910	1,475
Redwood plywood	—	125	440	295	670	475	800	575	965	695	1,070	845	1,250
Douglas-fir plywood	—	110	270	190	390	255	500	345	555	425	770	515	905
Douglas-fir	0.46	105	270	210	720	285	905	380	980	520	1,300	500	1,405
Southern Pine	0.45	135	320	275	605	315	710	335	710	445	1,180	525	1,355
Western redcedar	0.31	200	500	595	1,090	765	1,325	970	1,565	1,160	1,800	1,380	1,945
Redwood	0.36	165	405	315	650	440	835	555	965	670	1,180	835	1,385
Loblolly pine	0.66	80	205	160	345	220	490	—	—	—	—	—	—
Western redcedar	0.35	115	495	240	1,010	370	1,225	—	—	—	—	—	—
Southern Pine	0.57	95	330	180	640	195	670	—	—	—	—	—	—
Yellow-poplar	0.47	—	220	—	530	—	640	—	—	—	—	—	—
Douglas-fir	0.48	75	255	175	605	225	590	—	—	—	—	—	—
Red oak	0.57	180	245	340	555	440	750	—	—	—	—	—	—
Ponderosa pine	0.35	130	270	315	445	430	570	Decay	Decay	Decay	Decay	—	—
Lodgepole pine	0.38	105	255	265	465	320	580	475	745	560	810	—	—
Engelmann spruce	0.36	125	320	310	545	390	650	505	795	590	950	—	—
Western hemlock	0.34	145	320	310	575	415	680	515	1,255	600	1,470	—	—
Red alder	0.39	—	295	—	545	—	620	—	920	—	955	—	—

^aData from three studies are shown. Specimens were exposed vertically facing south. Radial surfaces were exposed with the grain vertical. EW denotes earlywood; LW, latewood.

^bSG is specific gravity.

^cAll erosion values are averages of nine observations (three measurements of three specimens).

growth rate, degree of exposure, grain orientation, temperature, and wetting and drying cycles affect erosion rate. Table 16–2 shows erosion rates for several wood species measured over 16 years.

Extractives

Extractives (chemicals in heartwood that give each species its distinctive color) change color when exposed to UV radiation or visible light, and this color change indicates degradation of extractives near the surface. The color change causes wood to lighten or darken. Some wood species change color within minutes of outdoor exposure. Wood also changes color indoors. Ordinary window glass blocks most UV radiation, therefore visible light causes indoor color change. UV stabilizers in finishes do not prevent color change.

Biological Factors

The most common biological factor is mildew, a microorganism that contributes to color change. Mildew does not cause degradation, but it may cause initial graying or an unsightly dark gray or black blotchy appearance. Dark-colored fungal spores and mycelia on the wood surface cause this color. In advanced stages of weathering, after extractives and lignin have been removed leaving a cellulose surface, wood may develop a bright silvery-gray sheen. This sheen on weathered wood occurs most frequently in arid climates or coastal regions (see Mildew).

Algae can also grow on wood, particularly in damp locations; algae is usually green, and it often grows in combination with mildew.

Effect on Paint Adhesion

Wood erosion is slow, but chemical changes occur within a few weeks of outdoor exposure. Badly weathered wood having loosely attached fibers on the surface cannot hold paint. This is not obvious on wood that has weathered for only 2 to 3 weeks. The wood appears unchanged. Research has shown that surface degradation of wood exposed to sunlight for 1, 2, 4, 8, or 16 weeks prior to painting (preweathering) affects service life of subsequently applied paint. The longer the wood preweathered, the shorter the time until the paint began to peel. For boards preweathered 16 weeks, the paint peeled within 3 years; for boards preweathered only 1 week, the paint peeled after 13 years. Panels that were not preweathered showed no sign of peeling after 20 years. Paints were commercial oil-alkyd or acrylic-latex primer with one acrylic-latex top-coat over planed all-heartwood vertical-grain western redcedar. For species with low specific gravity, finish the wood as soon as possible after installation, or better yet, prime it before installation. In other tests using wood species having higher specific gravity (such as Douglas-fir and southern yellow pine), little loss of paint adhesion occurred until boards had been preweathered for 3 to 4 weeks.

Effect on Wood Finishes

Finish resins (ingredients that form films or penetrate wood) are organic polymers, and as with lignin in wood, UV radiation degrades the polymer, causing slow erosion. Erosion rate depends on the resistance of the polymer to UV radiation. Paints and stains based on latex polymers are more resistant to UV radiation than those based on oil-alkyds. UV radiation does not usually degrade paint pigments; therefore, as resin degrades, pigments loosen and erode from the surface. Degraded resin and loose pigments give film-forming finishes a chalky appearance. Pigment erodes from oil-based semitransparent stains to expose wood.

Decay and Insects

Decayed wood does not hold paint. One expects wood used for new construction to be free of decay; contractors can do several things to keep it that way. If possible, paint all end grain surfaces with an oil-alkyd primer (such as ends of siding and trim, brick molding, railings, balustrade, posts, beams, and edges of panel products (plywood, T1-11 siding, medium-density fiberboard, and OSB).

When repainting, inspect wood for decay. Problematic areas include end grain of balustrade, brick molding, siding that butts against a roof, and bottoms of posts on porches. Decay often occurs in the center of wood and the surface can appear sound; probe several areas with an ice pick to ensure the wood is sound. Replace boards having decay. Siding intersecting a sloping roof should have a 2-in. (50-mm) gap between the end grain of the siding and the roof shingles. Check for a finish on the end grain; if there is no finish, treat end grain with a WRP, prime, and top-coat. If there is already a coating on the end grain, keep it painted. End grain of siding that butts directly against roof shingles (a bad practice—see *Structure Design and Construction Practices*) is not accessible for painting, however you can try to wick WRP into the end grain from a wet brush.

Insects seldom cause problems with finishes. However, when repainting a structure, inspect it for termite tunnels and carpenter ants. A termite tunnel is a sure sign of infestation. Presence of carpenter ants may indicate decay in the structure. Carpenter ants do not eat wood, but they often tunnel out decayed areas to build their nests. Note that woodpecker holes often indicate insect infestation.

Control of Water and Water Vapor

Control of liquid water and water vapor requires different types of finishes.

Water Repellents

Water repellents and WRPs retard the absorption of liquid water into wood, particularly at the end grain. They are an excellent treatment for wood used outdoors because they inhibit absorption of rain yet allow wood to dry after rain. WRPs and similar penetrating finishes (tinted clear finishes and oil-based semitransparent stains) have almost no effect

on diffusion of water vapor; that is, they have little effect on the change in wood moisture content caused by changes in RH.

Moisture-Excluding Effectiveness

Moisture-excluding effectiveness (MEE) of a finish is a measure of its resistance to diffusion of water vapor (that is, a measure of the permeability of a coating to water vapor); it is not a measure of water repellency. A coating that blocks all water vapor is 100% effective; however, no coating is impermeable. A coating that excludes water vapor merely slows its absorption or desorption; it cannot change the EMC (Chap. 4). MEE depends on a number of variables: coating film thickness, defects and voids in the film, type and amount of pigment, chemical composition and amount of resin, vapor-pressure gradient across the film, and length of exposure.

Table 16–3 lists coatings and their MEE. Note that maleic-alkyds, two-part polyurethane, and paraffin wax have high MEE. Coatings that retard water vapor diffusion also repel liquid water. Porous paints, such as latex and low-luster (flat) paints, afford little protection against water vapor transmission. They may not repel liquid water, either. In general, a low MEE value also indicates low resistance to absorption to liquid water. These finishes permit entry of water vapor and water from dew and rain unless applied over a nonporous primer (such as oil-alkyd primer). Latex finishes contain surfactants that can encourage absorption of water into the coating and wood, particularly just after the coating has been applied. Most of these surfactants wash out of the coating after a short time. MEE also gives a measure of vapor transmission out of wood. Paint film can inhibit drying (Fig. 16–13). Retardation of drying after periodic wetting of wood causes it to reach a MC where decay can occur. This type of wood paint failure usually occurs on painted fences and porch railings that are fully exposed to weather (Fig. 16–14). Paint coatings usually crack at the joint between two pieces of wood, water enters the wood through these cracks, and the coating slows drying. Priming the end grain of wood used in these applications inhibits water absorption; thus, end-grain priming works with the coating on the lateral surface to keep the wood dry.

Structure Design and Construction Practices

Structure design and construction practices affect finish performance. Design and construct structures to keep water out and to remove it when water gets through the structure envelope. This section summarizes recommendations for improving finish performance.

Large roof overhangs protect siding from rain and dew; gutters and downspouts greatly decrease the amount of water draining down the siding.

Flash all wall and roof penetrations. Shingle the flashing to keep water moving out of the structure. Sealants, caulking compounds, and similar compounds that come in a tube

Table 16-3. Moisture-excluding effectiveness of various finishes on ponderosa pine^a

Finish	No. of coats	Moisture-excluding effectiveness (%)		
		1 day	7 days	14 days
Linseed oil	1	12	0	0
	2	22	0	0
	3	33	2	0
Water repellent ^b	1	12	0	0
	2	46	2	0
	3	78	27	11
Latex flat wall paint (vinyl acrylic resin)	1	5	0	0
	2	11	0	0
	3	22	0	0
Latex primer wall paint (butadiene-styrene resin)	1	78	37	20
	2	86	47	27
	3	88	55	33
Alkyd flat wall paint (soya alkyd)	1	9	1	0
	2	21	2	0
	3	37	5	0
Acrylic latex house primer paint	1	43	6	1
	2	66	14	2
	3	72	20	4
Acrylic latex flat house paint	1	52	12	5
	2	77	28	11
	3	84	39	16
Solid-color latex stain (acrylic resin)	1	5	0	0
	2	38	4	0
	3	50	6	0
Solid-color oil-based stain (linseed oil)	1	45	7	1
	2	84	48	26
	3	90	64	42
Semitransparent oil-based stain (commercial)	1	7	0	0
	2	13	0	0
	3	21	1	0
Alkyd house primer paint (maleic-alkyd resin)	1	85	46	24
	2	93	70	49
	3	95	78	60
Urethane varnish (oil-modified)	1	55	10	2
	2	83	43	23
	3	90	64	44
	4	91	68	51
	5	93	72	57
	6	93	76	62
Polyurethane paint, gloss (two components)	1	91	66	44
	2	94	79	62
	3	96	86	74
Aluminum flake pigmented varnish (oil-modified)	3	98	91	84
	4	98	93	87
Paraffin wax, brushed	1	97	82	69
Paraffin wax, dipped	1	100	97	95

^aSapwood was initially finished and conditioned to 26 °C (80 °F) and 30% RH, then exposed to the same temperature and 90% RH.
^bWRP would be about the same.

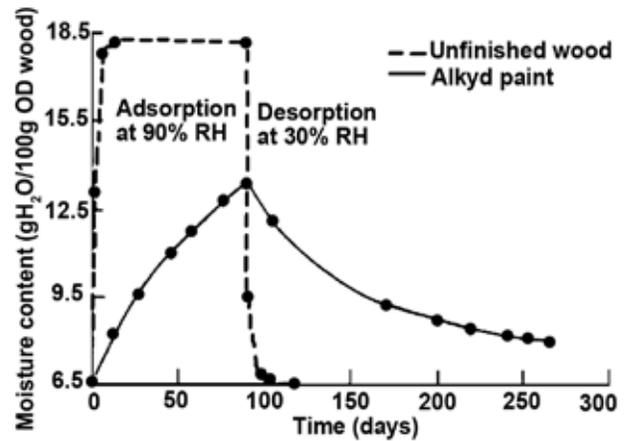


Figure 16-13. Change in moisture content of ponderosa pine sapwood finished with three coats of aluminum-pigmented alkyd paint and exposed to 90% and 30% RH at 26 °C (80 °F), compared with moisture content of unfinished wood.



Figure 16-14. Decay and paint failure in wood railing fully exposed to weather.

need to work in concert with flashing; they are not a substitute for flashing.

Vent clothes dryers, showers, and cooking areas to outside, not to the crawl space or attic. Place an air barrier in exterior walls and top-floor ceilings, and flash penetration through exterior walls (doors, windows, and vents). Vent to soffits if possible. Avoid using humidifiers. If the structure contains a crawl space, cover the soil with a vapor-retarding material such as black plastic or tar paper.

Do not seal the overlap of lap siding.

In northern climates, use an air barrier-vapor retarder on the interior side of all exterior walls and top-floor ceiling to prevent condensation in the walls and attic. In buildings that are air-conditioned most of the year, place the air barrier-vapor retarder on the exterior side.



Figure 16–15. Demonstration of siding installation over a secondary drainage plane (rain screen) showing wall studs, sheathing, water-resistive barrier (WRB), furring strips, and interleaved WRB at the butt joint. Note that the butt joint is centered directly over the furring strip and the underlying stud and the end grain has been sealed.



Figure 16–16. Demonstration of proper and improper z-flashing installation: (top) siding installed with a 9-mm (3/8-in.) gap between the z-flashing and siding to allow water to drain off the siding; (bottom) siding installed without a gap, which gives easy access for water absorption into the siding and thus shows extractives staining.

Prevent moisture-related problems in siding by using rain-screen design (that is, by furring out the siding 9 to 19 mm (3/8 to 3/4 in.) from the sheathing–house wrap) (Fig. 16–15).



Figure 16–17. Shingles installed with insufficient gap later warped when they expanded after getting wet.

Seal all end-grain surfaces with oil-alkyd primer or WRP. Ensure adequate space (approximately 50 mm (2 in.)) between siding and roof shingles in places where a side-wall intersects a roof. Siding and panel products above z-flashing need to be placed approximately 9 to 12 mm (3/8 to 1/2 in.) above the flashing to form a drip edge (Fig. 16–16).

When installing siding or shingles, ensure that the spacing is commensurate with the MC of the wood and the anticipated MC during the service life. Figure 16–17 shows shingles that were spaced too closely and buckled in service. Avoid inside–outside beams and joists. For example, a second-floor floor joist that penetrates a wall to form a porch rafter is destined to have moisture problems and subsequent decay and finish failure. This type of wall penetration is difficult to seal to avoid air movement. Air carries water vapor that condenses in the space between floors or the porch ceiling.

Compliance of VOC Finishes with Pollution Regulations

Volatile organic compounds (VOCs) are organic chemicals in finishes that evaporate as finishes dry and cure. VOCs are air pollutants, and the amount that evaporates for a given amount of solids (such as binder and pigments) in finishes is regulated. Under the 1990 New Clean Air Act, the U.S. Environmental Protection Agency (EPA) required paint companies to decrease the amount of VOCs in their finishes.

Traditional solvent-borne wood finishes containing mineral spirits are no longer available, including oil-based semi-transparent stains, oil- and oil-alkyd-based primers and top-coats, solvent-borne water repellents, and solvent-borne water-repellent preservatives. Solvent-borne finishes are still available, but the solvent systems are more complex than mineral spirits. Prior to VOC regulations, penetrating finishes, such as semitransparent stains, had low solids content



Figure 16–18. Front view of exterior grade of plywood siding after 10 years of exposure. The right-hand portion was exposed to the weather, whereas the left-hand side was covered with a board to give a board-and-batten appearance.

(pigment, oils, and polymers). Reformulated finishes may contain more solids, new types of solvents and co-solvents, or other nontraditional additives. These high-solids formulations are prone to form films rather than penetrate wood.

The paint industry also reformulated latex-based finishes to meet stringent requirements for water-based paints.

Exterior Wood Finishes

Exterior finishes either penetrate wood cell walls or form films on the surface. Penetrating finishes give a more “natural” look to the wood than film-forming finishes—that is, they allow some of the character of wood to show through the finish. In general, the more natural a finish, the less durable it is. This section also discusses weathered wood as a “finish.”

Weathered Wood as Natural Finish

Leaving wood to weather to a natural finish may seem like an inexpensive low-maintenance alternative to finishing, but this approach leads to problems. Wood surfaces erode, some wood species decay, lumber is more prone to split and check, and in most climates in North America, exterior wood develops blotchy mildew growth. To avoid decay, wood must be all heartwood from a decay-resistant species such as redwood or western redcedar and be vertical grain to decrease the potential for splitting, raised grain, and cupping. Only limited areas have a climate conducive to achieving a driftwood-gray appearance as wood weathers naturally; the climate along the coast of New England seems conducive to developing the silvery-gray weathered patina that some people desire. Even when the climatic conditions favor the development of silvery-gray patina, it takes several years to achieve this appearance. Protected areas under the eaves will not weather as fast as areas that are not protected,

which leads to a different appearance at the top and bottom of a wall.

Do not leave composite wood products, such as plywood, unprotected. The surface veneer of plywood can be completely destroyed within 10 years if not protected from weathering. Figure 16–18 shows weathering of unfinished plywood (right); the intact portion of the plywood (left) had been covered with a board to give a board-and-batten appearance.

Penetrating Wood Finishes

Penetrating finishes such as transparent or clear WRPs, lightly colored WRPs, oil-based semitransparent stains, and oils do not form a film on wood. However, semitransparent stains having high-solids content may form a thin film.

Penetration into Wood

Finishes penetrate wood in two ways: flow of liquid into cut cells at the surface and absorption into cell walls.

Lumber is almost never cut aligned with axial wood cells; therefore, the surface has cut axial cells (and of course, ray cells) and, if it is a hardwood, cut vessels. Cut cells and vessels give macroscopic porosity. The diameter of lumina and vessels varies depending on the wood species, but in all species, the hollow spaces formed by cut lumina and vessels are quite large compared with pigment particles and binders in finishes (that is, a high-molecular-weight (MW) latex molecule is small compared with these openings). Any finish can easily flow into cut lumina and vessels.

Penetration of a finish into the cell wall takes place at the molecular scale. The finish or components of the finish absorb into void space of hemicelluloses, amorphous cellulose, and lignin polymers contained in the cell wall. Penetration is excellent for resins having a MW less than 1,000 Daltons. The limit to penetration into these void spaces is a MW of approximately 3,000 Daltons. Natural oils (such as linseed oil and tung oil), solvents, oil-alkyds, and low-MW polymer precursors can penetrate the cell wall and thus modify the properties of cells located near the surface. Cell walls modified with finish typically absorb less water and swell less than do unmodified cell walls.

Traditional solvent-borne finishes such as water-repellent preservatives and solvent-borne oil-based stains can penetrate cell walls. To some extent, some of the excess oil in a long-oil-alkyd primer can penetrate cell walls. High-molecular-weight polymers such as acrylics and vinyl acrylics and pigments are too large to penetrate cell walls and therefore cannot modify cell wall properties. Water in these formulations penetrates the cell wall, but the polymer does not. As water absorbs into wood, it enters the cell wall and hydrogen-bonds to the hemicelluloses and amorphous cellulose to cause swelling. Water absorption causes raised grain, and as a latex finish coalesces, the finish deforms around the raised grain while it is still flexible. Thus, latex finishes are less likely to crack if the surface develops raised grain.

Table 16–4. Suitability and expected service life of finishes for exterior wood surfaces^a

Type of exterior wood surface	Paint and solid-color stain						
	Tinted finishes such as deck finishes		Semitransparent stain		Expected service life ^d (years)		
	Suit-ability	Expected service life ^b (years)	Suit-ability	Expected service life ^c (years)	Suit-ability	Paint	Solid-color stain
Siding							
Cedar and redwood							
Smooth (vertical grain)	Low	1–2	Moderate	2–4	High	10–15	8–12
Smooth (flat grain)	Low	1–2	Moderate	2–4	Moderate	8–12	6–10
Saw-textured	High	2–3	High	4–8	Excellent	15–20	10–15
Pine, fir, spruce							
Smooth (flat grain)	Low	1–2	Low	2–3	Moderate	6–10	6–8
Saw-textured (flat grain)	High	2–3	High	4–7	Moderate	8–12	8–10
Shingles (sawn shingles used on side-walls)	High	2–3	High	4–8	Moderate	6–10	6–8
Plywood							
Douglas-fir and Southern Pine							
Sanded	Low	1–2	Moderate	2–4	Moderate	4–8	4–6
Saw-textured	Low	2–3	High	4–8	Moderate	8–12	6–10
MDO plywood ^e	—	—	—	—	Excellent ^f	12–15	10–15
Hardboard, medium density ^g							
Unfinished	—	—	—	—	High	8–12	6–10
Preprimed	—	—	—	—	High	8–12	6–10
MDO overlay	—	—	—	—	Excellent ^f	10–15	10–15
Decking							
New (smooth-sawn)	High	1–2	Moderate	2–3	Low	—	—
Weathered or saw-textured	High	2–3	High	3–6	Low	—	—
Oriented strandboard	—	—	Low	1–3	Moderate	4–5	4–5

^aEstimates were compiled from observations of many researchers. Expected life predictions are for average location in the contiguous USA; expected life depends on climate and exposure (such as desert, seashore, and deep woods).

^bThe higher the pigment concentration, the longer the service life. Mildew growth on surface usually indicates the need for refinishing.

^cSmooth unweathered surfaces are generally finished with only one coat of stain. Saw-textured or weathered surfaces, which are more adsorptive, can be finished with two coats; second coat is applied while first coat is still wet.

^dExpected service life of an ideal paint system: three coats (one primer and two top-coats). Applying only a two-coat paint system (primer and one top-coat) will decrease the service life to about half the values shown in the table. Top-quality latex top-coat paints have excellent resistance to weathering. Dark colors may fade within a few years.

^eMedium-density overlay (MDO) is painted.

^fEdges are vulnerable to water absorption and need to be sealed.

^gWater-repellent preservatives and semitransparent stains are not suitable for hardboard. Solid-color stains (latex or alkyd) will perform like paints. Paints give slightly better performance because the solids content of paint is higher than that for solid-color stains and thus paints give greater film build for the same volume of finish used.

Penetrating Clear and Lightly Colored (Tinted) Finishes

Penetrating transparent clear finishes have no pigments and the generic names for them are water repellents (WRs) or water-repellent preservatives (WRPs). A typical WR formulation contains 10% resin or drying oil, 1% to 3% wax or other water repellent, and solvent. WRPs contain a fungicide such as 3-iodo-2-propynyl butyl carbamate (IPBC). They were traditionally formulated using turpentine or mineral spirits, but now paint companies formulate them using VOC-compliant solvent and waterborne systems to comply with VOC regulations.

WRPs give wood a bright, golden-tan color close to the original appearance of the wood and are the first step in

protection from weathered wood as a finish. WRPs decrease checking, prevent water staining, and help control mildew growth. The first application of these finishes to smooth-planed lumber lasts approximately one year on exposed lateral wood surfaces; subsequent applications may last longer because weathered boards absorb more finish. WRPs absorb readily into end grain and can last for years to retard water absorption into end grain. WRPs last longer if applied to saw-textured wood.

Few companies manufacture traditional clear WRs and WRPs; almost all WR and WRP formulations are lightly pigmented and contain other additives to extend their service life (Table 16–4). Lightly pigmented finishes perform well on decks. Water- and solvent-borne formulations are available; waterborne formulations may be a water emulsion

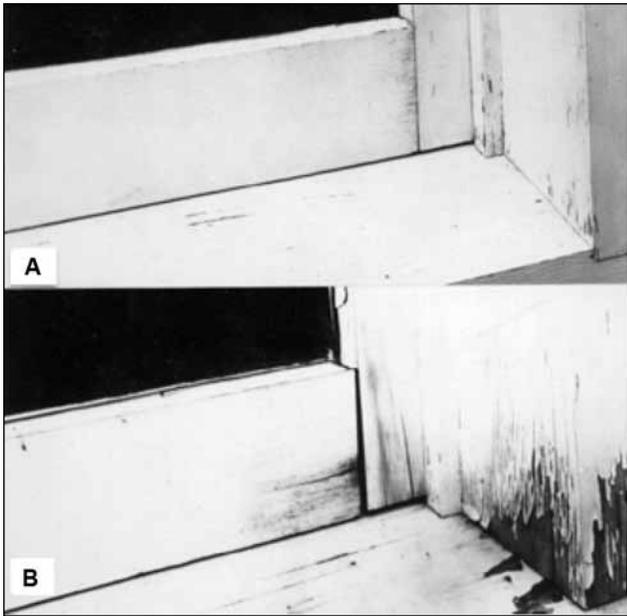


Figure 16–19. Effect of water-repellent preservative treatment after 5 years of outdoor exposure. A, window sash and frame treated with a water-repellent preservative and then painted; B, window sash and frame not treated before painting.

of synthetic polymers. Synthetic polymers do not penetrate the cell wall, but form a thin film, seal the surface, and provide water repellency. Finely ground pigment gives color and partially blocks UV radiation. Pigment, UV stabilizers, and other additives give these finishes a service life of 2 to 3 years, but they lack sufficient pigment to inhibit UV degradation of the wood. As with clear WRPs, they usually contain a preservative to retard mildew growth.

Caution: Fungicides in WRPs and semitransparent stains are toxic and may be herbicides; use caution to avoid skin contact and breathing vapors, and protect plants and the soil around them from accidental contamination.

Prior to changes in finish formulation because of VOC regulation, paint companies formulated solvent-borne WRPs for use as a pretreatment prior to priming. At this time, finding a WRP formulated for this use is difficult. In fact, paint manufacturers seldom honor a finish warranty, if customers apply a WRP prior to using their finish, particularly if a different paint company made the WRP. In spite of decades of research showing the benefits of WRP treatment of wood prior to priming, they are seldom used. Information on WRPs as a wood treatment, prior to priming, is included in this chapter in case a paint manufacturer markets a WRP specially formulated for this use in the future. They are particularly effective for improving the service life of paint on difficult-to-paint wood species and decay-prone areas (Fig. 16–19). Currently available WRPs can be used for sealing end grain

Protect wood and wood-based products from water and sunlight prior to delivery and while stored at the construction site. Avoid contaminating them with dirt, oil, or other contaminants. Finish wood as soon as possible after installing it.

of lumber, edges of plywood, and back-priming and are discussed in several sections of this chapter.

Penetrating finishes that use paraffin oil as the solvent are also available. These formulations penetrate wood, and the oil helps improve water repellency. Paraffin oil is not a volatile solvent; therefore, these finishes comply with air quality requirements. They are usually a good value, because virtually all of what comes in the can ends up in the wood. The service life is approximately 1 year, but they are easy to apply. If an excessive amount is applied, the wood surface may remain oily for a few weeks. Do not use them as a pretreatment prior to applying other finishes.

Application, New Construction

For new construction, the most effective method for applying a WR or WRP is to dip the entire board into the finish (Table 16–5). If finish is roller or spray applied, back brush following application to work the finish into the wood. Finish the back side of siding, particularly for highly colored wood species (see Back-Priming).

When wood is finished following installation, apply liberal amounts of WRP to all end grain areas, edges of panel products, and other areas vulnerable to water, such as the bottoms of doors and window frames. Coverage is approximately $6.1 \text{ m}^2 \text{ L}^{-1}$ ($250 \text{ ft}^2 \text{ gal}^{-1}$) on a smooth surface or $3.7 \text{ m}^2 \text{ L}^{-1}$ ($150 \text{ ft}^2 \text{ gal}^{-1}$) on a saw-textured surface. Smooth wood will usually accept only a single coat; a second coat will not penetrate the wood. WRP treatment lasts longer on saw-textured surfaces than on smooth surfaces because more finish penetrates the wood. As a natural finish, the life expectancy of a WRP is only 1 to 2 years, depending upon the wood and exposure. However, reapplication is easy, particularly on decks and fences.

Refinishing

Clear and lightly colored finishes (penetrating natural finishes such as WRPs and lightly pigmented deck finishes) do not peel; they fade, and if pigmented, the pigments erode. As clear finishes weather, they lose their water repellency, turn gray, and develop mildew. Lightly pigmented finishes lose color. If not blackened by mildew, they can often be prepared for refinishing by removing dirt with a stiff-bristle brush. If discolored by mildew, wash the wood with commercial mildew cleaner or dilute liquid household bleach and detergent prior to refinishing (see Mildew).

Table 16–5. Initial application and maintenance of exterior wood finishes^a

Finish	Application process	Appearance of wood	Maintenance	
			Process	Service life ^b
Water-repellent preservative (WRP)	Brush-apply 1 coat or dip. Apply a second coat only if it will absorb.	Grain visible; wood tan to brown, fades to gray with age	Brush to remove surface dirt; wash to remove mildew	1–3 years
Tinted clear finish (slightly pigmented deck finish)	Brush-apply 1 coat or dip. Apply a second coat only if it will absorb.	Grain and natural color slightly changed	Same as with WRP	2–3 years
Semitransparent stain	Brush-apply 1 coat or dip. Apply a second coat only if it will absorb.	Grain visible; color as desired	Same as with WRP	4–8 years (on saw-textured or weathered wood)
Paint and solid-color stain	Brush-, roller-, or spray-apply primer and 2 top-coats	Grain and natural color obscured	Clean and apply topcoat if old finish is sound; if not sound, remove peeled finish, prime, and apply topcoats ^d	10–20 years for paint ^e ; 6–15 years for solid-color stain ^e

^aCompilation of data from observations of many researchers.

^bVertical exposure; service life depends on surface preparation, climate and exposure, amount and quality of finish, and the wood species and its surface texture.

^cService life of 20 years if primer and two coats of top-quality latex top-coats are used on gradual transition wood species having a saw-textured surface. Dark colors may fade within a few years.

^dIf old finish does not contain lead, sand to feather rough edges of paint surrounding bare areas and areas of weathered wood (see Lead-Based Paint).

^eService life of 15 years if primer and two top-coats are used on saw-textured wood.

Refinish exterior wood when the old finish has worn thin and no longer protects the wood. If all factors are working in concert (good structure design to shed water, effective flashing, paintable wood surface, and end grain sealed), paint degradation is benign weathering of paint to expose the primer or in the case of a penetrating finish, to expose the wood surface. In these cases, there is rarely much surface preparation other than mild washing prior to refinishing. Mildew growth is not paint degradation, but an appearance problem; remove it with a commercial cleaner or bleach–detergent solution. If factors are not working in concert, paint may crack and peel.

Oil-Based Semitransparent Stains

Oil-based semitransparent stains have more pigment than tinted WRPs, and the pigment gives more protection to wood. Stains usually contain a WR and fungicide. Additional pigment maintains color and increases finish service life, but pigments give stain a less natural appearance than lightly colored finishes because they partially hide wood grain and color. Pigment content in semitransparent stains can vary, thus providing a range of UV protection and color. Most people prefer colors that accentuate the natural color of the wood.

Oil or oil-alkyd resin in oil-based semitransparent stains can flow into cut lumina at the wood surface carrying pigment with it. Some resin penetrates the cell wall; the rest remains on the surface and bonds the pigments to the surface.

Semitransparent stains are porous and do not form surface films like paints and solid-color stains; therefore, they will not blister or peel even in the presence of excessive water. Service life varies considerably depending on substrate and amount of pigment (Table 16–4).

Resin and paint manufacturers have tried to achieve the properties of solvent-borne semitransparent stains using waterborne formulations. These finishes achieve a semitransparent appearance by forming a thin coating on the wood.

Recently, paint companies have developed “semipenetrating” stains. Semipenetrating stains partially penetrate the cell wall and form a surface film. This finish is similar to a high-solids oil-based semitransparent stain.

Application, New Construction

Semitransparent stains perform well on saw-textured surfaces. If used on smooth wood, expect approximately half the service life compared with saw-textured surfaces (Table 16–4). They are an excellent finish for weathered wood.

To get consistent application and good penetration of stain, brush-apply oil-based semitransparent penetrating stains. The finish is too fluid to use a roller and spraying leads to an uneven appearance and lap-marks. Brushing works the finish into the wood and evens out the application to minimize lap marks. Lap-marks form when application of a stain overlaps a previously stained area (Fig. 16–20). Prevent lap-marks by staining two or three boards at a time and keeping a wet edge. This method prevents the front edge of the stained area from drying before reaching a logical stopping



Figure 16–20. Lap marks on wood finished with semitransparent stain.

place (corner, door, or window). If possible, work in the shade to slow drying. Coverage is approximately 4.9 to 9.8 m² L⁻¹ (200 to 400 ft² gal⁻¹) on smooth wood and from 2.4 to 4.9 m² L⁻¹ (100 to 200 ft² gal⁻¹) on saw-textured or weathered wood.

To increase service life of oil-based semitransparent stains on saw-textured or weathered lumber, apply two coats. Apply the first coat keeping a wet edge to prevent lap marks. Then, work on another area so that the first coat can soak into the wood for 20 to 60 min. Apply the second coat before the first dries (wet on wet application). (Again, apply stain keeping a wet edge to prevent lap-marks.) If the first coat dries completely, it seals the wood surface so that the second coat cannot penetrate. About an hour after applying the second coat, use a cloth, sponge, or brush lightly wetted with stain to wipe off excess stain that has not penetrated into the wood. Where stain failed to penetrate, it forms an unsightly shiny surface film. Stir the stain occasionally and thoroughly during application to prevent settling of pigment.

Two coats of semitransparent penetrating stain may last 10 years on saw-textured wood. By comparison, the life expectancy of one coat of stain on new smooth wood is only 2 to 4 years; however, as the stained wood ages, it becomes more porous and subsequent staining lasts longer (Table 16–5).

Semitransparent stain formulations have changed because of VOC regulations. Solvent systems have changed, and the amount of solids has increased. Formulations having high solids may leave excess resin on the surface (particularly the LW) even if the resin has a low MW. If the finish appears shiny an hour after application, the finish has not penetrated the wood. Remove the excess finish on the surface to avoid forming a thin film; thin films crack and peel within a year or two. Even if the wood surface has weathered or is saw-textured, it may not be possible for a second coat of these finishes to absorb into wood.

Caution: Sponges, cloths, and paper towels that are wet with oil-based stain, any other oil or oil-alkyd, or urethane finish are particularly susceptible to spontaneous combustion. To prevent fires, immerse such materials in water and seal in a water-filled air-tight metal container immediately after use.

Refinishing

Oil-based semitransparent penetrating stains degrade by slow erosion of pigments to give a gray slightly weathered appearance. Refinish when wood begins to show before all pigment is lost. Stains do not crack or peel unless excessive stain formed a film. Simply use a dry stiff-bristle brush to remove surface dirt, dust, and loose wood fibers and re-stain. As with clear finishes, remove mildew prior to refinishing. The subsequent application of penetrating stain often lasts longer than the first because it penetrates the porous weathered surface.

If oil-based semitransparent stain did not penetrate properly and formed a film, it may fail by cracking and flaking. In this case, surface preparation may involve scraping and sanding. For wood having a thick film, it may be necessary to remove all the old finish with a paint stripper prior to re-staining. This is a difficult situation; parts of the structure may have areas where the old finish eroded and the surface is weathered; parts may have an intact or peeling film. Oil-based stains do not penetrate areas having a film; film-forming finishes (paint or solid color stain) do not bond to weathered areas. Either remove the finish in places having a film and re-stain or scuff sand the weathered area, scrap and scuff sand the area having a film, and refinish with solid-color stain or paint.

When refinishing semitransparent stains, the stain must penetrate wood. As mentioned above, stain service life varies with exposure (that is, the weathering of the stain); therefore, stain may not penetrate well in some areas. For example, an area under the eaves, even on the south side of a structure, may be relatively unweathered compared with the lower part of the wall. When applying stain to such an area, feather the new stain into the old. If the stain does not penetrate the wood within an hour, remove excess stain to avoid forming shiny spots, which indicate a film. The north side of a structure may not need to be re-stained nearly as often as the south side (northern hemisphere).

Do not apply oil-based semitransparent stains over solid-color stain or paint.

Note: Do not use steel wool or wire brushes to clean wood or to prepare a surface for refinishing because they contaminate the wood with iron. Minute amounts of iron react with tannins in woods like western redcedar, redwood, and oak to yield dark blue–black stains (see Finish Failure or Discoloration).

Oils

Drying oils, such as linseed and tung, are appropriate natural finishes for indoor use and are fine for indoor furniture and other interior uses not subjected to water or high humidity. Oils perform poorly outdoors because they are natural products and therefore provide food for mildew. When used on highly colored woods such as redwood or the cedars, they tend to increase mildew growth. Even if formulated with a mildewcide, they may not give adequate performance outdoors. The original “Madison Formula” for a semitransparent stain could be formulated with up to 60% linseed oil and it contained 5% pentachlorophenol as a mildewcide. Even with this mildewcide, it was prone to develop mildew.

Film-Forming Finishes

In a range of least to most protection from UV radiation and photochemical degradation of wood, film-forming finishes are ranked as follows: clear varnish, pigmented varnish, waterborne latex semitransparent stains, solid-color stains, and paints.

Clear Varnish

Clear varnish is a transparent film-forming finish that enhances the natural beauty and figure of wood. In a book originally published in 1904, A.H. Sabin listed 16 types of varnish (architectural, cabinet, carriage, marine, and piano, to name just a few) (Sabin 1927). These varnishes were a solution of natural resins, linseed or tung oil, or both, and turpentine. In a recent publication, Wicks and others (2007) describe modern varnishes as urethane-modified alkyds. Spar varnish (a combination of novolac phenolics resin and tung and linseed oils) is also available. Urethane-based varnishes have good abrasion resistance and perform well on furniture, floors, and interior woodwork. However, varnish lacks exterior permanence unless protected from direct sunlight; varnishes in direct sunlight generally require refinishing every 1 to 2 years. Varnishes embrittle by exposure to sunlight and develop severe cracking and peeling. They last longer in protected areas, such as soffits, doors protected by porches, or the north side of structures; however, even in protected areas, apply a minimum of three coats. Staining the wood (oil-based semitransparent stain) prior to applying varnish improves its service life; the pigments in the stain decrease the photodegradation of the wood, thus maintaining varnish adhesion. Varnish is a high-maintenance finish and is not generally used on the exterior of structures.

Clear varnish usually fails by a combination of cracking and UV degradation of the wood at the wood–varnish interface. This can be identified by examining the back of a chip of varnish and finding wood fiber attached. Refinishing usually requires scraping, sanding, or power-washing the finish off and then reapplying the finish.

Pigmented Varnish

Finish manufacturers have modified clear varnish to improve exterior performance by adding finely ground inor-

ganic pigments (nanopigments). These pigments partially block UV radiation yet allow much of the visible light to pass through the finish—that is, they appear transparent. The particle size of these pigments is similar to the wavelength of UV radiation (300–400 nm), and much like dust in the atmosphere that blocks UV radiation and blue wavelengths of visible light to make the sun appear red during a sunset, pigments block UV radiation to protect wood. These products perform better than traditional clear varnishes. However, as with clear varnishes, pigmented varnish gives excellent performance in protected areas. The varnish is less prone to peel; degradation initially occurs on the film surface as crazing. Refinishing before the crazing develops into cracks restores the appearance. Eventually, however, the buildup of coats will block visible light and the wood will appear dark.

Varnish can give years of service on outdoor furniture if the furniture is covered with an opaque waterproof cover when not in use. The cover protects the varnished wood from UV degradation and discourages birds from roosting on the furniture. Several coats of varnish eliminate splinters, allow the beauty of the wood to show, and give a cleanable surface.

Waterborne Latex Semitransparent Stains

Waterborne latex semitransparent stains (introduced in the section on Oil-Based Semitransparent Stains) are discussed here because they form films. These finishes are usually an acrylic or modified acrylic and have high MW; the polymers are too large to penetrate the cell wall. Considerable confusion remains concerning penetration of these finishes. As mentioned previously, penetration of a finish into cut lumina on the wood surface is not penetration into wood. Filling the lumen does not modify the wood cells near the surface. Latex semitransparent stains give the look of an oil-based semitransparent stain by forming a thin film.

Whereas oil-based semitransparent stains slowly erode, latex semitransparent stains tend to crack and flake. The film buildup is not sufficient to give performance needed for a film-forming finish. If applied in sufficient coats to give more than a few years performance, they give the appearance of a solid-color stain. Some formulations are modified with oil-alkyds. The oil penetrates the surface, thus improving the performance of the finish. Paint companies continue to improve these formulations; check with paint suppliers for the latest information on new products.

Application, New Construction

Latex-based semitransparent stains should be brush-applied. As with oil-based semitransparent stains, they are susceptible to forming lap marks. Apply the second coat within 2 weeks after the first has dried. Latex-based stains last longer on saw-textured wood.

Refinishing

Scrape areas where the stain has flaked, wash, if necessary, and refinish. As with oil-based semitransparent stains, to avoid an uneven appearance, it may be necessary to feather the new finish into the old in areas where the old stain is still in good condition. Waterborne latex stains form a thin film and may not adhere well to weathered wood.

Solid-Color Stains

Solid-color stains are opaque finishes (also called hiding, heavy-bodied, or blocking stains) that come in many colors and are made with a higher concentration of resin and pigment than are semitransparent penetrating stains; therefore, solid-color stains obscure the natural color and grain of wood. They are available in latex-based (usually acrylic or modified acrylic polymers) and oil-based formulations. Oil and latex solid-color stains are similar to paints; they form a film.

Application

Apply solid-color stains by brush, sprayer, or roller. If using a sprayer or roller, back-brush to even out the application and work the finish into the surface, particularly on saw-textured wood. One coat of solid-color stain is not adequate for smooth wood; apply a sufficient number of coats to give a 0.10–0.13-mm (0.004–0.005-in., or 4–5-mil) dry film thickness. If applied in a single coat to smooth wood, they tend to crack and flake; the film lacks sufficient cohesive strength to accommodate moisture-driven changes in dimension of the substrate. Two coats of solid-color stain applied over a quality latex or oil primer should give service life similar to that of a good paint system on smooth-planed wood. Some manufacturers recommend using the first coat of a solid-color stain as a primer, but primer paint might be better, particularly for wood containing extractives (such as cedar and redwood). On saw-textured wood, sufficient film thickness may be possible with a single coat, but primer and one top-coat will usually give 15 to 20 years service life. Solid-color stains lack abrasion resistance and manufacturers do not generally recommend them for horizontal wood surfaces such as decks.

Refinishing

Solid-color stains can usually be applied over paint. See the following section (Paint) for additional information on refinishing. If the old finish has cracked or peeled, remove it and scuff-sand the wood prior to refinishing.

Paint

Paint appears somewhere on almost all buildings. For example, brick-, vinyl-, and aluminum-sided buildings often have painted wood trim. Paints are highly pigmented film-forming coatings and give the most protection against UV radiation. Paints protect wood surfaces from weathering, conceal some surface defects, provide a cleanable surface, offer many colors, and give high gloss (high gloss is not

possible with stains). Paint is the only finish that can give a bright white appearance. Paint retards penetration of moisture, decreases discoloration by wood extractives, and retards checking and warping of wood. However, paint is not a preservative. It will not prevent decay if conditions are favorable for fungal growth.

Paint is available in two general types: solvent-borne oil-alkyds and waterborne latexes (usually acrylic or vinyl acrylic polymers).

Oil-based paint is a mixture of finely ground inorganic pigment in a resin (binder) with additives to speed curing, improve application, and give mildew resistance. The simplest resin is a drying oil, such as linseed oil. Modern oil-based paints have the drying oil combined with a poly functional alcohol to form an oil-alkyd. Oil-alkyds for wood have excess oil (that is, long-oil-alkyds), making them more flexible than short-oil-alkyds (that is, having a shortage of oil). Oil-alkyds form a film by reacting with oxygen in the air to give a cross-linked polymeric network. Prior to regulation of the amount of organic solvent in oil-alkyds, they contained turpentine or mineral spirits. Modern oil-alkyds have complex solvent systems to meet VOC requirements.

Latex-based paint is also a mixture of finely ground pigment in a resin. The resin is a synthetic polymer, and it coalesces to form a film; these polymers do not react with oxygen. The main solvent is water, with other solvents to keep the polymer flexible while it coalesces. Acrylics and vinyl acrylics are typical resins in wood finishes.

Oil-alkyd or latex primers link wood to top-coats and provide a base for all succeeding top-coats (initial top-coats and refinishing). Primers seal the surface to prevent extractives bleed, provide adhesion between the wood and top-coats, and give color base to even out differences in wood color and top-coat color. Primers flow into void spaces at the wood surface to improve top-coat adhesion and block extractives in species such as redwood and western redcedar. At this time, oil-alkyd primers block extractives better than do latex primers, but paint manufacturers continue to improve latex primers. Oil-alkyd primers block water absorption into end grain and, to a limited extent, can penetrate wood cell walls, thus modifying the surface and improving its dimensional stability. Latex primers do not penetrate cell walls but merely flow into cut cells and vessels. Latex primers do not seal the end grain as well as oil-alkyd primers do. Latex primers are more flexible and stay more flexible; thus, they are less likely to crack as they age. Latex primers are porous and thus permeable to water and water vapor; oil-alkyd paints are less permeable to water and water vapor (Table 16–3).

Latex top-coats can be applied over oil-alkyd primers. Latex paints formulated with acrylic resins are resistant to weathering; they maintain their gloss better than oil-alkyd paints. Oil-alkyd top-coats tend to lose gloss within a year or two

and are prone to embrittle over time. Latex paints (primers and top-coats) permit water cleanup; oil-alkyd paints require organic solvents for cleanup. Sufficient dry film thickness on smooth-planed surfaces obscures wood grain and texture; on saw-textured surfaces, some surface texture remains.

Application, New Construction

On smooth-planed wood, apply a primer and two top-coats to achieve a 0.10–0.13-mm (4–5-mil) dry film thickness; on saw-textured wood, primer and one top-coat may suffice. As with solid-color stains, apply paints with brush, roller, or sprayer. If using a roller or sprayer, back-brush to get an even coating and ensure the finish wets the surface. Apply the first coat of film-forming finishes (paint, latex semitransparent stains, and solid-color stains) within 2 weeks after installing smooth-planed exterior wood products; timely application ensures good paint adhesion. Improve film adhesion to smooth-planed flat-grain products, particularly those species having abrupt grain transition, by wetting the wood to raise the grain and scuff sanding (lightly sanding with 50–80 grit sandpaper) after it dries.

For woods with water-soluble extractives, such as redwood and western redcedar, primers block extractives bleed into the top-coat. Use a primer that is labeled to “block extractives bleed,” usually an oil-alkyd-based paint. Some manufacturers also formulate stain-blocking acrylic-latex primers. Allow latex stain-blocking primer to dry for at least 24 to 48 h before applying the first top-coat. If the primer has not fully coalesced, extractives may bleed into the top-coat. For species, such as pine, that do not tend to have extractives bleed, a quality primer is still necessary to give a good base for top-coats. Follow the application rates recommended by the manufacturer to achieve sufficient film thickness. A uniform primer coating having sufficient thickness distributes wood swelling stresses and thus helps prevent premature paint failure. Primer should cover approximately 6.1 to 7.4 m² L⁻¹ (250 to 300 ft² gal⁻¹) on smooth unfinished wood; coverage is considerably less on saw-textured wood.

Apply two coats of acrylic latex paint over the primer. If applying two top-coats to the entire structure is not practical, consider two top-coats for fully exposed areas on the south and west sides and a single top-coat on other areas. Two top-coats over a properly applied primer should last more than 10 years on smooth wood (Tables 16–4 and 16–5) and many three-coat paint systems in test at FPL have lasted 20 years. To avoid peeling between paint coats, paint manufacturers recommend applying the first top-coat within 2 weeks after the primer and the second top-coat within 2 weeks of the first. If more than 2 weeks elapse between paint coats, it may be necessary to wash the paint with mild detergent and rinse thoroughly. If the primer has been exposed for several months, it may need to be primed again prior to applying the top-coats. However, some primer may not weather as quickly and some top-coats may adhere well to weathered primer; check with manufacturers for information on their products.

Avoid applying oil-alkyd paint to a hot surface in direct sunlight and to a cool surface that the sun will heat within a few hours. The heat causes the surface of the coating to dry, trapping solvent in the film. The trapped solvent forms a “temperature blister,” which usually occurs within a day or two after painting. They do not contain water. Do not cool the surface by spraying with water.

Apply latex-based waterborne paints when the temperature is at least 10 °C (50 °F) and expected to remain above this temperature for 24 h. (The dew point is a good estimate of nighttime low temperature.) Most latex paints do not coalesce properly if the temperature drops below 10 °C (50 °F). Oil-alkyd paint may be applied when the temperature is at least 4 °C (40 °F). Check with paint manufacturers on the temperature requirements because some paints can be applied at lower temperatures than these. As with oil-alkyd paints, avoid painting hot surfaces in direct sunlight. Prior to applying latex paints, the surface can be cooled with water spray and allowed to dry.

Avoid painting late in the afternoon if heavy dew is expected during the night. Water absorption into partially cured oil-alkyds or partially coalesced latexes can cause wrinkling, fading, loss of gloss, and streaking.

Refinishing

In the absence of catastrophic failure such as cracking, flaking, and peeling, solid-color stains and paints slowly erode. A three-coat finish system (0.10–0.13 mm thick) may last 20 years on saw-textured wood. When the top-coats begin to wear thin exposing the primer, reapply one or two new top-coats. One coat may be adequate if the old paint surface is in good condition. Surface preparation merely involves washing the surface to remove mildew, dirt, and chalk. Paint erodes at different rates, depending on the exposure to sunlight; therefore, different sides of a structure do not need to be painted on the same schedule. Paint on the north side lasts twice as long as that on the south side (northern hemisphere). When repainting, coverage should be approximately 9.8 m² L⁻¹ (400 ft² gal⁻¹).

Clean areas that are protected from sun and rain, such as porches, soffits, and walls protected by overhangs. These areas tend to collect dirt that decreases adhesion of new paint. Repainting protected areas every other time the structure is painted usually gives adequate performance.

Do not paint too often. If paint is sound, but discolored with mildew, wash it. It does not need repainting. Frequent repainting may form an excessively thick film; thick oil-based paint is likely to crack across the grain of the wood (see Cross-Grain Cracking). Latex paints seldom develop cross-grain cracking because they are more flexible than are oil-based paints. Since latex paints have replaced oil-based top-coats for most exterior applications, cross-grain cracking is rare except for latex paint applied over thick oil-based

paint. However, too many coats of latex paint can eventually lead to adhesion failure of the primer.

In situations where catastrophic failure has occurred, refinishing paint and solid-color stains may require extensive surface preparation. First, scrape off all loose paint. **In the absence of lead-based paint**, sand areas of exposed wood with 50- to 80-grit sandpaper to remove the weathered surface and to feather the abrupt paint edge. Wash the remaining old paint using a commercial cleaner or a dilute household bleach and detergent solution to remove dirt and mildew and rinse thoroughly (see Mildew). Prime the areas of exposed wood, then top-coat. If the old paint has excessive chalking, it may be necessary to re-prime (see Chalking).

Note: Do not sand lead-based paint. Use special precautions if the old paint contains lead (see Lead-Based Paint).

Table 16–4 summarizes the suitability and expected life of commonly used exterior finishes on several wood species and wood-based products. The information in these tables gives general guidelines. Many factors affect paintability of wood and service life of wood finishes. Table 16–5 summarizes the properties, treatment, and maintenance of exterior finishes.

Application of Finishes, Special Uses

Porches, Decks, Deck Railings, and Fences

Porches get wet from windblown rain; therefore, apply a WRP or primer to end grain of flooring, railings, posts, and balustrade prior to or during construction. Primers and top-coats for porch floors are formulated to resist abrasion.

Decks are usually finished with penetrating clears, lightly pigmented clears, or semitransparent stains. These finishes need more frequent application than does paint but do not need extensive surface preparation, because they seldom fail by cracking and peeling. Limit the application of semitransparent stain to what the surface can absorb. The best application method is by brush; roller and spray application may put too much stain on horizontal surfaces. Unless specially formulated for use on decks, solid-color stains should not be used on decks or porches because they lack abrasion resistance and they tend to fail by peeling.

Like decks, fences are fully exposed to the weather, and some parts (such as posts) are in contact with the ground; therefore, wood decay and termite attack are potential problems. Use lumber pressure-treated with preservatives or naturally durable wood species for all posts and other fence components that are in ground contact. When designing and constructing fences and railings for decks and porches, architects and contractors need to consider protecting exposed end-grain of components to resist water absorption.

Film-forming finishes on fences and railings trap moisture if the end grain is not sealed during construction. Figure 16–14 shows a railing 8 years after construction. Water flowed down the railing and absorbed into the end grain, and the paint kept the wood from drying. If railings are to be painted, seal the end grain or use pressure-treated wood, particularly where decay of wood is a safety hazard (railings on decks and porches high off the ground).

Concerning the service life of naturally durable wood species compared with wood pressure-treated with preservatives, there are no absolute “rules.” However, for in-ground contact uses and structural components of decks and porches (beams, joist, and railings), pressure-treated wood is probably better and may be a code requirement in some areas. The service lives of naturally durable and preservative-treated woods are quite comparable in aboveground exposures, such as decking boards. In selecting wood for porches, decks, and fences, whether preservative treated or a naturally durable species, consider the exposure conditions, design of the structure, properties of the wood, and the finish to be used. Wood weathering can be as much a factor in long-term service life of decks and fences as decay. Protect naturally durable wood species and preservative-treated wood with a finish. Periodic treatment with a penetrating sealer, such as a WRP or lightly pigmented deck finish will decrease checking and splitting. Pigmented finishes retard weathering.

Treated Wood

Copper-based preservatives (copper azole, ammoniacal copper quat (ACQ), ammoniacal copper zinc arsenate (ACZA), chromated copper arsenate (CCA)), creosote, and pentachlorophenol are common factory-applied preservatives. Of these, wood treated with copper azole and ACQ is often used to construct porches, decks, and fences. The treatment has little effect on finishing once the wood has dried; species and grain orientation affect finishing more than preservative treatment does. Waterborne treatments containing copper may maintain a brown color for approximately 2 years. Some copper-based preservatives may have a water repellent included in the treatment to give the treated wood better resistance to weathering. Even if the manufacturer treated the wood with water repellent, maintain it with a finish to extend its service life. People often replace decking because of weathering, not decay.

Creosote and pentachlorophenol are generally used for industrial and commercial applications where applying a finish is not considered practical. Creosote is oily, and wood treated with creosote does not accept a finish. Pentachlorophenol is often formulated in heavy oil. Wood treated with preservatives formulated in oil will not accept a finish.

Marine Uses

The marine environment is particularly harsh on wood because of wind-blown salt spray, abrasion by sand, and direct and reflected UV radiation. Any of the types of finish discussed previously can be used in marine environments.

Chapter 16 Finishing of Wood

WRPs, tinted clears, and oil-based semitransparent stains give some protection; however, a paint system gives the best protection against photochemical degradation. If possible, finish wood with a WRP prior to painting. Consult paint manufacturers for products formulated for marine use.

Note: Any wood in contact with water must be pressure treated to specifications for marine use. Chromated copper arsenate (CCA) is still used in marine environments, and the chromium in the formulation improves the performance of stains and paints.

Boats

Varnish enhances the appearance and protects wood trim on boats (hence the name spar varnish), but it is exposed to more sunlight and water than on structures. Therefore, it needs regular and frequent refinishing. Paint manufacturers recommend three to six coats for best performance. Applying oil-based semitransparent stain to wood prior to varnishing increases the service life of the varnish, but the stain obscures some of the color of the wood. Keeping the appearance of wood trim bright and new is labor intensive but often well worth the effort.

Finish hulls with marine paint (two-part epoxy- or urethane-paint). Protect areas below the water line with antifouling paint. Consult manufacturers for information on these products.

Panel Products

The edges of panel products such as plywood, OSB, and fiberboard are vulnerable to absorption of water. To minimize edge swelling and subsequent finish peeling, seal the edges of these products with a WRP, oil-alkyd primer, or sealer formulated for this use. The type of edge sealer depends on the surface finish. Prior to staining (oil-based semitransparent stain), seal with the stain or a WRP; prior to painting (paint or solid-color stain), seal with an oil-alkyd primer.

Plywood siding products may have a saw-textured surface (such as T1–11 siding) or a paper overlay (MDO). Saw-textured surfaces may be finished with oil-based semitransparent stain, solid-color stain, or paint. Paint gives the longest service. Paper overlay products will not accept a penetrating finish (such as oil-based semitransparent stain); finish with paint or solid-color stain.

During pressing of OSB and fiberboard panels for exterior use, manufacturers usually include MDO. The panels are cut to give lap siding. The MDO protects the surface from moisture and gives a good surface for film-forming finishes. However, as with plywood, the edges and areas around fasteners are vulnerable to water absorption and need to be sealed.

Fire-Retardant Coatings

Fire-retardant finishes have low surface flammability, and when exposed to fire, they “intumesce” to form an expanded

low-density film. The expanded film insulates the wood from heat and retards combustion. The finishes have additives to promote wood decomposition to charcoal and water rather than flammable vapors.

Back-Priming

Back-priming is applying primer or WRP to the back side of wood (usually siding) before installing it. Back-priming with stain-blocking primer retards extractives staining, particularly run-down extractives bleed. It decreases absorption of water, thus improving dimensional stability. Siding is less likely to cup, an important consideration for flat-grain wood. Improved dimensional stability decreases stress on the finish, thus decreasing paint cracking.

At the time siding is back-primed, seal end grain with oil-alkyd primer. This process has an even greater effect in stopping water absorption than back-priming. Primed end-grain eliminates paint failure near the ends of boards. Prime ends cut during installation.

Factory Finishing

Factory priming hardboard siding has been a standard industry practice for many years, and recently, factory-finished (primer and top-coats) siding, trim, and decking have become common. Factory finishing offers several advantages: avoids finishing during inappropriate weather, gives consistent film thickness, contributes to timely completion of structures, and decreases overall cost. Factory finishing is advantageous in northern climates where exterior finishing is impossible during the winter. Controlled application ensures consistent 0.10 to 0.13 mm (4 to 5 mil) dry film thickness. Siding is normally primed on all sides, including the end grain. When installing factory-finished siding, prime following cross-cuts. Controlled conditions enable many factory finishers to guarantee their products against cracking, peeling, and blistering for 15 years.

Finish Failure or Discoloration

Properly applied to a compatible substrate on a well-designed and constructed structure, finishes rarely fail prematurely. In the absence of finish failure (cracking and peeling) or discoloration (extractives bleed, iron stain, and mildew growth), finishes undergo a slow erosion lasting several years—even decades. This section is about “when things go wrong”.

The most common causes of premature failure of film-forming finish (paint and solid-color stains) are water, weathering of wood prior to painting, inadequate surface preparation, and insufficient film thickness. Structure design, wood species, and grain angle can also affect performance. Topics covered in this section are paint cracking (parallel to grain), cross grain cracking, peeling, intercoat peeling, chalking, mill-glaze, mildew, blue stain, iron stain, and brown stain over knots.

Exterior paint is subject to wetting from rain, dew, and frost. Equally serious is “unseen moisture” (water vapor) that moves from inside to outside structures in cold climates and from outside to inside of air-conditioned buildings in hot climates. Effective air and vapor barriers can minimize water vapor movement (see Chapter 13).

Paint Cracking (parallel to grain)

Cracking parallel to grain occurs on smooth flat-grain lumber, particularly with wood species having abrupt transition between EW and LW bands (such as southern yellow pine, Douglas-fir, and oak). LW bands are compressed into EW during planing. Normal rebound of LW bands after wood is in service causes films to crack along the EW–LW boundary. Other contributing factors are coatings having insufficient thickness and lacking flexibility. If the cracking is not too severe, scuff sand and apply one or two top-coats to give additional film-build.

Peeling and Flaking

Peeling and flaking (adhesion failure between wood and the primer) can have several causes: water, wood weathering, and dimensional change of thick LW bands on flat grain of high-density wood species. Flaking often follows cracking; small cracks in paint caused by raised grain allow water to enter. Flaking is similar to peeling; small pieces of finish peel from the surface usually along an EW–LW boundary. Flaking often occurs with cracking parallel to grain and is attributed to thin films. It can occur with thinly applied film-forming finishes and with oil-based semitransparent stains if they do not absorb properly. Water is the main cause, but other factors can also cause it.

Water speeds the failure by other causes. One cause is weathering of wood prior to primer application. Protect wood from the weather prior to installation and paint it as soon as possible after installing it. Leaving smooth-planed lumber exposed to the weather for as little as 2 weeks decreases its paint-holding properties. If wood was exposed more than 2 weeks, scuff sand it prior to painting. In fact, scuff sanding is always a good idea on planed lumber. The wide bands of LW on flat-grain surfaces hold paint poorly. If possible, flat-grain boards should be installed “bark-side” out to minimize raised grain particularly with wood species having abrupt EW/LW transition. Paint applied to weathered wood often fails over large areas and can be easily diagnosed by inspecting the back side of the peeled paint. Wood fibers are attached to the film clearly showing the grain of the wood.

Priming end grain with oil-alkyd paint eliminates peeling at the ends of boards. Saw-texture greatly improves finish adhesion to all species and grain angles. Paint and solid-color stains adhere quite well to difficult-to-paint wood species such as flat-grain southern yellow pine, Douglas-fir, and radiata pine, if applied to saw-textured surfaces.



Figure 16–21. Water blisters (also called moisture blisters) caused bubble-like deformation of paint film.

Cross-Grain Cracking

Modern waterborne latex finishes seldom fail by cross-grain cracking. If latex finishes crack across the grain, dimensional instability of wood under the finish causes it. For example, cross-grain checking of juvenile wood causes paint to crack. In this case, replace the board and repaint.

If juvenile wood is not to blame, cross-grain cracking usually occurs on structures having thick layers of oil-alkyd paint. If the wood is not the cause of paint failure, remove the old paint and apply new finish to the bare wood. Old paint probably contains lead (see Lead-Based Paint).

Water Blisters

Water Blisters (also called moisture blisters) are bubble-like deformation of paint films (Fig. 16–21). As the name implies, these blisters usually contain water when they form. Water blisters form between the wood substrate and the first coat of paint. After the blisters appear, they may dry out and collapse. Small blisters may disappear completely and large ones may leave rough spots; in severe cases, the paint peels. Oil-alkyd paint recently applied to wet wood is most likely to blister. Old paint films are too rigid to swell and form blisters; they usually crack and peel. Water blisters are not common on latex paint systems.

Minimizing water absorption into wood is the only way to prevent water blisters. Water blisters may occur on siding and trim where rain enters through improperly flashed doors, windows, and vents; they are common near unsealed end grain of siding and trim. Water from ice dams and overflow from blocked gutters can also cause water blisters. Movement of water vapor from the inside of a structure to siding and trim may also cause water blisters. Plumbing leaks, humidifiers, and shower spray are sources of inside water. Minimizing water absorption also prevents decay (rot), warping, and checking of wood.

Mill Glaze

Since the mid-1980s, a condition known as “mill glaze” (also called planer’s glaze) has been reported to cause paint

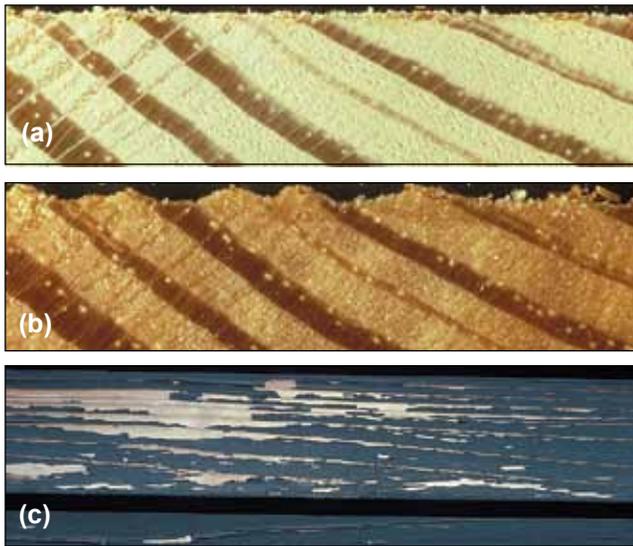


Figure 16-22. (a) Cross-section view of flat-grain southern yellow pine showing dense LW bands crushed into less dense EW directly beneath them; (b) raised grain caused by rebound of LW bands following wetting; (c) a thin coat of film-forming finish applied over a stressed flat-grain surface will crack as the wood rebounds.

failure. Controversy exists over the exact cause of this condition, and many people use it as a catch all for unexplained paint failures. They attributed the paint failure to dull planer blades or excessive heat during planing. However, investigations of reported mill glaze by FPL scientists showed that other factors caused finish failure; scientists were unable to duplicate mill glaze in the laboratory. FPL scientists found three causes for paint failures that others had attributed to “mill glaze”: (1) raised grain under a thin film, particularly on smooth flat-grain lumber, (2) wood weathering prior to application of film-forming finishes, and (3) moisture (usually water). These factors often occurred together.

Paint failure occurred because of raised grain on flat-grain boards, particularly on species having abrupt EW–LW transitions. Planer blades tend to crush dense LW bands into less dense EW that lie directly beneath them on flat-grain surfaces (Fig. 16-22a). Later, when these boards are exposed to moisture, crushed EW absorbs moisture and rebounds, which causes the surface LW bands to protrude from the surface (Fig. 16-22b). A thin coat of film-forming finish applied over a stressed flat-grain surface will crack as the wood rebounds (Fig. 16-22c; see Paint Cracking). Failure is most common on flat-grain siding finished with insufficient film build of oil-based solid-color stain. Thin coatings of oil-based solid-color stain and to some extent waterborne latex stains are weak and do not withstand the stresses caused by raised grain. These low-solids coatings provide only 0.03 to 0.05 mm (1 to 2 mil) of dry-film thickness, whereas a brush-applied three-coat paint system (primer and two top-coats)

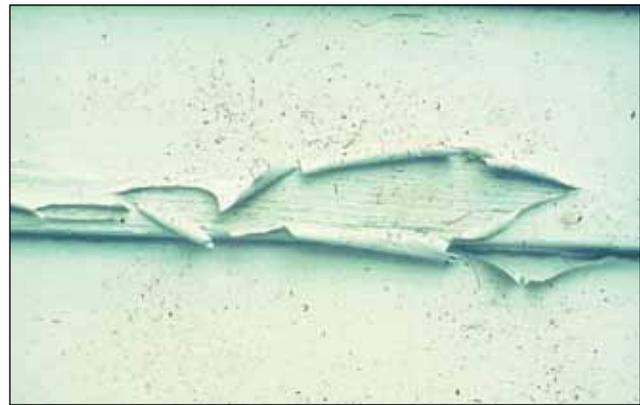


Figure 16-23. Intercoat peeling of paint, usually caused by poor preparation of old paint surface or excessive weathering of primer prior to application of top coat.

provides 0.10 to 0.13 mm (4 to 5 mil) of dry-film thickness. Raised grain is less likely to occur with vertical-grain wood because the EW–LW bands are perpendicular to the surface and the EW is not crushed during planing.

Install flat-grain bevel siding saw-textured side out. Saw-textured surfaces do not have LW bands compressed into the EW. The saw-textured side is the side of choice for application of penetrating semitransparent stains and film-forming finishes. The film buildup on the saw-textured side will be greater than on a planed surface, and the film will have greater mechanical adhesion or “bite.”

If flat-grain siding must be installed smooth-side out, remove the planing stresses by wetting the surface, then allow 2 to 3 days for the surface to dry. Scuff-sand the surface with 50- to 80-grit sandpaper and apply primer and two top-coats.

Another paint failure that has been attributed to “mill glaze” is peeling caused by wood weathering prior to applying film-forming finishes (see Weathering, Effect on Paint Adhesion). Water causes paint to peel (see Peeling and Flaking and Water Blisters).

Intercoat Peeling

As the name implies, intercoat peeling is loss of adhesion between coats of finish, usually peeling of a new paint from old paint (Fig. 16-23). It usually occurs within a year of repainting. Prevent intercoat peeling by ensuring that old paint is free of dirt, mildew, and chalk prior to repainting.

Intercoat peeling can also result from allowing too much time between applying primer and top-coat. If more than 2 weeks elapse between applying an oil-based primer and a top-coat, clean the surface before applying the second coat. If the primer (particularly oil-alkyd primers) has weathered for several months, it may be necessary to re-prime prior to applying the top-coats (see Testing for Adhesion).



Figure 16–24. Mildew is most common in shaded, moist, or protected areas (a) on wood and (b) on painted wood.

Chalking

Weathering of paint causes chalking; chalk is a residue of degraded resin and pigments. These degradation products form a fine powder. Some chalking is desirable because it allows the paint to self-clean. However, chalking is objectionable when the degradation products (especially the pigments) wash down a surface having a different color or when it causes premature paint failure through excessive erosion. Most paints chalk to some extent, but chalking is minimal with modern latex paints.

Latex paint or solid-color stain can be applied over existing paint if the old paint is clean and sound (chalk free). Prior to refinishing a chalky surface, scrub it thoroughly with a detergent solution to remove degraded finish residue and dirt. Rinse thoroughly before repainting. To check for excessive chalking, lightly rub the paint surface with a dark (for light-colored paint) or white (for dark-colored paint) cloth. The amount of pigment removed by the cloth is a good indication of chalking. If the surface is still chalky after cleaning, it may need to be primed prior to repainting. Otherwise, the new paint may peel. Before repainting surfaces, conduct a simple test (see Testing for Adhesion).

Testing for Adhesion

After preparing old paint for repainting, repaint a small inconspicuous area and allow it to dry at least overnight. To test for adhesion, firmly press one end of an adhesive bandage onto the repainted surface. Remove the bandage with a snapping action. If the tape is free of paint, the new paint is well-bonded to the old surface and does not need priming or additional cleaning. If the new latex paint adheres to the tape, the old surface is too chalky and needs additional cleaning or priming with an oil-alkyd primer. If both the new latex paint and the old paint coat adhere to the tape, the old paint is not well bonded to the wood and must be removed before repainting. You should test several areas of the structure to determine the extent of poor paint bonds before stripping all the paint.

Mildew

In the absence of catastrophic paint failures described above, mildew is probably the most common problem with finishes. Mildew is the term for fungi that infect wood (Fig. 16–24a) and painted wood (Fig. 16–24b). These microorganisms can live on any surface that supplies a food source from either within the material or from air or liquids that contact the surface. Although the organisms cannot decay wood, they can metabolize some of the extractives in wood and natural oils (such as linseed oil) in finishes. They usually discolor wood or finishes with black deposits and often grow in combination with algae (usually green discoloration).

Mildew may be found anywhere on a building and is common on walls behind trees or shrubs where air movement is restricted and walls stay damp. Mildew may also be associated with dew patterns of structures. Dew forms on parts of structures that cool rapidly, such as eaves, soffits, and ceilings of carports and porches. The dew provides a source of water for mildew.

Mildew can be distinguished from dirt by examining it with a 10× magnifying glass (such as a jeweler’s eye loupe). In the growing stage, when the surface is damp or wet, the fungus has threadlike growth. In the dormant stage, when the surface is dry, the fungus has numerous egg-shaped spores; by contrast, granular particles of dirt appear irregular in size and shape. A simple test for the presence of mildew on wood or paint is to apply a drop or two of liquid household bleach (5% sodium hypochlorite) to the discolored area. The dark color of mildew will usually bleach out in 1 to 2 min. Surface discoloration that does not bleach is probably dirt, extractives bleed, or iron stain. Mildew can grow through a surface coating or under a clear finish. In these cases, it may be difficult to test for or to clean the mildew; the finish protects the mildew from the cleaning solution.

To remove mildew, use a commercial cleaner or a dilute solution of household bleach with detergent. If using household bleach, use as dilute a solution as possible. One part

bleach to five parts water should be adequate. In no case should a mixture stronger than one part bleach to three parts water be necessary. Add a little powdered detergent to help remove the dirt. Do not use liquid detergent because it may contain ingredients that react with bleach to give toxic fumes. Gently scrub the surface with a bristle brush or sponge and rinse thoroughly. Rinse using a garden hose, keeping the water stream pointed down to avoid flooding the back side of siding with water. If using a power-washer, keep the pressure low to avoid damaging the wood and, as with the garden hose, keep the water stream pointed down. Refinish the cleaned surface as soon as it has dried using a finish containing a mildewcide.

Household bleach mildew remover

- 1 part (5%) sodium hypochlorite (household bleach) (1 gallon)
- 3 to 5 parts warm water (3–5 gallons)
- A little powdered household detergent (1/2 cup)

Warning: Do not mix bleach with ammonia or with any detergents or cleansers that contain ammonia. Mixed together, bleach and ammonia form a toxic combination, similar to mustard gas. Many household cleaners contain ammonia, so be careful in selecting the type of cleaner to mix with bleach. Avoid splashing the cleaning solution on yourself or plants.

Loss of Gloss and Fading

Loss of gloss and fading typically occurred with traditional oil-alkyd finishes. Although modern acrylic-based latex finishes do not give the high gloss of an oil-alkyd, they maintain gloss much longer. Some pigments fade more than others; check with the paint manufacturer to ensure that the colors will last. White is always a safe choice. The paint and solid-color service-life estimates given in Tables 16–4 and 16–5 do not take into account loss of gloss and fading. Many dark-colored finishes will fade to give unacceptable performance long before the finish fails.

Water-Soluble Extractives

In many hardwoods and softwoods, the heartwood contains water-soluble extractives. (Sapwood does not contain water-soluble extractives.) Western redcedar and redwood are two common softwoods that contain highly colored water-soluble extractives; extractives give these species their attractive color, but they can also discolor paint. When wood gets wet, water dissolves some extractives; then as the wood dries, water carries water-soluble extractives to the surface. The water evaporates leaving extractives behind as a reddish brown stain. Discoloration shows in two ways: diffused and run-down extractives bleed.

Diffused extractives bleed is caused by (1) water from rain and dew that penetrates a porous or thin paint coating, (2) water that penetrates joints in the siding, railings, or trim,

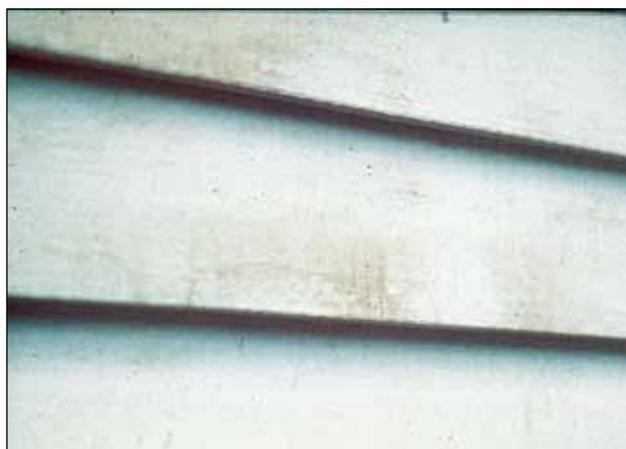


Figure 16–25. High moisture content of wood can cause diffuse extractives bleed, particularly if a stain-blocking primer is not used.



Figure 16–26. Water-soluble extractive discoloration can result from water wetting the back of the siding and then running down the front of the board.

and (3) absorption of water vapor in high humidity areas such as bathrooms, swimming pools, and greenhouses (Fig. 16–25).

Good painting practices prevent diffused extractives bleed. Use an oil-alkyd stain-blocking primer or a latex primer formulated for use over woods like redwood. Do not use porous paints such as flat alkyds or latexes directly over extractive-rich woods. If the wood is already painted and is discolored by extractives, clean the surface and apply a stain-blocking primer. Allow sufficient time for the primer to cure so that it blocks the extractives, and then apply top-coat.

Run-down extractives bleed is caused by (1) water draining behind siding from roof leaks, faulty gutters, or ice dams, (2) condensation of water vapor, originating inside the structure, on the back side of siding, and (3) wind-blown water that wets the back side of siding. The water on the back side of the siding dissolves extractives and runs off of the back



Figure 16–27. Blue stain may infect sapwood.

side of the siding onto the front side of the siding below it, where it evaporates leaving red streaks (Fig. 16–26).

Prevent run-down extractives bleed by (1) fixing roof leaks, maintaining gutters, and preventing ice dams, (2) decreasing condensation or the accumulation of moisture in wall by lowering indoor humidity and installing effective air barriers in wall systems, (3) designing structures having adequate roof overhang to minimize wetting by dew and wind-blown rain, (4) back-priming siding prior to installation with a stain-blocking primer, and (5) using rain-screen construction to vent the back side of siding (see Back-Priming).

By eliminating the cause of extractives bleed, the discoloration will usually weather away in a few months. However, extractives in protected areas (under the eaves, soffits, and porch ceilings) become darker and more difficult to remove with time. In these cases, wash the discolored areas with a mild detergent soon after the problem develops. Paint cleaners containing oxalic acid may remove stains.

Blue Stain

Blue stain is a fungus that can infect sapwood of trees and logs (Fig. 16–27). Insects, such as the pine beetle, may carry it into a living tree. Pine beetle infestation often disrupts the flow of nutrients, thus killing the tree. Sapwood of lumber from beetle-killed trees usually contains blue stain. Blue stain may also infect logs after harvest while the MC is still high. The fungus causes a blue discoloration of the wood, but the organism does not weaken wood structurally. The fungus lacks the enzymes necessary to digest wood polymers; it lives off the unpolymerized sugars in the sapwood (see Chap. 14). Neither commercial mildew cleaners nor household bleach with detergent can remove it. If the color is objectionable, use a pigmented finish to hide it (see Mildew).

Effective control of blue stain takes place prior to using lumber at the construction site: maintain healthy forests,

apply fungicides to logs while in storage prior to cutting lumber, use kiln dry lumber, and keep lumber dry.

Iron Stain

Iron stains occur from rusting of fasteners or by the reaction of iron with tannins in wood. The appearance is different for each of these reactions.

In wood species that lack tannins, iron merely rusts, giving a brown stain to the wood surrounding the fastener. The iron also causes slight degradation of the wood near it (often referred to as “wood sickness”). This discoloration develops over many months or years of exposure.

In those wood species that have tannins, a chemical reaction takes place between the iron and the tannins. Tannins are just one of the many chemicals (extractives) in wood. Species such as the cedars, the oaks, and redwood are rich in tannins. Iron reacts immediately with the tannins to give a blue-black discoloration.

Steel fasteners are the most common source of iron (Fig. 16–28), but traces of iron left from cleaning wood with steel wool or wire brushes cause iron stain. Poor quality galvanized nails corrode easily and, like uncoated steel nails, usually cause unsightly staining of the wood.

If iron stain is a serious problem on a painted surface, countersink the fastener, caulk, spot prime, and top-coat. This costly and time-consuming process is only possible with opaque finishes. Little can be done to give a permanent fix to iron stains on wood having a natural finish. Removing fasteners, cleaning the affected areas with oxalic acid solution, and replacing the fasteners may not give a permanent fix because residual iron left behind continues to cause staining. Removing the fasteners often splits the siding. Using the wrong fastener can be costly—it may become necessary to replace all the siding (Fig. 16–28). Use corrosion-resistant fasteners such as stainless steel rather than risk iron stain, particularly when using natural finishes on wood containing high amounts of tannin (such as western redcedar, redwood, and oak). If using galvanized fasteners, they must be hot-dipped galvanized fasteners meeting ASTM A 153/A specification. Other galvanized fasteners fail. Unfortunately, contractors and their employees may have difficulty recognizing the difference among galvanized fasteners (Fig. 16–28).

Iron stain occurring beneath a finish is extremely difficult to fix. The coating must be removed before the iron stain can be removed. Oxalic acid will remove the blue–black discoloration. Apply a saturated solution (0.5 kg of oxalic acid per 4 L (1 lb gal⁻¹) of hot water) to the stained surface. Many commercial brighteners contain oxalic acid, and these are usually effective for removing iron stains. After removing the stain, wash the surface thoroughly with warm water to remove the oxalic acid. If even minute traces of iron remain, the discoloration will recur.



Figure 16-28. Iron stain on newly installed wood siding. Poor quality galvanized nails corrode easily and, like uncoated steel nails, usually cause unsightly staining of the wood.



Figure 16-29. Pitch flow from wound.

Caution: Oxalic acid is toxic; take care when using it. (It is the poison in rhubarb leaves.)

Knots

Knots in many species contain an abundance of resins and other highly colored compounds. These compounds can sometimes cause paint to peel or turn brown. Eliminating paint discoloration caused by extractives in knots is difficult because some of the extractives are soluble in oil-based primers and diffuse through them. Latex-based formulations do not block them either. Coat the knot with shellac or specially formulated knot sealer. Do not use varnish to seal knots; varnish is not formulated for this use. After sealing knots, apply primer and two top-coats. Knots usually check as wood dries; if the checks form after the wood has been

painted, the checks cause the paint to crack (see Wood Extractives).

Pitch

Pitch and other resins are one of the defense mechanisms that a tree uses to protect itself from harmful pathogens and insects following injury. When a tree's bark is damaged, pitch flows into these areas to protect the wound (Fig. 16-29). Pitch exists as a normal part of the wood of pines (*Pinus* spp.), spruces (*Picea* spp.), larches (*Larix* spp.), and Douglas-firs (*Pseudotsuga* spp.), and it can be found in specialized wound structures called pitch pockets in the wood of most softwood species. Pitch is a solution of natural rosins and turpentine in species such as spruce, pine, and fir. It remains in the lumber from these species. The ease with which it exudes to the surface of lumber depends on the amount of turpentine in which the pitch is dissolved and the temperature (that is, the more turpentine, the more fluid the pitch; the higher the temperature, the more fluid the pitch). Pitch exudation can occur in isolated spots (Fig. 16-30a) or in large pockets or seams (Fig. 16-30b). When pitch bleed occurs, high temperature is the cause. If the temperature at the surface of the wood increases, usually from being exposed to direct sunlight, the pitch oozes to the surface. If the wood is finished, the pitch may exude through the coating or cause the finish to discolor or blister.

The only way to prevent pitch bleed is to remove the turpentine from the wood during lumber processing. Depending on the species, specific kiln schedules can be used to drive off most of the turpentine, thus "fixing" or "setting" the pitch (making it less fluid). However, not all end uses of lumber require pitch to be set; construction grades of lumber, even if kiln-dried, seldom have the pitch set. This is usually not a problem for construction grades because the wood surface is seldom visible. The difficulty occurs with appearance grades of lumber, such as for siding and trim.

Kiln schedules for setting pitch involve higher temperatures and last longer than normal drying schedules. For a complete guide to drying schedules, refer to publications such as the *Dry Kiln Operator's Manual*.

Pitch can be removed in several ways, depending on how fluid it is. If the pitch has not hardened (it still contains a lot of turpentine), remove it with turpentine or mineral spirits. Once it has hardened, scrape it off with a putty knife or paint scraper. However, if the pitch is still soft, such procedures smear it over the surface of wood or paint. Let it harden, and then scrape it off. After removing pitch, sand to bare wood, spot prime, and top-coat. Shellac seals extractives but not pitch. Paint will not prevent future bleeding of pitch during periods of high temperature. If pitch is a recurring problem, it may be necessary to replace the board. One should note that many paints, particularly oil-alkyds, fade as they age and repainting the spots where pitch was removed may show color differences.

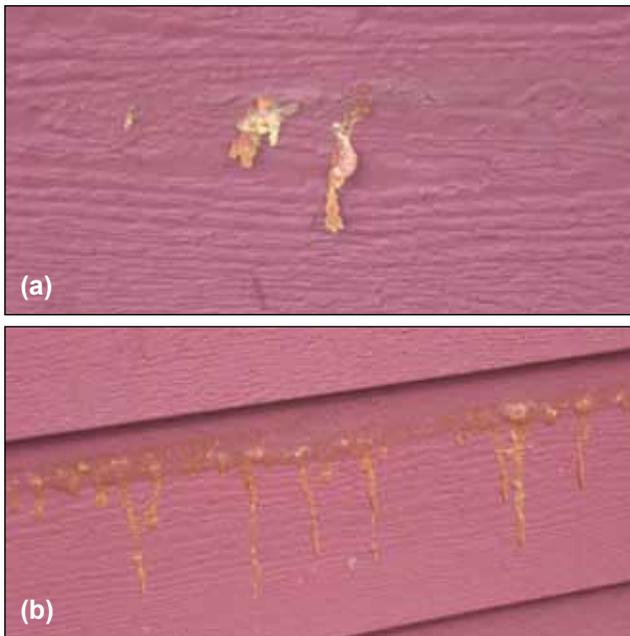


Figure 16–30. (a) Pitch exudation from an isolated spot; (b) pitch exudation from a large pocket or seam.

Finishing Interior Wood

Many finishes and finishing methods are used indoors because of the breadth of wood products and uses—from wood floors to cutting boards. This section includes general information on a few common products used for interior wood finishing and brief subsections on finishing wood floors and kitchen utensils. Many finishing methods exist for just furniture. Factory finishing of furniture is often proprietary and may involve more than a dozen steps. Methods for furniture finishing are not included in this chapter, but most public libraries contain books on furniture finishing. Product literature for furniture finishes often contains recommendations for application. Interior wood products require less protection against water and UV radiation than do exterior wood products, and finishes usually last for decades. However, interior wood products have more exacting standards for appearance and cleanability than do exterior wood products.

As with wood used outdoors, wood changes color as it ages indoors, whether unfinished or finished. In general, dark wood gets lighter and light wood gets darker. Color change is natural aging of newly cut wood and is caused by visible light, not UV radiation associated with outdoor weathering. If removing a picture from paneling shows a color difference (shadowing by the picture), correct it by leaving the wood exposed to light. The color will usually even out within several months. To avoid shadowing, keep all paintings and other wall coverings off paneling until most color change has occurred (usually 2 to 3 months, depending on the light intensity).

Fingerjointed lumber has become common for interior trim. Pieces of wood for fingerjointed lumber often come from different trees having different amounts of extractives. These extractives can discolor finishes, particularly in humid environments such as bathrooms and kitchens (Fig. 16–10). When painting fingerjointed lumber, use a stain-blocking primer to minimize discoloration. In new buildings, allow wood adequate time to reach EMC before finishing.

Types of Finish and Wood Fillers

Opaque Finishes

Interior woodwork, especially wood trim, requires smooth surfaces, consistent color, and a lasting sheen. Therefore, enamels, high-gloss or semi-gloss, are preferable to flat paints. However, the higher the gloss, the more the finish accentuates imperfections such as planer marks, hammer marks, and raised grain. Raised grain is troublesome on flat-grain surfaces having abrupt EW–LW transitions, because planing crushes LW bands into the EW; later, when the MC changes, the EW swells causing raised grain. To obtain a smooth finish, sponge unfinished wood with water to raise the grain, allow it to dry thoroughly, sand, remove surface dust with a tack cloth, and finish.

Stains

Stains accentuate wood grain by absorbing differently into EW, LW, knots, vessels, and flaws. Stains color EW more than LW, reversing the natural color gradation. For uniform color, apply a penetrating sealer (“wash coat”) before applying stain. It impedes stain absorption into the EW. Interior stains are often natural or synthetic dyes dissolved in water or organic solvent. Water-soluble stains give depth to a finish, dry slowly, raise the grain, and require sanding. Solvent-borne stains dry quickly, do not raise the grain, and need little or no sanding. A combination of solvent- and water-borne stains or dyes can give the finish color “depth.”

If stain absorbs into wood unevenly, causing a blotchy appearance, blue-stain fungi or bacteria probably infected the tree prior to cutting for lumber. Blue stain on lumber is easy to see. However, bacteria-infected areas have no color and wood appears normal. Infected areas absorb excessive amounts of stain quickly, giving wood an uneven blotchy appearance. The infection occurs across grain boundaries. This problem is not very common, but should it occur, it cannot be fixed once the stain is applied. If wood is to be used for furniture or fine woodwork, it might be a good idea to check lumber before using it by applying a stain or denatured alcohol to identify infected areas. (Schofield (2008) describes diagnosing blotching and treating boards prior to staining.) Discard pieces on which stain appears blotchy, apply a wash coat to decrease absorption, or use them where they will not show. Sealing the lumber with dewaxed shellac prior to staining may help; commercial sealers are also available.

Fillers

Hardwoods are ring porous, semi-ring porous, or diffuse porous according to size and location of vessels (see Anatomy). Diffuse-porous and semi-ring-porous hardwoods with small vessels may be finished with paints, enamels, and varnishes in the same way as softwoods. Vessels in most ring-porous hardwoods need to be filled to obtain a smooth finished surface. Filler may be a paste or liquid, natural or colored. Wipe the filler across wood grain to pack it into the vessels; then, wipe with a few light strokes with the grain. Remove surplus filler immediately after the glossy wet appearance disappears. After the filler dries thoroughly, lightly sand it before finishing the wood.

Use slightly different methods for opaque and clear coatings. For opaque finishes, fill vessels, sand, and apply primer/sealer and top-coats. For clear finishes, stain prior to filling to bring out the color of the vessels. Transparent fillers do not affect finish or wood color; colored fillers match or contrast with wood color.

Sealers

Sealers are thinned varnish, shellac, or lacquer used to prevent absorption of finish and prevent bleeding of stains into surface coatings, especially lacquer coatings. Lacquer and shellac sealers dry quickly.

Transparent Finishes

Transparent film-forming finishes such as varnish give excellent performance on wood indoors. However, as with high-gloss finishes, transparent finishes accentuate surface blemishes. Remove all blemishes, such as planer marks and raised grain before finishing. Transparent finishing consists of sanding, staining, filling, sealing, finishing, and sometimes waxing.

Transparent coatings may be gloss varnish, semi-gloss varnish, shellac, nitrocellulose lacquer, natural oils, or wax. Wax provides protection without forming a thick coating and enhances the natural luster of wood. Other coatings, such as shellac, linseed or tung oil, lacquer, and varnish accentuate the natural luster of some hardwoods and seem to give the surface “depth.” Shellac applied by the laborious process of French polishing probably achieves this impression of depth most fully, but the coating is expensive and easily marred by water. Rubbing varnishes give almost as much depth. Lacquers have the advantages of drying rapidly and forming a hard surface, but lacquer requires more coats than varnish to obtain a lustrous appearance. Sufficient film thickness is needed for long service life, particularly for products that are cleaned often, such as kitchen cabinets and tabletops. Varnishes are usually alkyd-modified polyurethane and are available in solvent-borne and waterborne formulations. Waterborne finishes are more likely to raise grain than are solvent-borne finishes and may appear like a plastic film, rather than bringing out the “depth” of the wood



Figure 16–31. Number 2 grade of hickory finished to accentuate the beauty of the various colors, knots, and grain pattern of this species.

substrate. Apply varnish directly to wood or stain prior to varnishing.

Varnish and lacquer usually dry to a high gloss. To decrease gloss, rub finish surface with polishing compound (waterproof sandpaper or powdered pumice stone and water or polishing oil). The final sheen varies with the fineness of the polishing compound; coarse powders make a dull surface and fine powders produce a bright sheen. For a smooth surface with high polish, use rottenstone and oil for final polishing. Varnish and lacquer that give a semi-gloss or satin finish are also available. Do not use steel wool (see Iron Stain).

Natural oils such as linseed oil or teak oil and commercial formulations such as Danish oil are popular. These finishes penetrate wood and do not form a film. Apply two or more coats of oil followed by a paste wax. Oil finishes are easy to apply and maintain, but they soil more easily than film-forming finishes.

Finishes for Wood Floors

Wood is highly desirable flooring for homes, factories, and public buildings and is available in many wood species. Natural color and grain accentuate many architectural styles. Finishes enhance the natural beauty of wood floors, protect them from excessive wear, and make them easier to clean (Fig. 16–31). Detailed procedures and specific products depend largely on the species of wood used and finish preference. Obtain additional information specific to your needs from flooring associations or individual flooring manufacturers.

Finishing floors consists of four steps: sanding the surface, applying filler, staining to achieve a desired color, and finishing with a clear coat. Careful sanding to provide a

smooth surface is essential for a good appearance because the finish accentuates any irregularities or roughness in the surface. A smooth surface requires sanding in several steps with progressively finer sandpaper, usually with a machine unless the area is small. After sanding, remove all dust. Never use steel wool on floors because minute steel particles left in wood cause iron stains. Filler is necessary for wood with large pores, such as red oak, to obtain a smooth glossy appearance (Table 16–1). Stain to obtain a uniform color or to accent the grain pattern. Stain should be an oil-based or non-grain-raising type. Stains penetrate wood only slightly; therefore, protect the stained surface with a clear coating. Refinish the clear top-coats as needed to prevent wearing through to the stained wood. Staining worn spots in a way that will match the color of the surrounding area is difficult.

Whether the wood is stained or not, sealers or varnishes give a clear finish for wood floors. Floor varnish is usually alkyd-modified polyurethane. Sealers are usually thinned varnish and penetrate the surface without forming a coating of appreciable thickness. Prolong the service life of floor finishes by keeping them waxed. Paste wax generally provides better appearance and lasts longer than liquid wax. Re-waxing or resealing and waxing of high traffic areas are relatively simple maintenance procedures, as long as the stained surface of the wood has not been worn.

Finishes for Items Used for Food

The durability and beauty of wood make it an attractive material for bowls, butcher blocks, and other items used to serve or prepare food. A finish helps keep wood dry, which makes it less prone to harbor bacteria, check, or crack. Finishes that repel water decrease the effects of brief periods of wetting (washing). Finished wood is easier to clean than unfinished wood.

Types of Finish

Sealers and Drying Oils

Sealers and drying oils penetrate wood and cure (dry) to form a barrier to liquid water. Many commercial sealers are similar to thinned varnish (e.g., polyurethane or alkyd-modified polyurethane). Drying oils such as tung, linseed, and walnut can also be used as sealers. Sealers and drying oils give a surface that is easy to clean and resistant to scratching. Sealers are easy to apply and cure quickly. Drying oils may require several weeks to cure.

Nondrying Oils

Nondrying oils (vegetable and mineral oils) penetrate wood but do not cure. As with sealers and drying oils, they improve water resistance. Vegetable oils (such as olive, corn, peanut, and safflower) are food for microorganisms such as mildew or bacteria. Vegetable oils can become rancid and may impart undesirable odors or flavors to food. Mineral (or paraffin) oil is a nondrying oil from petroleum. Mineral oil is not a natural product; therefore, it is not prone to mildew or to harbor bacteria.

Varnish and Lacquer

Finishes that form a film, such as varnish or lacquer, give a smooth cleanable surface. These finishes resist staining and should perform well if you minimize their exposure to water; avoid placing them in a dishwasher. However, eventually the finish may crack, chip, and peel.

Paraffin Wax

Paraffin wax is similar to paraffin oil but is solid at room temperature. Paraffin wax is one of the simplest ways to finish wood utensils, especially countertops, butcher blocks, and cutting boards.

Food Service Items

Food service items such as salad bowls and eating utensils need a finish that is easy to clean and resistant to abrasion, water, acids, and stains. Varnishes, lacquers, penetrating wood sealers, and drying oils can be used; however, varnishes and lacquers are easiest to keep clean and most resistant to absorption of stains.

Note: Whatever finish is chosen for wood utensils used to store, handle, or eat food, be sure the finish is safe and not toxic. Also, be sure the finish you select is recommended for use with food or is described as food grade. For information on the safety and toxicity of any finish, check the label, contact the manufacturer or the Food and Drug Administration, or check with your local extension home economics expert or county agent.

Butcher Blocks and Cutting Boards

The simplest finish for wood butcher blocks and cutting boards is melted paraffin wax (the type used for home canning). Melt wax using hot plate or other low-temperature heat source—**do not use an open flame**. Brush melted wax on the wood. Use an iron to melt excess wax that has solidified on the surface so that it absorbs into the wood, or just scrape off the excess wax. Refinishing is simple and easy. Other penetrating finishes (sealers, drying and nondrying oils) may be used for butcher blocks and cutting boards, but as mentioned in the subsection on eating utensils, vegetable oils may become rancid. Film-forming finishes such as varnish or lacquer perform poorly on butcher blocks and cutting boards.

Wood Cleaners and Brighteners

The popularity of wood decks and the desire to keep them looking bright and new has led to a proliferation of commercial cleaners and brighteners. The active ingredient in many of these products is sodium percarbonate ($2\text{Na}_2\text{CO}_3 \cdot 3\text{H}_2\text{O}_2$). Sodium percarbonate is bleach; however, it is oxygen bleach rather than chlorine bleach such as laundry bleach—sodium hypochlorite and calcium hypochlorite. Oxygen bleaches remove mildew and have been reported to be less likely to damage wood surfaces than “chlorine” bleaches, particularly with low-density woods like western redcedar, Alaska

yellow-cedar, and redwood. However, it is difficult to compare the advantages and disadvantages of the two types of cleaner (oxygen versus chlorine) because of the wide range of active ingredient concentrations in the cleaners, additives in the cleaners, and various wood substrates that have been used for evaluating the cleaners. Some commercial products contain household bleach. Commercial cleaners usually have a surfactant or detergent to enhance the cleansing action.

At the other extreme from the reported gentle bleaching action of sodium percarbonate are those cleaners containing sodium hydroxide. Sodium hydroxide is a strongly alkaline chemical that pulps wood and is used in some paint strippers. These cleaners may be necessary where mildew is imbedded in a surface finish; however, they should be used only as a last resort.

Manufacturers of some cleaners and brighteners report that their products restore color to wood. Cleaning wood does not add color. Removing mildew reveals the original color. Brightening the wood may make it appear as if it has more color. Weathered wood has a silvery gray appearance because weathering removes colored components from the surface. If you want to restore color, stain the wood. Some commercial cleaners pulp the wood surface and subsequent power washing removes the pulped surface. In this case, the color is “restored” because the surface of the wood was removed. Sanding would give the same result.

Some brighteners contain oxalic acid. Oxalic acid removes extractives bleed and iron stains, but it is not effective for removing mildew.

Paint Strippers

Removing paint and other film-forming finishes from wood is a time-consuming and often difficult process. Finish removal is necessary if a finish has extensive cracking or peeling (see Finish Failure or Discoloration). It may be necessary to remove paint containing lead; however, if the paint is still sound and it is not illegal to leave it on the structure, paint over the lead-based paint to seal in the lead (see Lead-Based Paint).

Methods described here can remove finishes from furniture; however, companies that specialize in stripping furniture usually immerse the furniture in a vat of paint stripper, then clean and brighten the wood.

Mechanical and chemical are general types of stripping methods. Consult product literature for additional information on appropriate uses and safety precautions. Regardless of the method used to strip paint, sand the wood prior to applying new finish.

Note: Dust caused by mechanical stripping methods and fumes given off by chemical strippers are usually toxic. Use effective safety equipment, including a respirator, even if the paint does not contain lead (see Lead-Based Paint). Dust masks sold in hardware stores do not block chemical fumes and are not very effective against dust.

Mechanical Methods

Scraping, sanding, wet or dry sandblasting, spraying with pressurized water (power washing), and using electrically heated pads, hot air guns, and blowtorches are mechanical methods for removing finishes.

Scraping is effective for removing loosely bonded paint or paint that has already partially peeled from small areas of the structure. If possible, sand weathered surfaces and feather edges of paint still bonded to wood. ***Do not sand if the old paint contains lead*** (see Lead-Based Paint).

If paint has partially debonded on large areas of a structure, contractors usually remove the finish by power washing. This methods work well for paint that is loosely bonded. If paint is tightly bonded, complete removal can be difficult without severely damaging wood. The pressure needed to debond tightly bound paint from wood can easily cause deep erosion of wood. If high pressure is necessary to remove paint, the paint probably does not need to be removed prior to refinishing. Power washing erodes less dense EW more than dense LW, leaving behind ridges of LW, which are difficult to repaint. Power washing is less damaging to wood than is wet or dry sandblasting, particularly if low pressure is used. If more aggressive mechanical methods are required, wet sandblasting can remove even tightly-bonded paint. Dry sandblasting is not suitable for removing paint from wood because it severely erodes wood along with the paint and it tends to glaze the surface. ***Power washing and wet and dry sandblasting are not suitable for paint containing lead.***

Power sanders and similar devices are available for complete paint removal. Some devices are suitable for removing paint that contains lead; they have attachments for containing the dust. Equipment that has a series of blades similar to a power hand-planer is less likely to “gum up” with paint than equipment that merely sands the surface. Planers and sanders cannot be used unless the fasteners are countersunk. Consult the manufacturers’ technical data sheets for detailed information to determine the suitability of their equipment for your needs and to meet government regulations on lead-containing paint.

Paint can be softened using electrically heated pads, hot air guns, or blow torches, then removed by scraping it from the wood. Heated pads and hot air guns are slow methods and cause little damage to the wood. Blowtorches have been

used to remove paint, but they are extremely hazardous; the flame can easily ignite flammable materials beneath the siding through gaps in the siding. These materials may smolder, undetected, for hours before bursting into flame and causing loss of the structure. **Heated pads, hot air guns, and blowtorches are not suitable for paint containing lead.** These methods volatilize lead at their operating temperatures. Lead fumes are released at approximately 371 °C (700 °F).

Note: Removing paint from wood with a blowtorch is not recommended.

Chemical Methods

Efficient paint removal may involve mechanical and chemical methods. Stripping paint chemically has the following steps: apply paint stripper, wait, scrap off the softened paint, neutralize the stripper (if necessary), wash the wood, and sand the surface to remove wood damaged by the stripper and raised grain caused by washing. Chemical paint strippers, although tedious to use, are sometimes the most reasonable choice. Some are extremely strong chemicals that quickly remove paint but are dangerous to use. Others remove the paint slowly but are safer. With the exception of alkali paint stripper, how safe a product is and how fast it removes paint seem to be inversely correlated.

Solvent-Based Strippers

Fast-working paint strippers usually contain methylene chloride, a possible carcinogen that can burn eyes and skin. Eye and skin protection and a supplied-air respirator are essential when using this paint stripper. Paint strippers having methylene chloride can remove paint in as little as 10 min. Some paint strippers are formulated using other strong solvents because of concerns with methylene chloride; the same safety precautions should be used with these formulations as with those containing methylene chloride. Consult product literature and strictly observe safety precautions.

Alkali-Based Strippers

As an alternative to strong solvents, some paint strippers contain strong bases (alkali). As with solvent-based paint strippers, alkali-based strippers require eye and skin protection. Follow manufacturers' recommendations concerning use of a respirator. Although alkali-based paint strippers soften paint rather slowly, they are strong chemicals and can severely damage wood. Strong alkali pulps the wood surface. After paint removal, neutralize the surface with mild acid. Unfortunately, balancing the acid and base concentrations is difficult. If excess alkali remains in the wood, it may degrade the wood and subsequent paint coating. Excess acid can also damage wood. Alkali strippers are often left on painted wood a full day or overnight and are usually covered to slow evaporation. These covered types of products have the advantage of containing the paint stripper and paint quite well, an important consideration when removing paint

containing lead. Do not let alkali chemicals dry on the surface, particularly on those finishes containing lead. The dry chemicals contain lead dust.

Note: Alkali-based strippers require extra care to ensure that the wood is neutralized and that residual salts are washed from the wood. The surface usually needs to be sanded before repainting to remove raised grain.

“Safe” Paint Strippers

Several manufacturers have marketed “safe” paint strippers. These strippers work slower than those having methylene chloride. The active ingredient in such paint strippers is usually proprietary. Concerning safety, follow the manufacturer's recommendations.

Avoidance of Problems

Avoid finish failure subsequent to removing the old finish by using methods that do not damage wood. The best way to remove paint may involve a combination of methods. For example, use power washing to remove as much loosely bound paint as possible. Then, use a chemical paint stripper on tightly-bonded paint. Avoid using excessive amounts of chemical stripper. Applying too much stripper or leaving it on painted wood too long can damage wood. Use less paint stripper and reapply it rather than trying to remove all the paint with one application and risk damaging wood.

The range of wood species and finishes and the possibility of finishes containing lead complicates paint removal. Companies may optimize paint stripper formulation without considering the effects on wood. Removing paint from wood is only half the task. Getting a paintable surface is the other half. Companies that formulate paint strippers should consider this other half. Those who use paint strippers need to understand the added burden of surface preparation.

Disposal of Old Paint

No matter what method you use to remove paint, be careful in disposing of old paint, particularly paint that contains lead. Lead paint is hazardous waste; follow all regulations, national and local, during the removal, storage, and disposal of all paint, especially paint containing lead (see Lead-Based Paint).

Lead-Based Paint

Lead-based paint was widely used in residential structures in the United States until the early 1940s, and its use continued to some extent, for the exterior of dwellings, until 1976. In 1971, Congress passed the Lead-Based Paint Poisoning Prevention Act, and in 1976, the Consumer Product Safety Commission (CPSC) issued a ruling under this Act that limited the lead content of paint used in residential dwellings, toys, and furniture to 0.06%. Prior to any paint restoration on structures built prior to 1976 (and probably a good idea on any structure), check paint for lead. Check for lead using a solution of 6% to 8% sodium sulfide in water or using a

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test kit. Test kits should be available in most paint and hardware stores. Be certain to check all paint layers, because the older ones are more likely to contain lead.

Lead-based paint is still manufactured for applications not covered by the CPSC ruling, such as paint for metal products, particularly those made of steel. Occasionally, such lead-based paint inadvertently gets into the hands of consumers. **Imported products may also contain lead paint.** Studies have shown that ingestion of even minute amounts of lead can have serious effects on health; lead causes hypertension, fetal injury, damage to the brain, kidneys, and red blood cells, partial loss of hearing, impairment of mental development, growth retardation, and inhibited metabolism of vitamin D. The American Academy of Pediatrics regards lead as one of the foremost toxicological dangers to children.

Lead-based paint on the exterior of structures weathers to give flakes and powder. The degraded paint particles accumulate in the soil near the structure. Lead-based paint used on interior surfaces can also degrade to produce lead-containing dust. Sanding coatings prior to repainting generates lead dust. Sanding the exterior of a structure without proper equipment can cause lead contamination inside the structure.

Methods used to remove lead paint can themselves generate lead dust. This is particularly true when unacceptable methods and work practices are used. Poorly performed abatement can be worse than no abatement. Micron-sized lead dust particles can remain airborne for substantial periods and cannot be completely removed by standard cleaning methods. When working on old painted surfaces, assume that one or more of the paint coats contain lead. Take precautions accordingly.

Check with the U.S. Department of Health and Urban Development (HUD), U.S. Environmental Protection Agency (EPA), and American Coatings Association for the latest regulations and guidelines for remediating lead-based paint (www.hud.gov/offices/lead) (www.epa.gov/lead) (www.paint.org/issues/lead.cfm).

Caution: Remodeling or refinishing projects that require disturbing, removing, or demolishing portions of structures coated with lead-based paint pose serious health risk. The consumer should seek information, advice, and perhaps professional assistance for addressing these risks. Contact HUD for the latest information on the removal of lead-based paints. Debris coated with lead-based paint is hazardous waste and must be disposed of in accordance with federal and local regulations.

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Use of Wood in Buildings and Bridges

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In North America, most housing and commercial structures built prior to the 20th century used wood as the major structural material. The abundant wood resource formed the basic structure for most houses, commercial buildings, bridges, and utility poles. Today, houses and many light commercial and industrial buildings are made using modern wood structural materials. Recently, there has been increased interest in using wood for various types of transportation structures, including highway bridges.

In this chapter, the features of various types of building systems are described. Emphasis is placed on how these systems have adapted to the use of modern materials and techniques. For example, where floor, wall, and roof sheathing for light-frame construction were once commonly made from wood boards, sheathing is now commonly made from structural panel products, such as plywood and oriented strandboard (OSB). Compared with boards, these panel products are quicker to install and provide improved structural resistance to wind and earthquake loadings. Furthermore, prefabricated floor and wall panels along with prefabricated roof and floor trusses or I-joists are replacing piece-by-piece on-site construction with dimension lumber. A structure can be enclosed within a short time on site using factory-made panelized systems.

Engineered wood products are being used increasingly for transportation structures. A brief description of the uses of wood in railroad and highway bridges and other transportation structures is included.

Light-Frame Buildings

Historically, two general types of light-frame construction have been used—balloon and platform framing. Balloon framing, which was used in the early part of the 20th century, consists of full-height wall framing members for two-story construction. Additional information on balloon framing is available from older construction manuals. Since the latter part of the 20th century, platform framing has dominated the housing market and is widely used in commercial and light industrial applications. Platform framing features the construction of each floor on top of the one beneath. Platform framing construction differs from that of 60 years ago in the use of new and innovative materials, panel products for floor and roof sheathing, and prefabricated components and modules as opposed to “stick built” or on-site construction. A detailed description of the platform-type of construction

is given in *Wood Frame House Construction* (Sherwood and Stroh 1989); additional information is given in the *Wood Frame Construction Manual for One- and Two-Family Dwellings, 2001* (AF&PA 2001).

Foundations

Light-frame buildings with basements are typically supported on cast-in-place concrete walls or concrete block walls supported by footings. This type of construction with a basement is common in northern climates. Another practice is to have concrete block foundations extend a short distance above ground to support a floor system over a “crawl space.” In southern and western climates, some buildings have no foundation; the walls are supported by a concrete slab, thus having no basement or crawl space.

Treated wood is also used for basement foundation walls. Basically, such foundations consist of wood-frame wall sections with studs and plywood sheathing supported on treated wood plates, all of which are preservatively treated to a specified level of protection. To distribute the load, the plates are laid on a layer of crushed stone or gravel. Walls, which must be designed to resist the lateral loads of the backfill, are built using the same techniques as conventional walls. The exterior surface of the foundation wall below grade is draped with a continuous moisture barrier to prevent direct water contact with the wall panels. The backfill must be designed to permit easy drainage and provide drainage from the lowest level of the foundation.

Because a foundation wall needs to be permanent, the preservative treatment of the plywood and framing and the type of fasteners used for connections are very important. A special foundation (FDN) treatment has been established for the plywood and framing, with strict requirements for depth of chemical penetration and amount of chemical retention. Corrosion-resistant fasteners (for example, stainless steel) are recommended for all preservatively treated wood. Additional information and materials and construction procedures are given in *Permanent Wood Foundation Basic Requirements* (AF&PA 2007).

Floors

For houses with basements, the central supporting structure may consist of wood posts on suitable footings that carry a built-up girder, which is frequently composed of planks the same width as the joists (standard 38 by 184 mm to 38 by 286 mm (nominal 2 by 8 in. to 2 by 12 in.)), face-nailed together, and set on edge. Because planks are seldom sufficiently long enough to span the full length of the beam, butt joints are required in the layers. The joints are staggered in the individual layers near the column supports. The girder may also be a glulam beam or steel I-beam, often supported on adjustable steel pipe columns. Similar details may be applied to a house over a crawl space. The floor framing in residential structures typically consists of wood joists on

400- or 600-mm (16- or 24-in.) centers supported by the foundation walls and the center girder (Fig. 17–1).

Joist size depends on the anticipated loading, spacing between joists, distance between supports (span), species, and grade of lumber. Commonly used joists are standard 38- by 184-mm or 38- by 235-mm (nominal 2- by 8-in. or 2- by 10-in.) lumber, prefabricated wood I-joists, or parallel chord trusses. Lumber joists typically span from 3.6 to 4.8 m (12 to 16 ft). Span tables are available from the American Forest & Paper Association (AF&PA 2005b). Span capabilities of prefabricated wood I-joists or parallel chord trusses are recommended by the manufacturer.

Floor openings for stairways, fireplaces, and chimneys may interrupt one or more joists. Preferably, such openings are parallel to the length of the joists to reduce the number of joists that will be interrupted. At the interruption, a support (header) is placed between the uninterrupted joists and attached to them. A single header is usually adequate for openings up to about 1.2 m (4 ft) in width, but double headers are required for wider openings. Special care must be taken to provide adequate support at headers (using joist hangers, for example).

Cutting of framing members to install items such as plumbing lines and heating ducts should be minimized. Cut members may require a reinforcing scab, or a supplementary member may be needed. Areas of highly concentrated loads, such as under bathtubs, require doubling of joists or other measures to provide adequate support. One advantage of framing floors with parallel-chord trusses or prefabricated I-joists is that their longer span capabilities may eliminate the need for interior supports. An additional advantage is that the web areas of these components are designed for easy passing of plumbing, electrical, and heating ducts.

Floor sheathing, or subflooring, is used over the floor framing to provide a working platform and a base for the finish flooring. Older homes have board sheathing but newer homes generally use panel products. Common sheathing materials include plywood and OSB, which are available in a number of types to meet various sheathing requirements. Exterior-type panels with water-resistant adhesive are desirable in locations where moisture may be a problem, such as floors near plumbing fixtures or situations where the subfloor may be exposed to the weather for some time during construction.

Plywood should be installed with the grain direction of the face plies at right angles to the joists. Oriented strandboard also has a preferred direction of installation. Nailing patterns are either prescribed by code or recommended by the manufacturer. About 3 mm (1/8 in.) of space should be left between the edges and ends of abutting panels to provide for dimensional changes associated with moisture content.

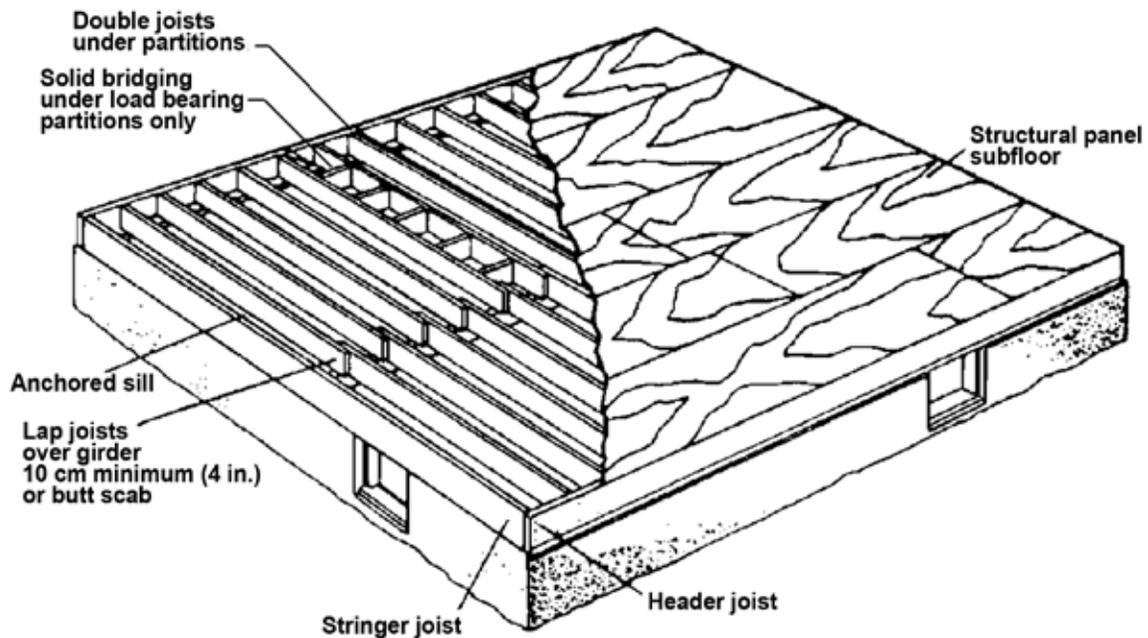


Figure 17-1. Typical floor details for platform construction with joists spliced on center beam.

Literature from APA—The Engineered Wood Association includes information on the selection and installation of the types of structural panels suitable for subfloors (APA 2007).

Exterior Walls

Exterior walls of light-frame structures are generally load bearing; they support upper floors and the roof. An exception is the gable ends of a one- or two-story building. Basically, wall framing consists of vertical studs and horizontal members, including top and bottom plates and headers (or lintels) over window and door openings. The studs are generally standard 38- by 89-mm, 38- by 114-mm, or 38- by 140-mm (nominal 2- by 4-in., 2- by 5-in., or 2- by 6-in.) members spaced between 300 and 600 mm (12 and 24 in.) on center. Selection of the stud size depends on the load the wall will carry, the need for support of wall-covering materials, and the need for insulation thickness in the walls. Headers over openings up to 1.2 m (4 ft) are often 38 by 140 mm (2 by 6 in.), nailed together face to face with spacers to bring the headers flush with the faces of the studs. Special headers that match the wall thickness are also available in the form of either prefabricated I-joists or structural composite lumber. Wall framing is erected over the platform formed by the first-floor joists and subfloor. In most cases, an entire wall is framed in a horizontal position on the subfloor, then tilted into place. If a wall is too long to make this procedure practical, sections of the wall can be formed horizontally and tilted up, then joined to adjacent sections.

Corner studs are usually prefabricated in such a configuration as to provide a nailing edge for the interior finish

(Fig. 17-2). Studs are sometimes doubled at the points of intersection with an interior partition to provide backup support for the interior wall finish. Alternatively, a horizontal block is placed midheight between exterior studs to support the partition wall. In such a case, backup clips on the partition stud are needed to accommodate the interior finish.

Upper plates are usually doubled, especially when rafters or floor joists will bear on the top plate between studs. The second top plate is added in such a way that it overlaps the first plate at corners and interior wall intersections. This provides a tie and additional rigidity to the walls. In areas subject to high winds or earthquakes, ties should be provided between the wall, floor framing, and sill plate that should be anchored to the foundation. If a second story is added to the structure, the edge floor joist is nailed to the top wall plate, and subfloor and wall framing are added in the same way as the first floor.

Sheathing for exterior walls is commonly some type of panel product. Here again, plywood or OSB may be used. Fiberboard that has been treated to impart some degree of water resistance is another option. Several types of fiberboard are available. Regular-density board sometimes requires additional bracing to provide necessary resistance to lateral loads. Intermediate-density board is used where structural support is needed. Numerous foam-type panels can also be used to impart greater thermal resistance to the walls.

In cases where the sheathing cannot provide the required racking resistance, diagonal bracing must be used. Many foam sheathings cannot provide adequate racking resistance,

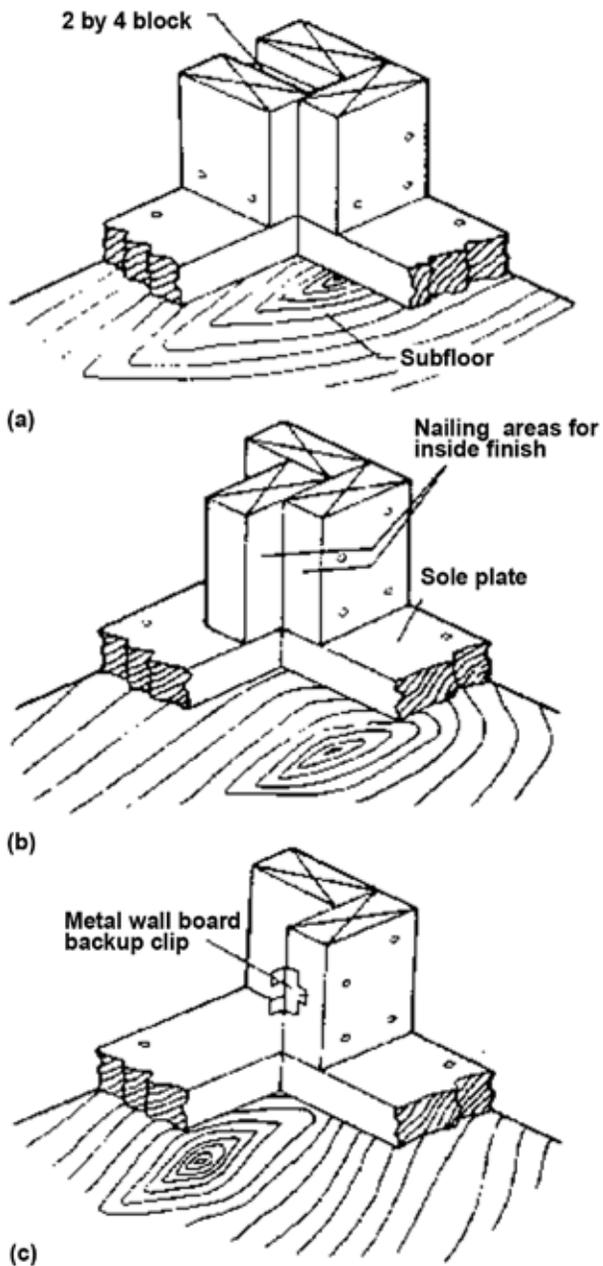


Figure 17-2. Corner details for wood stud walls that provide support for interior sheathing: (a) traditional three-stud corner with blocking; (b) three-stud corner without blocking; (c) two-stud corner with wallboard backup clips.

so either diagonal braces must be placed at the corners or structural panels must be applied over the first 1.2 m (4 ft) of the wall from the corner. When light-weight insulating foam sheathings are used, bracing is commonly provided by standard 19- by 89-mm (nominal 1- by 4-in.) lumber or steel strapping.

Ceiling and Roof

Roof systems are generally made of either the joists-and-rafter systems or with trusses. Engineered trusses reduce on-site labor and can span greater distances without intermediate support, thus eliminating the need for interior load-carrying partitions. This provides greater flexibility in the layout of interior walls. Prefabricated roof trusses are used to form the ceiling and sloped roof of more than two-thirds of current light-frame buildings. For residential buildings, the trusses are generally made using standard 38- by 89-mm (nominal 2- by 4-in.) lumber and metal plate connectors with teeth that are pressed into the pieces that form the joints (TPI 2007).

Joists and rafter systems are found in most buildings constructed prior to 1950. Rafters are generally supported on the top plate of the wall and attached to a ridge board at the roof peak. However, because the rafters slope, they tend to push out the tops of the walls. This is prevented by nailing the rafters to the ceiling joists and nailing the ceiling joists to the top wall plates (Fig. 17-3a).

A valley or hip is formed where two roof sections meet perpendicular to each other. A valley rafter is used to support short-length jack rafters that are nailed to the valley rafter and the ridge board (Fig. 17-3b). In some cases, the roof does not extend to a gable end but is sloped from some point down to the end wall to form a “hip” roof. A hip rafter supports the jack rafters, and the other ends of the jack rafters are attached to the top plates (Fig. 17-3c). In general, the same materials used for wall sheathing and subflooring are used for roof sheathing.

Wood Decks

A popular method of expanding the living area of a home is to build a wood deck adjacent to one of the exterior walls. Decks are made of preservative-treated lumber, which is generally available from local building supply dealers and, depending upon the complexity, may be built by the “do-it-yourselfer.” To ensure long life, acceptable appearance, and structural safety, several important guidelines should be followed. Proper material selection is the first step. Then, proper design and construction techniques are necessary. Finally, proper maintenance practices are necessary. Detailed recommendations for all these areas are included in *Wood Decks: Materials, Construction, and Finishing* (McDonald and others 1996) and *Prescriptive Residential Wood Deck Construction Guide* (AWC 2009).

Post-Frame and Pole Buildings

In post-frame and pole buildings, round poles or rectangular posts serve both as the foundation and the principal vertical framing element. This type of construction was known as “pole buildings” but today, with the extensive use of posts,

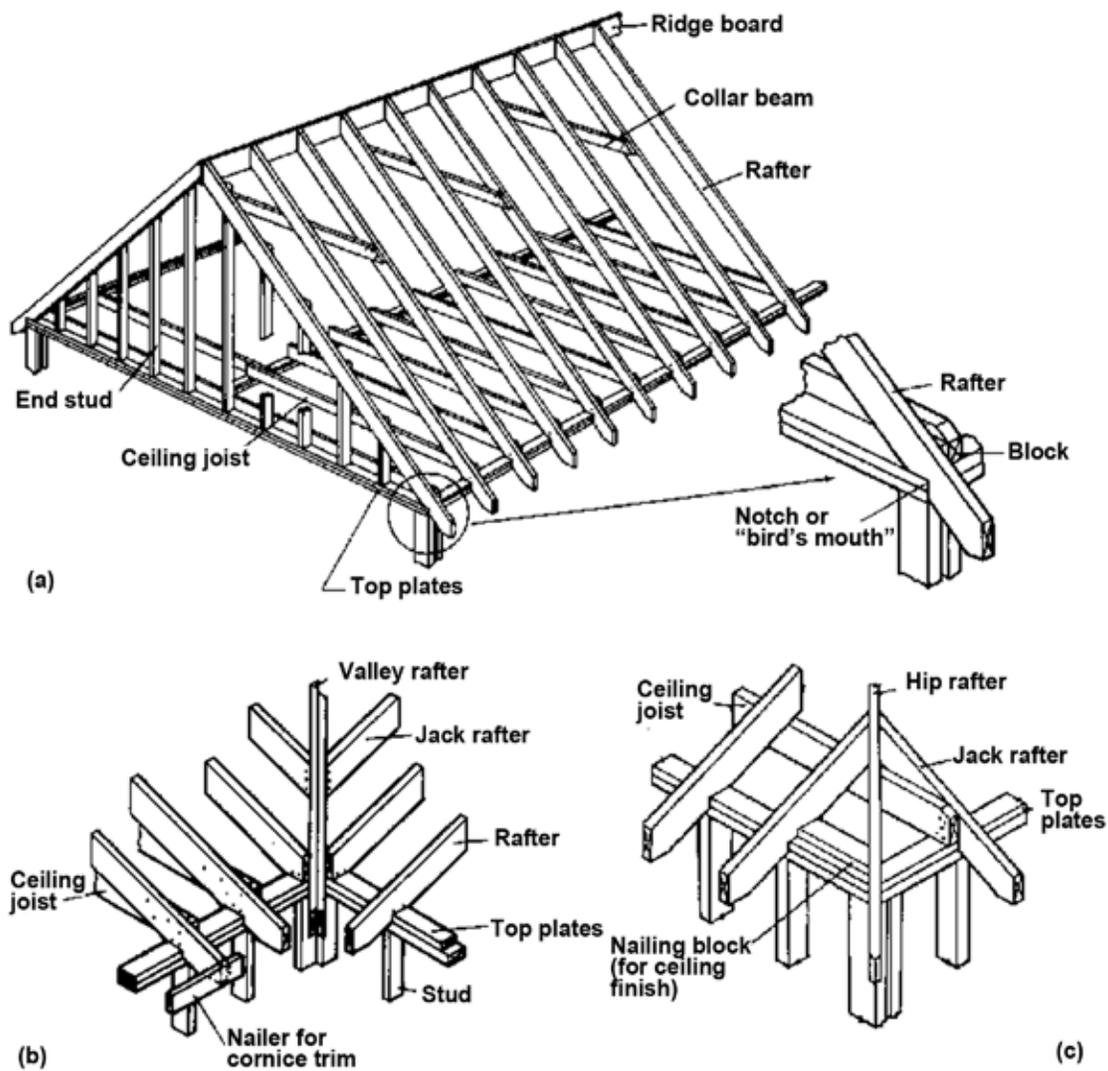


Figure 17-3. (a) A rafter-type roof with typical framing details for (b) a valley and (c) a hip corner.

is commonly referred to as “post-frame” construction. For relatively low structures, light wall and roof framing are nailed to poles or posts set at fairly frequent centers, commonly 2.4 to 3.6 m (8 to 12 ft). This type of construction was originally used with round poles for agricultural buildings, but the structural principle has been extended to commercial and residential buildings (Fig. 17-4).

Round poles present some problems for connecting framing members; these problems can be eased by slabbing the outer face of the pole. For corner poles, two faces may be slabbed at right angles. This permits better attachment of both light and heavy framing by nails or timber connectors. When the pole is left round, the outer face may be notched to provide seats for beams.

Rectangular posts are the most commonly used and may be solid sawn, glulam, or built-up by nail laminating. Built-up

posts are advantageous because only the base of the post must be preservative treated. The treated portion in the ground may have laminations of various lengths that are matched with the lengths of untreated laminations in the upper part of the post. The design of these types of posts must consider the integrity of the splice between the treated and untreated lumber. The wall system consists of horizontal girts often covered by light-gauge metal that provides some degree of racking resistance. Roof trusses made with metal plate connectors are attached to each pole, or post, and roof purlins are installed perpendicular to the trusses at spacings from 1.2 to 3.7 m (4 to 12 ft), with 2.4 m (8 ft) as a common spacing. For 2.4-m (8-ft) truss spacing, these purlins are often standard 38 by 89 mm (nominal 2 by 4 in.) spaced on 0.6-m (2-ft) centers and attached to either the top of the trusses or between the trusses using joists hangers. The roofing is often light-gauge metal that provides some diaphragm

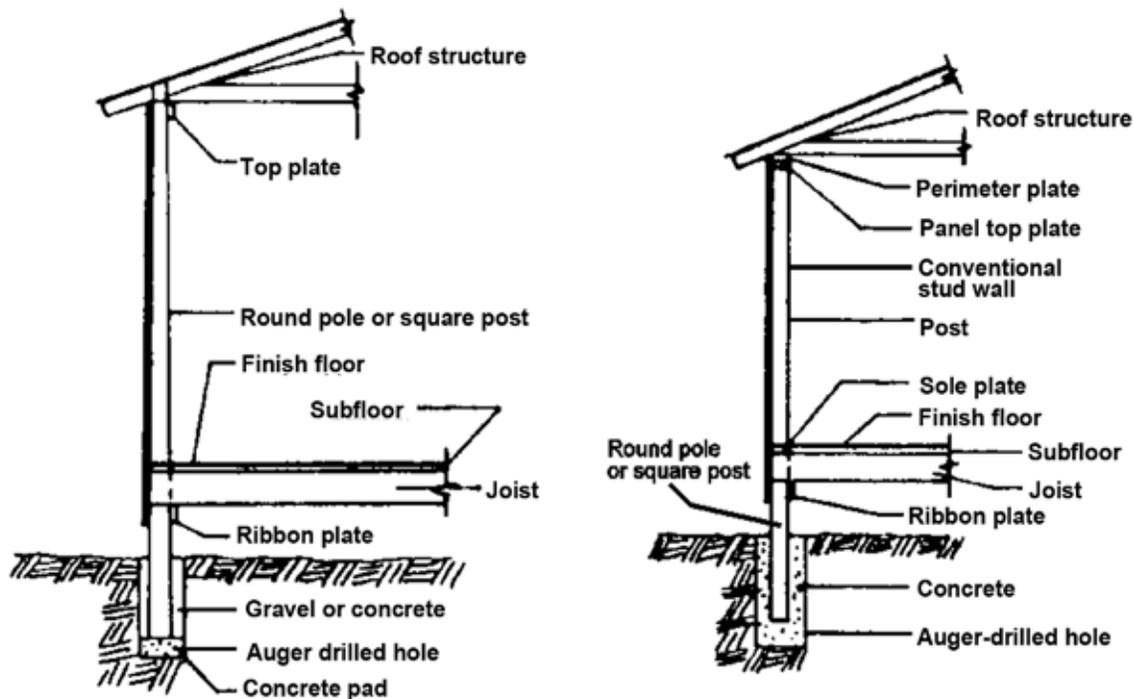


Figure 17-4. Pole and post-frame buildings: (left) pole or post forms both foundation and wall; (right) pole or post forms only the foundation for conventional platform-framed structure.

stiffness to the roof and transmits a portion of the lateral loading to the walls parallel to the direction of the load. Detailed information on the design of post-frame buildings is provided by the National Frame Builders Association (1999) or Walker and Woeste (1992).

Log Buildings

Interest is growing in log houses—from small, simple houses for vacation use to large, permanent residences (Fig. 17-5). Many U.S. firms specialize in the design and materials for log houses. Log houses nearly always feature wall systems built from natural or manufactured logs rather than from dimension lumber. Roof and floor systems may also be built with logs or conventional framing. Log house companies tend to categorize log types into two systems: round and shaped. In the round log system, the logs are machined to a smooth, fully rounded surface, and they are generally all the same diameter. In the shaped system, the logs are machined to specific shapes, generally not fully round. The exterior surfaces of the logs are generally rounded, but the interior surfaces may be either flat or round. The interface between logs is machined to form an interlocking joint.

Consensus standards have been developed for log grading and the assignment of allowable properties, and these standards are being adopted by building codes (ASTM 2009). Builders and designers need to realize that logs can reach the building site at moisture content levels greater than ideal. The effects of seasoning and the

consequences of associated shrinkage and checking must be considered. Additional information on log homes is available from The Log Home Council, National Association of Home Builders, Washington, D.C., or in *Standard on the Design and Construction of Log Structures* (ICC 2007).

Heavy Timber Buildings

Timber Frame

Timber frame houses were common in early America and are enjoying some renewed popularity today. Most barns and factory buildings dating prior to the middle of the 20th century were heavy timber frame. The traditional timber frame is made of large sawn timbers (larger than 114 by 114 mm (5 by 5 in.)) connected to one another by hand-fabricated joints, such as mortise and tenon. Construction of such a frame involves rather sophisticated joinery, as illustrated in Figure 17-6.

In today's timber frame home, a prefabricated, composite sheathing panel (1.2 by 2.4 m (4 by 8 ft)) is frequently applied directly to the frame. This panel may consist of an inside layer of 13-mm (1/2-in.) gypsum, a core layer of rigid foam insulation, and an outside layer of exterior plywood or OSB. Finish siding is applied over the composite panel. In some cases, a layer of standard 19-mm (nominal 1-in.) tongue-and-groove, solid-wood boards is applied to the frame, and a rigid, foam-exterior, plywood composite panel is then applied over the boards to form the building exterior.



Figure 17-5. Modern log homes are available in a variety of designs.

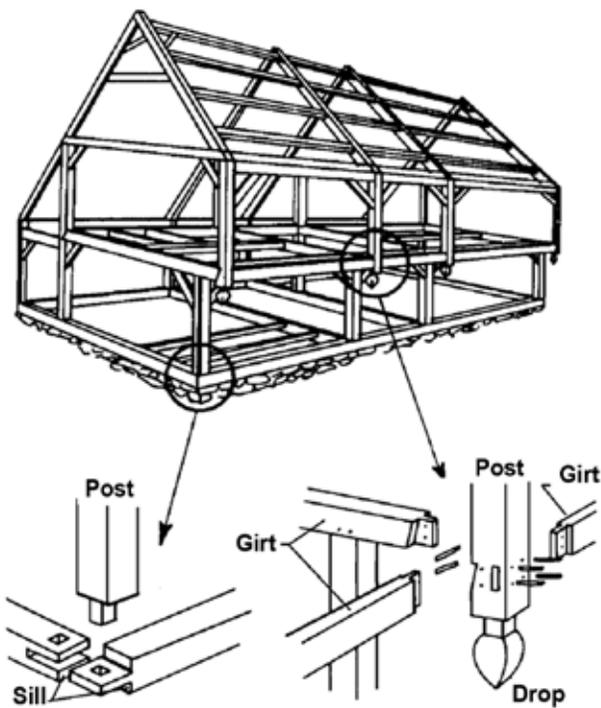


Figure 17-6. Timber frame structure with typical joint details.

Local fire regulations should be consulted about the acceptance of various foam insulations.

Framing members are cut in large cross sections; therefore, seasoning them before installation is difficult, if not impossible. Thus, the builder (and the owner) should recognize the dimensional changes that may occur as the members dry in place. The structure must be designed to accommodate these dimensional changes as well as seasoning checks, which are almost inevitable.

Mill Type

Mill-type construction has been widely used for warehouse and manufacturing structures, particularly in the eastern United States. This type of construction uses timbers of large cross sections with columns spaced in a grid according to the available lengths of beam and girder timbers. The size of the timbers makes this type of construction resistant to fire. The good insulating qualities of wood as well as the char that develops during fire result in slow penetration of fire into the large members. Thus, the members retain a large proportion of their original load-carrying capacity and stiffness for a relatively lengthy period after the onset of fire.

To be recognized as mill-type construction, the structural elements must meet specific sizes—columns cannot be less than standard 184 mm (nominal 8 in.) in dimension, and beams and girders cannot be less than standard 140 by 235 mm (nominal 6 by 10 in.) in cross section. Other limitations must be observed as well. For example, walls must be made of masonry, and concealed spaces must be avoided. The structural frame has typically been constructed of solid-sawn timbers, which should be stress graded. These timbers can now be supplanted with glulam timbers, and longer spans are permitted.

Glulam Beam

A panelized roof system using glulam roof framing is widely used for single-story commercial buildings in the southwestern United States. This system is based on supporting columns located at the corners of pre-established grids. The main glulam beams support purlins, which may be sawn timbers, glulam, parallel chord trusses, or prefabricated wood I-joists. These purlins, which are normally on 2.4-m (8-ft) centers, support preframed structural panels. The basic unit of the preframed system is a 1.2- by 2.4-m (4- by 8-ft) structural panel nailed to standard 38- by 89-mm or 38- by 140-mm (nominal 2- by 4-in. or 2- by 6-in.) stiffeners (subpurlins). The stiffeners run parallel to the 2.4-m (8-ft) dimension of the structural panel. One stiffener is located at the centerline of the panel; the other is located at an edge, with the plywood edge at the stiffener centerline. The stiffeners are precut to a length equal to the long dimension of the plywood less the thickness of the purlin, with a small allowance for the hanger.

In some cases, the purlins are erected with the hangers in place. The prefabricated panels are lifted and set into place in the hangers, and the adjoining basic panels are then attached to each other. In other cases, the basic panels are attached to one purlin on the ground. An entire panel is lifted into place to support the loose ends of the stiffeners. Additional details on this system and other glulam details are available from the American Institute of Timber Construction (www.aitc-glulam.org).

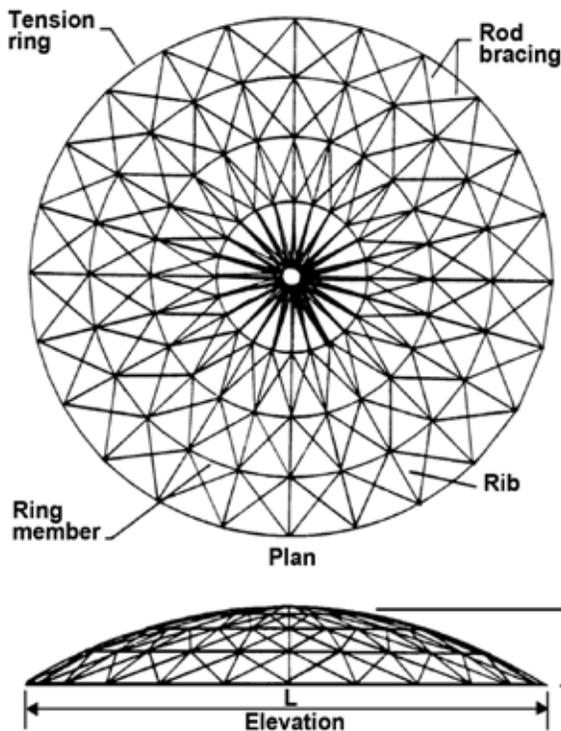


Figure 17-7. Member layout for a radial-rib dome.

Arch Structure

Arch structures are particularly suited to applications in which large, unobstructed areas are needed, such as churches, recreational buildings, and aircraft hangars. Many arch forms are possible with the variety limited only by the imagination of the architect. Churches have used arches from the beginning of glulam manufacture in the United States. Additional information on the use and design of arches is given in *The Timber Construction Manual* (AITC 2004).

Dome

Radial-rib domes consist of curved members extending from the base ring (tension ring) to a compression ring at the top of the dome along with other ring members at various elevations between the tension and compression rings (Fig. 17-7). The ring members may be curved or straight. If they are curved to the same radius as the rib and have their centers at the center of the sphere, the dome will have a spherical surface. If the ring members are straight, the dome will have an umbrella look. Connections between the ribs and the ring members are critical because of the high compressive loads in the ring members. During construction, care must be taken to stabilize the structure because the dome has a tendency to rotate about the central vertical axis.

Other dome patterns called Varax and Triax are also used. Their geometries are quite complex, and specialized computer programs are used in their design. Steel hubs used at the joints and supports are critical. An example of a Triax dome is shown in Figure 17-8.



Figure 17-8. This 161.5-m- (530-ft-) diameter Tacoma dome (Tacoma, Washington), built in 1982–1983, is one of the longest clear roof spans in the world. (Photo courtesy of Western Wood Structures, Inc., Tualatin, Oregon.)

Timber Bridges

Prior to the 20th century, timber was the major material used for both highway and railroad bridges. The development of steel and reinforced concrete provided other options, and these have become major bridge building materials. However, the U.S. inventory does contain a substantial number of timber bridges, many of which continue to carry loads beyond their design life. A recent initiative in the United States has focused research and technology transfer efforts on improving the design and performance of timber bridges. As a result, hundreds of timber highway bridges were built across the United States during the past several years, many using innovative designs and materials.

Bridges consist of a substructure and a superstructure. The substructure consists of abutments, piers, or piling, and it supports the superstructure that consists of stringers and/or a deck. The deck is often covered with a wearing surface of asphalt. Timber may be combined with other materials to form the superstructure, for example, timber deck over steel stringers. Several bridge railing systems were recently crash-tested and approved for use by the Federal Highway Administration (Faller and others 1999). Covered bridges are also undergoing a resurgence of interest, with a recent national program for the rehabilitation and restoration of numerous historic structures. The various types of timber bridge superstructures are described in the following sections. Detailed information on modern timber bridges is given in *Timber Bridges: Design, Construction, Inspection, and Maintenance* (Ritter 1992).

Log Stringer

A simple bridge type that has been used for centuries consists of one or more logs used to span the opening. Several logs may be laid side-by-side and fastened together. The log stringer bridge has been used to access logging areas and is advantageous when adequate-sized logs are available and the bridge is needed for only a short time. Unless built with a durable species, the life span of log stringer bridges is usually limited to less than 10 years.



Figure 17–9. Glulam beam bridge over the Dangerous River, near Yukatat, Alaska, consists of three 43.5-m (143-ft) spans. Each span is supported by four 2.3-m (91.5-in.-) deep glulam beams.

Sawn Lumber

Several types of bridges can be built with sawn lumber. Even though the span is usually limited to about 9 m (30 ft) because of the limited size of lumber available, this span length entails the majority of timber bridges in the United States.

Several timbers can be used to span the opening, and a transverse lumber deck can be placed over them to form a stringer and deck bridge. Lumber can be placed (on-edge) side-by-side and used to span the entire opening, forming a longitudinal deck bridge. The lumber can be fastened together with nails or large spikes in partial-width panelized bridge systems or compressed together with high-strength tension rods to form a “stress-laminated” slab-type deck.

Glulam

Structural glued-laminated (glulam) timber greatly extends the span capabilities of the same types of bridges described in the previous paragraph. Glulam stringers placed 0.6 to 1.8 m (2 to 6 ft) on center can support a glulam deck system and result in spans of 12 to 30 m (40 to 100 ft) or more (Fig. 17–9). Using glulam panels to span the opening results in a longitudinal deck system, but this is usually limited to about 9-m (30-ft) spans. These panels are either interconnected or supported at one or more locations with transverse distributor beams. Glulam beams can be used to form a solid deck and are held together with high-stress tension rods to form a stress-laminated slab-type deck. Curved glulam members can be used to produce various aesthetic effects and long-span bridges (Fig. 17–10).

Structural Composite Lumber

Two types of structural composite lumber (SCL)—laminated veneer and oriented strand—are beginning to be used to build timber bridges. Most of the same type of bridges built with either solid-sawn or glulam timber can be built with SCL (Chap. 11).

Considerations for Wood Buildings

Many factors must be considered when designing and constructing wood buildings, including structural, insulation, moisture, and sound control. The following sections provide a brief description of the design considerations for these factors. Fire safety, another important consideration, is addressed in Chapter 18.

Structural

The structural design of any building consists of combining the prescribed performance requirements with the anticipated loading. One major performance requirement is that there be an adequate margin of safety between the structure’s ultimate capacity and the maximum anticipated loading. The probability that the building will ever collapse is minimized using material property information recommended by the material manufacturers along with code-recommended design loads.

Another structural performance requirement relates to serviceability. These requirements are directed at ensuring that the structure is functional, and the most notable one is that deformations are limited. It is important to limit deformations so that floors are not too “bouncy” or that doors do not bind under certain loadings. Building codes often include recommended limits on deformation, but the designer may be provided some latitude in selecting the limits. The basic reference for structural design of wood in all building systems is the *National Design Specification for Wood Construction* (AF&PA 2005a).

Thermal Insulation and Air Infiltration Control

For most U.S. climates, the exterior envelope of a building needs to be insulated either to keep heat in the building or prevent heat from entering. Wood frame construction is well-suited to application of both cavity insulation and surface-applied insulation. The most common materials used for cavity insulation are glass fiber, mineral fiber, cellulose insulation, and spray-applied foams. For surface applications, a wide variety of sheathing insulations exist, such as rigid foam panels. Insulating sheathing placed on exterior walls may also have sufficient structural properties to provide required lateral bracing. Prefinished insulating paneling can be used as an inside finish on exterior walls or one or both sides of the interior partitions. In addition, prefinished insulation can underlay other finishes.

Attic construction with conventional rafters and ceiling joists or roof trusses can be insulated between framing members with batt, blanket, or loose-fill insulation. In some warm climates, radiant barriers and reflective insulations can provide an additional reduction in cooling loads. The “Radiant Barrier Attic Fact Sheet” from the U.S. Department of Energy (1991) provides information on climatic areas that are best suited for radiant barrier applications. This document also provides comparative information on



Figure 17–10. The Alton Saylor Memorial Bridge is a glulam deck arch bridge crossing Joncy Gorge in Angelica, New York. The center three-hinged arch spans 52 m (171 ft) and is the longest clear span in the United States. (Photo courtesy of Laminated Concepts, Inc., Big Flats, New York.)

the relative performance of these products and conventional fibrous insulations.

Existing frame construction can be insulated pneumatically using suitable loose-fill insulating material. When loose-fill materials are used in wall retrofit applications, extra care must be taken during the installation to eliminate the existence of voids within the wall cavity. All cavities should be checked prior to installation for obstructions, such as fire stop headers and wiring, that would prevent the cavity from being completely filled. Care must also be taken to install the material at the manufacturer's recommended density to ensure that the desired thermal performance is obtained. Accessible space can be insulated by manual placement of batt, blanket, or loose-fill material.

In addition to being properly insulated, the exterior envelope of all buildings should be constructed to minimize air flow into or through the building envelope. Air flow can degrade the thermal performance of insulation and cause excessive moisture accumulation in the building envelope.

More information on insulation and air flow retarders can be found in the ASHRAE *Handbook of Fundamentals*, chapters 22 to 24 (ASHRAE 2005).

Moisture Control

Moisture sources for buildings can be broadly classified as follows: (1) surface runoff of precipitation from land areas, (2) ground water or wet soil, (3) precipitation or irrigation water that falls on the building, (4) indoor humidity, (5) outdoor humidity, (6) moisture from use of wet building materials or construction under wet conditions, and (7) errors, accidents, and maintenance problems associated with indoor plumbing. At a given instant of time, the categories are distinct from each other. Water can change phase and

can be transported over space by various mechanisms. Water may therefore be expected to move between categories over time, blurring the distinctions between categories. Christian (1994) provides quantitative estimates of potential moisture loads from various sources.

Moisture accumulation within a building or within parts of a building can affect human comfort and health, influence building durability, and necessitate maintenance and repair activities (or can require that these activities be undertaken more frequently). Moisture accumulation in the building's thermal envelope is also likely to influence the building's energy performance. Some problems associated with moisture accumulation are easily observed. Examples include: (a) mold and mildew, (b) decay of wood-based materials, (c) corrosion of metals, (d) damage caused by expansion of materials from moisture (such as buckling of wood floors), and (e) decline in visual appearance (such as paint peeling, distortion of wood-based siding, or efflorescence on masonry surfaces). Some problems associated with moisture accumulation may not be readily apparent but are nonetheless real; an example is reduced performance of insulated assemblies (resulting in increased energy consumption). Detailed discussions on the effects and the control of moisture in buildings can be found in an ASTM standard (ASTM 2008), the ASHRAE *Handbook of Fundamentals*, chapters 23 and 24 (ASHRAE 2005), and Lstiburek and Carmody (1999).

Mold, Mildew, Dust Mites, and Human Health

Mold and mildew in buildings are offensive, and the spores can cause respiratory problems and allergic reactions in humans. Mold and mildew will grow on most surfaces if the relative humidity at the surface is above a critical value and the surface temperatures are conducive to growth. The longer the surface remains above this critical relative humidity level, the more likely mold will appear; the higher the humidity or temperature, the shorter the time needed for germination. The surface relative humidity is a complex function of material moisture content, material properties, local temperature, and humidity conditions. In addition, mold growth depends on the type of surface. Mildew and mold can usually be avoided by limiting surface relative humidity conditions >80% to short periods. Only for nonporous surfaces that are regularly cleaned should this criterion be relaxed. Most molds grow at temperatures approximately above 4 °C (40 °F). Moisture accumulation at temperatures below 4 °C (40 °F) may not cause mold and mildew if the material is allowed to dry out below the critical moisture content before the temperature increases above 4 °C (40 °F).

Dust mites can trigger allergies and are an important cause of asthma. They thrive at high relative humidity levels (>70%) at room temperature, but will not survive at sustained relative humidity levels less than 50%. However, these relative humidity levels relate to local conditions in the typical places that mites tend to inhabit (for example, mattresses, carpets, soft furniture).

Paint Failure and Other Appearance Problems

Moisture trapped behind paint films may cause failure of the paint (Chap. 16). Water or condensation may also cause streaking or staining. Excessive swings in moisture content of wood-based panels or boards may cause buckling or warp. Excessive moisture in masonry and concrete can produce efflorescence, a white powdery area or lines. When combined with low temperatures, excessive moisture can cause freeze–thaw damage and spalling (chipping).

Structural Failures

Structural failures caused by decay of wood are rare but have occurred. Decay generally requires a wood moisture content equal to or greater than fiber saturation (usually about 30%) and temperatures between 10 and 43 °C (50 and 100 °F). Wood moisture content levels above fiber saturation are only possible in green lumber or by absorption of liquid water from condensation, leaks, ground water, or other saturated materials in contact with the wood. To maintain a safety margin, a 20% moisture content is sometimes used during field inspections as the maximum allowable level. Once established, decay fungi produce water that enables them to maintain moisture conditions conducive to their growth. See Chapter 14 for more information on wood decay.

Rusting or corrosion of nails, nail plates, or other metal building products is also a potential cause of structural failure. In the rare cases of catastrophic structural failure of wood buildings (almost always under the influence of a large seismic load or an abnormally high wind load), failure of mechanical connections usually plays a critical role. Corrosion may occur at high relative humidity levels near the metal surface or as a result of liquid water from elsewhere. Wood moisture content levels >20% encourage corrosion of steel fasteners in wood, especially if the wood is treated with preservatives. In buildings, metal fasteners are often the coldest surfaces, which encourages condensation on, and corrosion of, fasteners.

Effect on Heat Flow

Moisture in the building envelope can significantly degrade the thermal performance of most insulation materials but especially the thermal resistance of fibrous insulations and open cell foams. The degradation is most pronounced when daily temperature reversals across the insulation drive moisture back and forth through the insulation.

Moisture Control Strategies

Strategies to control moisture accumulation fall into two general categories: (1) minimize moisture entry into the building envelope and (2) provide for removal (dissipation) of moisture from the building envelope. Inasmuch as building materials and assemblies are often wetted during construction, design strategies that encourage dissipation of moisture from the assemblies are highly recommended. Such strategies will also allow the building to better withstand wetting events that occur rarely, and thus are largely

unanticipated, but which nonetheless occur at least once during the building's lifespan. Effective moisture dissipation strategies typically involve drainage and ventilation.

The transport mechanisms that can move moisture into or out of building envelopes have various transport capabilities. The mechanisms, in order of the quantities of moisture that they can move, are as follows: (a) liquid water movement, including capillary movement; (b) water vapor transport by air movement; and (c) water vapor diffusion. Trechsel (2001) discusses these in detail. In design for control of moisture entry, it is logical to prioritize control of the transport mechanisms in the order of their transport capabilities. A logical prioritization is thus as follows: (a) control of liquid entry by proper site grading and installing gutters and downspouts and appropriate flashing around windows, doors, and chimneys; (b) control of air leakage by installing air flow retarders or careful sealing by taping and caulking; and (c) control of vapor diffusion by placing vapor retarders on the “warm” side of the insulation. Trechsel (2001) makes the point that although air leakage can potentially move much greater amounts of moisture than diffusion, the potential for moisture damage is not necessarily proportional to the amount of moisture movement, and thus that moisture diffusion in design of building envelopes should not be ignored.

In inhibiting vapor diffusion at the interior surfaces of building assemblies in heating climates (or alternatively, encouraging such diffusion at interior surfaces of building assemblies in cooling climates), control of indoor humidity levels is usually important. In heating climates, ventilation of the living space with outdoor air and limiting indoor sources of moisture (wet firewood, unvented dryers, humidifiers) will lower indoor humidity levels. This is very effective at lowering the rate of moisture diffusion into the building's thermal envelope. In cooling climates, the lower indoor humidity levels afforded by mechanical dehumidification will encourage dissipation of moisture (to the interior) from the building's thermal envelope. More information on the definition of heating and cooling climates and specific moisture control strategies can be found in the *ASHRAE Handbook of Fundamentals*, chapter 24 (ASHRAE 2005).

Sound Control

An important design consideration for residential and office buildings is the control of sound that either enters the structure from outside or is transmitted from one room to another. Wood frame construction can achieve levels of sound control equal to or greater than more massive construction, such as concrete. However, to do so requires designing for both airborne and impact noise insulation.

Airborne noise insulation is the resistance to transmission of airborne noises, such as traffic or speech, either through or around an assembly such as a wall. Noises create vibrations on the structural surfaces that they contact, and the design challenge is to prevent this vibration from reaching and

Table 17–1. Sound transmission class (STC) ratings for typical wood-frame walls

STC rating	Privacy afforded	Wall structure
25	Normal speech easily understood	6-mm (1/4-in.) wood panels nailed on each side of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
30	Normal speech audible but not intelligible	9.5-mm (3/8-in.) gypsum wallboard nailed to one side of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
35	Loud speech audible and fairly understandable	20-mm (5/8-in.) gypsum wallboard nailed to both sides of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
40	Loud speech audible but not intelligible	Two layers of 20-mm (5/8-in.) gypsum wallboard nailed to both sides of standard 38- by 89-mm (nominal 2- by 4-in.) studs.
45	Loud speech barely audible	Two sets of standard 38- by 64-mm (nominal 2- by 3-in.) studs staggered 0.2 m (8 in.) on centers fastened by standard 38- by 89-mm (nominal 2- by 4-in.) base and head plates with two layers of 20-mm (5/8-in.) gypsum wallboard nailed on the outer edge of each set of studs.
50	Shouting barely audible	Standard 38- by 89-mm (nominal 2- by 4-in.) wood studs with resilient channels nailed horizontally to both sides with 20-mm (5/8-in.) gypsum wallboard screwed to channels on each side.
55	Shouting not audible	Double row of standard 38- by 89-mm (nominal 2- by 4-in.) studs 0.4 m (16 in.) on centers fastened to separate plates spaced 25 mm (1 in.) apart. Two layers of 20-mm (5/8-in.) gypsum wallboard screwed 0.3 m (12 in.) on center to the studs. An 89-mm- (3.5-in.-) thick sound-attenuation blanket installed in one stud cavity.

leaving the opposite side of the structural surface. Sound transmission class (STC) is the rating used to characterize airborne noise insulation. A wall system with a high STC rating is effective in preventing the transmission of sound. Table 17–1 lists the STC ratings for several types of wall systems; detailed information for both wall and floor are given in FPL–GTR–43 (Rudder 1985).

Impact noise insulation is the resistance to noise generated by footsteps or dropping objects, generally addressed at floor–ceiling assemblies in multi-family dwellings. Impact insulation class (IIC) is the rating used to characterize the impact noise insulation of an assembly. Both the character of the flooring material and the structural details of the floor influence the IIC rating. Additional information on IIC ratings for wood construction is given in FPL–GTR–59 (Sherwood and Moody 1989).

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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

^aAdditional data for domestic solid-sawn and panel products are provided in the AF&PA–AWC DCA No. 1, “Flame Spread Performance of Wood Products.”

^bIn 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.

^cData 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.

^dCWC, 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).

^eFootnote of UL: In 18 tests of ponderosa pine, three had values over 200 and the average of all tests is 154.

^fFootnote 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

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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 $181 \text{ }^\circ\text{C}$ 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 CO₂, formic acid, acetic acid, and H₂O. 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 deacetylation 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 H₂O and CO₂ 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 CO₂, CO, and H₂O 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 $A = 6.23 \times 10^7 \text{ s}^{-1}$ and $E = 124 \text{ kJ mol}^{-1}$. If these same woods were exposed to steam instead of being oven dried, degradation was much faster. With the corresponding kinetic parameters, $A = 82.9 \text{ s}^{-1}$ 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, $A_1 = 3.2 \times 10^5 \text{ s}^{-1}$, $E_1 = 96 \text{ kJ mol}^{-1}$, $A_2 = 6.5 \times 10^{16} \text{ s}^{-1}$, and $E_2 = 226 \text{ kJ mol}^{-1}$. 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 phenomenology, 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 (kg m ⁻³) ρ	Moisture content (%) M	Material emissivity	r^a	T_{ig} (K)	$k/\rho c^a$ (m ² /s) $\times 10^7$	$k\rho c^a$ (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

^aFormulas 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:

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

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

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

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 m⁻² to 377 °C at imposed heat flux of 18 kW 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 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 m⁻² to 930 s for heat flux of 18 kW 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 oven-dried 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.

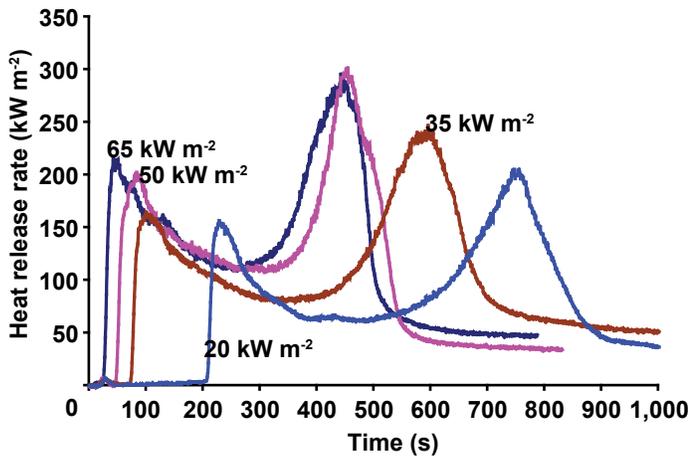


Figure 18–2. Heat release rate curves for 12-mm-thick oriented strandboard (OSB) exposed to constant heat flux of 20, 35, 50 and 65 kW m⁻².

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

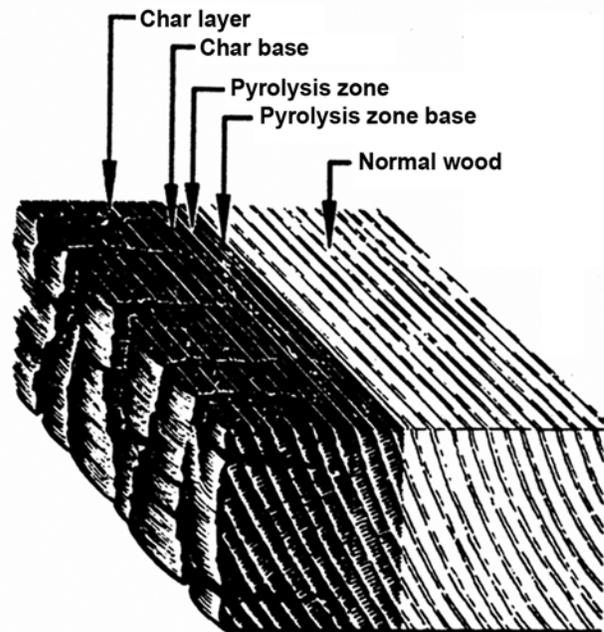


Figure 18–3. Illustration of charring of wood slab.

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

$$t = Cx_c \quad (18-1)$$

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

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

Species	Density ^c (kg m ⁻³)	Wood exposed to ASTM E 119 exposure ^a				Wood exposed to a constant heat flux ^b					
		Char contraction factor ^d	Linear charring rate ^e (min mm ⁻¹)	Non-linear charring rate ^f (min mm ^{-1.23})	Thermal penetration depth ^g (mm)	Linear charring rate ^e (min mm ⁻¹)		Thermal penetration depth ^g (mm)		Average mass loss rate (g m ⁻² s ⁻¹)	
						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	—	—	—	—	—	—

^aMoisture contents of 8% to 9%.

^bCharring 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%.

^cBased on weight and volume of oven-dried wood.

^dThickness of char layer at end of fire exposure divided by original thickness of charred wood layer (char depth).

^eBased on temperature criterion of 288 °C and linear model.

^fBased on temperature criterion of 288 °C and nonlinear model of Equation (18–3).

^gAs 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

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

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

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

where μ is moisture content (fraction of oven-dry 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

$$t = mx_c^{1.23} \quad (18-3)$$

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:

$$m = -0.147 + 0.000564\rho + 1.21\mu + 0.532f_c \quad (18-4)$$

where ρ is density, oven-dry 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

$$T = T_i + (300 - T_i) \left(1 - \frac{x}{d}\right)^2 \quad (18-5)$$

where T is temperature ($^{\circ}\text{C}$), T_i initial temperature ($^{\circ}\text{C}$), 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.

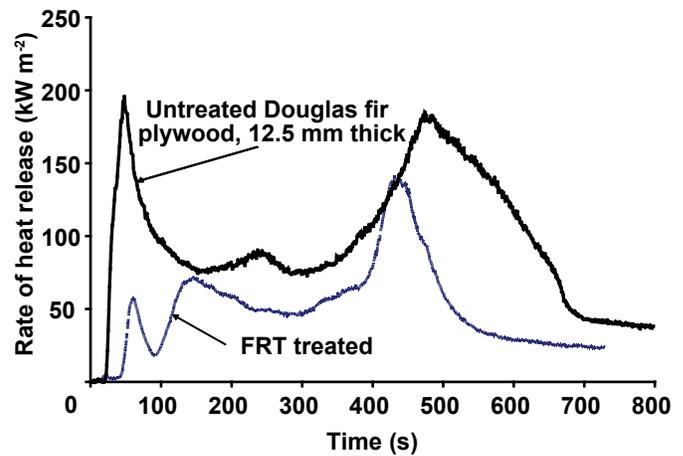


Figure 18–4. Heat release curves for untreated and fire-retardant-treated (FRT) Douglas-fir plywood, 12.5 mm thick.

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 guanidylurea 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 guanidylurea 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 paraffins. 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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Specialty Treatments

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Many specialty treatments can be applied to wood to either improve its performance or change its properties. Treatments addressed in this chapter are those that make permanent changes in the shape of a wood product, improvements in dimensional stability, or improvements in performance through combinations with nonwood resources.

Plasticizing Wood

Principles of Plasticizing and Bending

In simple terms, the wood cell wall is a composite made of a rigid cellulose polymer in a matrix of lignin and the hemicelluloses. The lignin polymer in the middle lamella and S2 layer is thermoplastic; that is, it softens upon heating. The glass transition temperature T_g of the lignin in the matrix is approximately 170 °C (338 °F). Above the matrix T_g , it is possible to cause the lignin to undergo thermoplastic flow and, upon cooling, reset in the same or modified configuration. This is the principle behind bending of wood.

The matrix can be thermoplasticized by heat alone, but the T_g of the unmodified matrix is so high that some fiber decomposition can occur if high temperatures are maintained for a lengthy period. The T_g of the matrix can be decreased with the addition of moisture or through the use of plasticizers or softeners.

Heat and moisture make certain species of wood sufficiently plastic for bending operations. Steaming at atmospheric or a low gauge pressure, soaking in boiling or nearly boiling water, or microwave heating moist wood are satisfactory methods of plasticizing wood. Wood at 20% to 25% moisture content needs to be heated without losing moisture; at lower moisture content, heat and moisture must be added. As a consequence, the recommended plasticizing processes are steaming or boiling for about 15 min cm⁻¹ (38 min in⁻¹) of thickness for wood at 20% to 25% moisture content and steaming or boiling for about 30 min cm⁻¹ (75 min in⁻¹) of thickness for wood at lower moisture content levels. Steaming at high pressures causes wood to become plastic, but wood treated with high pressure steam generally does not bend as successfully as does wood treated at atmospheric or low pressure. Microwave heating requires much shorter times.

Wood can be plasticized by a variety of chemicals in addition to water. Common chemicals that plasticize wood include urea, dimethylol urea, low-molecular-weight phenol-formaldehyde resin, dimethyl sulfoxide, and liquid ammonia. Urea and dimethylol urea have received limited

commercial attention, and a bending process using liquid ammonia has been patented. Wood members can be readily molded or shaped after immersion in liquid ammonia or treatment under pressure with ammonia in the gas phase. As the ammonia evaporates, the lignin resets, the wood stiffens and retains its new shape. Plasticization of the lignin matrix alone can be done using chemical modification technologies, which are covered later in this chapter.

It is also possible to bend wood without softening or plasticizing treatments. However, the stability of the final product may not be as permanent as from treatments in which softening and plasticizing methods are used.

Bent Wood Members

Bending can provide a variety of functional and esthetically pleasing wood members, ranging from large curved arches to small furniture components. The curvature of the bend, size of the member, and intended use of the product determine the production method.

Laminated Members

At one time in the United States, curved pieces of wood were laminated chiefly to produce small items such as parts for furniture and pianos. However, the principle was extended to the manufacture of arches for roof supports in farm, industrial, and public buildings and other types of structural members (see Chap. 11). The laminations are bent without end pressure against a form and adhesively bonded together. Both softwoods and hardwoods are suitable for laminated bent structural members, and thin material of any species can be bent satisfactorily for such purposes. The choice of species and adhesive depends primarily on the cost, required strength, and demands of the application.

Laminated curved members are produced from dry stock in a single bending and adhesive bond formation operation. This process has the following advantages compared with bending single-piece members:

- Bending thin laminates to the required radius involves only moderate stress and deformation of the wood fibers, eliminating the need for treatment with steam or hot water and associated drying and conditioning of the finished product. In addition, the moderate stresses involved in curving laminated members result in stronger members when compared with curved single-piece members.
- The tendency of laminated members to change shape with changes in moisture content is less than that of single-piece bent members.
- Ratios of thickness of member to radius of curvature that are impossible to obtain by bending single pieces can be attained readily by laminating.
- Curved members of any desired length can be produced.

Straight-laminated members can be steamed and bent after they are bonded together. However, this type of procedure requires an adhesive that will not be affected by the steaming or boiling treatment and complicates conditioning of the finished product.

Curved Plywood

Curved plywood is produced either by bending and adhesive bonding the plies in one operation or by bending previously bonded flat plywood. Plywood curved by bending and bonding simultaneously is more stable in curvature than plywood curved by bending previously bonded material.

Plywood Bent and Adhesively Bonded Simultaneously

In bending and bonding plywood in a single operation, adhesive-coated pieces of veneer are assembled and pressed over or between curved forms. Pressure and sometimes heat are applied through steam or electrically heated forms until the adhesive sets and holds the assembly to the desired curvature. Some laminations are at an angle, usually 90°, to other laminations, as in the manufacture of flat plywood. The grain direction of the thicker laminations is normally parallel to the axis of the bend to facilitate bending.

A high degree of compound curvature can be obtained in an assembly made up of a considerable number of thin veneers. First, for both the face and back of the assembly, the two outer plies are bonded at 90° to each other in a flat press. The remaining veneers are then adhesive-coated and assembled at any desired angle to each other. The entire assembly is hot-pressed to the desired curvature.

Bonding the two outer plies before molding allows a higher degree of compound curvature without cracking the face plies than could otherwise be obtained. Where a high degree of compound curvature is required, the veneer should be relatively thin (less than 3 mm (1/8 in.)) with a moisture content of about 12%.

The molding of plywood with fluid pressure applied by flexible bags of some impermeable material produces plywood parts of various degrees of compound curvature. In “bag molding,” fluid pressure is applied through a rubber bag by air, steam, or water. The veneer is wrapped around a form, and the whole assembly is enclosed in a bag and subjected to pressure in an autoclave, the pressure in the bag being “bled.” Or the veneer may be inserted inside a metal form and, after the ends have been attached and sealed, pressure is applied by inflating a rubber bag. The form may be heated electrically or by steam.

The advantages of bending and bonding plywood simultaneously to form a curved shape are similar to those for curved-laminated members. In addition, the cross plies give the curved members properties that are characteristic of cross-banded plywood. Curved plywood shells for furniture manufacture are examples of these bent veneer and adhesive-bonded products.

Plywood Bent after Bonding

After the plies are bonded together, flat plywood is often bent by methods that are somewhat similar to those used in bending solid wood. To bend plywood properly to shape, it must be plasticized by some means, usually moisture or heat, or a combination of both. The amount of curvature that can be introduced into a flat piece of plywood depends on numerous variables, such as moisture content, direction of grain, thickness and number of plies, species and quality of veneer, and the technique applied in producing the bend. Plywood is normally bent over a form or a bending mandrel.

Flat plywood bonded with a waterproof adhesive can be bent to compound curvatures after bonding. However, no simple criterion is available for predetermining whether a specific compound curvature can be imparted to flat plywood. Soaking the plywood prior to bending and using heat during forming are aids in manipulation. Usually, the plywood to be postformed is first thoroughly soaked in hot water, and then dried between heated forming dies attached to a hydraulic press. If the use of postforming for bending flat plywood to compound curvatures is contemplated, exploratory trials to determine the practicability and the best procedure are recommended. Remember that in postforming plywood to compound curvatures, all the deformation must be by compression or shear because plywood cannot be stretched. Hardwood species, such as birch, poplar, and gum, are usually used in plywood that is to be postformed.

Veneered Curved Members

Veneered curved members are usually produced by bonding veneer to one or both faces of a curved solid-wood base. The bases are ordinarily sawn to the desired shape or bent from a piece grooved with saw kerfs on the concave side at right angles to the direction of bend. Pieces bent by making saw kerfs on the concave side are commonly reinforced and kept to the required curvature by bonding splines, veneer, or other pieces to the curved base. Veneering over curved solid wood is used mainly in furniture. The grain of the veneer is commonly laid in the same general direction as the grain of the curved wood base. The use of crossband veneers, that is, veneers lay with the grain at right angles to the grain of the back and face veneer, decreases the tendency of the member to split.

Bending of Solid Members

Wood of certain species that is steamed, microwaved, or soaked in boiling water can be compressed as much as 25% to 30% parallel to the grain. The same wood can be stretched only 1% to 2%. Because of the relation between attainable tensile and compressive deformations, if bending involves severe deformation, then most of the deformation must be compression. The inner or concave side must assume the maximum amount of compression, and the outer or convex side must experience zero strain or a slight tension. To accomplish this, a metal strap equipped with end

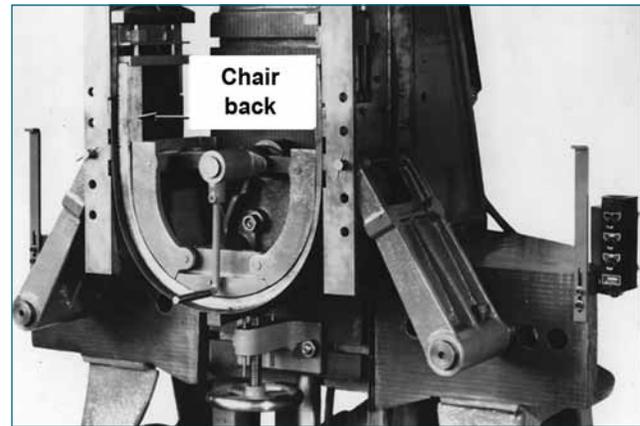


Figure 19–1. Chair back being bent through an arc of 180° in a bending machine.

fittings is customarily used. The strap makes contact with the outer or convex side and, acting through the end fittings, places the whole piece of wood in compression. The tensile stress that would normally develop in the outer side of the piece of wood during bending is borne by the metal strap. A bending form is shown in Figure 19–1.

Selection of Stock

In general, hardwoods possess better bending quality than softwoods, and certain hardwoods surpass others in this quality. This is interesting from a theoretical point of view because hardwoods contain less lignin than softwoods. Hardwoods also contain much more hemicelluloses in the matrix than do softwoods. The species commonly used to produce bent members are white oak, red oak, elm, hickory, ash, beech, birch, maple, walnut, sweetgum, and mahogany. As stated, most softwoods have a poor bending quality and are not often used in bending operations. However, Pacific yew and yellow-cedar are exceptions to this rule. In addition, Douglas-fir, southern yellow pine, northern and Atlantic white-cedar, and redwood are used for ship and boat planking for which purpose they are often bent to moderate curvature after being steamed or soaked.

Bending stock should be free from serious cross grain and distorted grain, such as may occur near knots. The slope of cross grain should not be steeper than about 1 to 15. Decay, knots, shake, pith, surface checks, and exceptionally light or brittle wood should be avoided.

Moisture Content of Bending Stock

Although green wood can be bent to produce many curved members, difficulties are encountered in drying and fixing the bend. Another disadvantage with green stock is that hydrostatic pressure may be developed during bending. Hydrostatic pressure can cause compression failures on the concave side if the wood is compressed by an amount greater than the air space in the cells of the green wood.

Bending stock that has been dried to low moisture content level requires a lengthy steaming or soaking process to increase its moisture content to the point where it can be made sufficiently plastic for successful bending. For most chair and furniture parts, the moisture content of the bending stock should be 12% to 20% before it is steamed or microwave heated. The preferred moisture content level varies with the severity of the curvature to which the wood is bent and the method used in drying and fixing the bent member. For example, chair-back slats, which have a slight curvature and are subjected to severe drying conditions between steam-heated platens, can be produced successfully from stock at 12% moisture content. For furniture parts that need a more severe bend where the part must be bent over a form, 15% to 20% moisture content is recommended.

Bending Operation and Apparatus

After being plasticized, the stock should be quickly placed in the bending apparatus and bent to shape. The bending apparatus consists essentially of a form (or forms) and a means of forcing the piece of steamed wood against the form. If the curvature to be obtained demands a difference of much more than 3% between lengths of the outer and inner surfaces of the pieces, then the apparatus should include a device for applying end pressure. This generally takes the form of a metal strap or pan provided with end blocks, end bars, or clamps.

Fixing the Bend

After being bent, the piece should be cooled and dried while held in its curved shape. One method is to dry the piece in the bending machine between the plates of a hot-plate press. Another method is to secure the bent piece to the form and place both the piece and the form in a drying room. Still another is to keep the bent piece in a minor strap with tie rods or stays so that it can be removed from the form and placed in a drying room. When the bent member has cooled and dried to moisture content suitable for its intended use, the restraining devices can be removed and the piece will hold its curved shape.

Characteristics of Bent Wood

After a bent piece of wood is cooled and dried, the curvature will be maintained. An increase in moisture content may cause the piece to lose some of its curvature. A decrease in moisture content may cause the curve to become sharper, although repeated changes in moisture content bring about a gradual straightening. These changes are caused primarily by lengthwise swelling or shrinking of the inner (concave) face, the fibers of which were wrinkled or folded during the bending operation.

A bent piece of wood has less strength than a similar unbent piece. However, the reduction in strength brought about by bending is seldom serious enough to affect the utility value of the member.

Modified Woods

Wood can be chemically modified to improve water repellency, dimensional stability, resistance to acids or bases, ultraviolet radiation, biodeterioration, and thermal degradation. Wood can also be chemically treated, then compressed to improve dimensional stability and increase hardness. Sheets of paper treated with resins or polymers can be laminated and hot pressed into thick panels that have the appearance of plastic rather than paper. These sheets are used in special applications because of their structural properties and in items requiring hard, impervious, and decorative surfaces.

Modified woods, modified wood-based materials, and paper-based laminates are usually more expensive than wood because of the cost of the chemicals and the special processing required producing them. Thus, modified wood use is generally limited to special applications where the increased cost is justified by the special properties needed.

Wood is treated with chemicals to increase hardness and other mechanical properties, as well as its resistance to decay, fire, weathering, and moisture. The rate and extent of swelling and shrinking of the wood when in contact with water is decreased by application of water-resistant chemicals to the surface of wood, impregnation of the wood with such chemicals dissolved in water or volatile solvents, or bonding chemicals to the cell wall polymer. Such treatments may also decrease the rate at which wood changes dimension as a result of humidity, even though these treatments do not affect the final dimensional changes caused by lengthy duration exposures. Paints, varnishes, lacquers, wood-penetrating water repellents, and plastic and metallic films retard the rate of moisture absorption but have little effect on total dimensional change if exposure to moisture is extensive and prolonged.

Resin-Treated Wood—Not Compressed (Impreg)

Permanent stabilization of the dimensions of wood is needed for certain specialty uses. This can be accomplished by depositing a bulking agent within the swollen structure of the wood fibers. The most successful bulking agents that have been commercially applied are highly water-soluble, thermosetting, phenol-formaldehyde resin-forming systems, with initially low molecular weights. No thermoplastic resins have been found that effectively stabilize the dimensions of wood.

Wood treated with a thermosetting, fiber-penetrating resin and cured without compression is known as impreg. The wood (preferably green veneer to facilitate resin pickup) is soaked in the aqueous resin-forming solution or, if air dry, is impregnated with the solution under pressure until the resin content equals 25% to 35% of the weight of dry wood. The treated wood is allowed to stand under nondrying conditions

for 1 to 2 days to permit uniform distribution of the solution throughout the wood. The resin-containing wood is dried at moderate temperatures to remove the water, and then heated to higher temperatures to cure the resin.

Uniform distribution of the resin has been effectively accomplished with thick wood specimens only in sapwood of readily penetrated species. Although thicker material can be treated, the process is usually applied to veneers up to about 8 mm (0.3 in.) thick, because treating time increases rapidly with increases in thickness. Drying thick, resin-treated wood may result in checking and honeycombing. For these reasons, treatments should be confined to veneer and the treated-cured veneer used to build the desired products. Any species can be used for the veneer except the resinous pines. The stronger the original wood, the stronger the end product.

Impreg has a number of properties differing from those of normal wood and ordinary plywood. These properties are given in Table 19–1, with similar generalized findings for other modified woods. Data for the strength properties of yellow birch impreg are given in Table 19–2. Information on thermal expansion properties of ovendry impreg is given in Table 19–3.

The good dimensional stability of impreg is the basis of one use where its cost is not a deterrent. Wood dies of automobile body parts serve as the master from which the metal-forming dies are made for actual manufacture of parts. Small changes in moisture content, even with the most dimensionally stable wood, produce changes in dimension and curvature of an unmodified wood die. Such changes create major problems in making the metal-forming dies where close final tolerances are required. The use of impreg, with its high antishrink efficiency (ASE) (Table 19–4), almost entirely eliminated the problem of dimensional change during the entire period that the wood master dies were needed. Despite the tendency of the resins to dull cutting tools, pattern makers accepted the impreg readily because it machines with less splitting than unmodified wood.

Patterns made from impreg are also superior to unmodified wood in resisting heat when used with shell-molding techniques where temperatures as high as 205 °C (400 °F) are required to cure the resin in the molding sand.

Resin-Treated Wood—Compressed (Compreg)

Compreg is similar to impreg except that it is compressed before the resin is cured within the wood. The resin-forming chemicals (usually phenol-formaldehyde) act as plasticizers for the wood so that it can be compressed under modest pressure (6.9 MPa, 1,000 lb in⁻²) to a specific gravity of 1.35. Some properties of compreg are similar to those of impreg, and others vary considerably (Tables 19–1 and 19–2). Compared with impreg, the advantages of compreg are its natural lustrous finish that can be developed on any cut

surface by sanding with fine-grit paper and buffing, its greater strength properties, and its ability to mold (Tables 19–1 and 19–2). However, thermal expansion coefficients of ovendry compreg are also increased (Table 19–3).

Compreg can be molded by (a) gluing blocks of resin-treated (but still uncured) wood with a phenolic glue so that the gluelines and resin within the plies are only partially set; (b) cutting to the desired length and width but two to three times the desired thickness; and (c) compressing in a split mold at about 150 °C (300 °F). Only a small flash squeeze out at the parting line between the two halves of the mold needs to be machined off. This technique was used for motor-test propellers and airplane antenna masts during World War II.

A more satisfactory molding technique, known as expansion molding, has been developed. The method consists of rapidly precompressing dry but uncured single sheets of resin-treated veneer in a cold press after preheating the sheets at 90 to 120 °C (195 to 250 °F). The heat-plasticized wood responds to compression before cooling. The heat is insufficient to cure the resin, but the subsequent cooling sets the resin temporarily. These compressed sheets are cut to the desired size, and the assembly of plies is placed in a split mold of the final desired dimensions. Because the wood was precompressed, the filled mold can be closed and locked. When the mold is heated, the wood is again plasticized and tends to recover its uncompressed dimensions. This exerts an internal pressure in all directions against the mold equal to about half the original compressing pressure. On continued heating, the resin is set. After cooling, the object may be removed from the mold in finished form. Metal inserts or metal surfaces can be molded to compreg or its handles are molded onto tools by this means. Compreg bands have been molded to the outside of turned wood cylinders without compressing the core. Compreg tubes and small airplane propellers have been molded in this way.

Past uses of compreg were related largely to aircraft; however, it is a suitable material where bolt-bearing strength is required, as in connector plates, because of its good specific strength (strength per unit of weight). Layers of veneer making up the compreg for such uses are often cross laminated (alternate plies at right angles to each other, as in plywood) to give nearly equal properties in all directions.

As a result of its excellent strength properties, dimensional stability, low thermal conductivity, and ease of fabrication, compreg is extremely useful for aluminum drawing and forming dies, drilling jigs, and jigs for holding parts in place while welding.

Compreg has also been used in silent gears, pulleys, water-lubricated bearings, fan blades, shuttles, bobbins, and picker sticks for looms, nuts and bolts, instrument bases and cases, musical instruments, electrical insulators, tool handles, and various novelties. At present, compreg finds considerable

Table 19–1. Properties of modified woods

Property	Impreg	Compreg	Staypak
Specific gravity	15% to 20% greater than normal wood	Usually 1.0 to 1.4	1.25 to 1.40
Equilibrium swelling and shrinking	1/4 to 1/3 that of normal wood	1/4 to 1/3 that of normal wood at right angle to direction of compression, greater in direction of compression but very slow to attain	Same as normal wood at right angle to direction of compression, greater in direction of compression but very slow to attain
Springback	None	Very small when properly made	Moderate when properly made
Face checking	Practically eliminated	Practically eliminated for specific gravities less than 1.3	About the same as in normal wood
Grain raising	Greatly reduced	Greatly reduced for uniform-texture woods, considerable for contrasting grain woods	About the same as in normal wood
Surface finish	Similar to normal wood	Varnished-like appearance for specific gravities greater than about 1.0; cut surfaces can be given this surface by sanding and buffing	Varnished-like appearance; cut surfaces can be given this surface by sanding and buffing
Permeability to water vapor	About 1/10 that of normal wood	No data, but presumably much less than impreg	No data, but presumably less than impreg
Decay and termite resistance	Considerably better than normal wood	Considerably better than normal wood	Normal, but decay occurs somewhat more slowly
Acid resistance	Considerably better than normal wood	Better than impreg because of impermeability	Better than normal wood because of impermeability, but not as good as compreg
Alkali resistance	Same as normal wood	Somewhat better than normal wood because of impermeability	Somewhat better than normal wood because of impermeability
Fire resistance	Same as normal wood	Same as normal wood for long exposures, somewhat better for short exposures	Same as normal wood for long exposures, somewhat better for short exposures
Heat resistance	Greatly increased	Greatly increased	No data
Electrical conductivity	1/10 that of normal wood at 30% RH; 1/1,000 that of normal wood at 90% RH	Slightly more than impreg at low relative humidity values due to entrapped water	No data
Heat conductivity	Slightly increased	Increased about in proportion to specific gravity increase	No data, but should increase about in proportion to specific gravity increase
Compressive strength	Increased more than proportional to specific gravity increase	Increased considerably more than proportional to specific gravity increase	Increased about in proportion to specific gravity increase parallel to grain, increased more perpendicular to grain
Tensile strength	Decreased significantly	Increased less than proportional to specific gravity increase	Increased about in proportion to specific gravity increase
Flexural strength	Increased less than proportional to specific gravity increase	Increased less than proportional to specific gravity increase parallel to grain, increased more perpendicular to grain	Increased proportional to specific gravity increase parallel to grain, increased more perpendicular to grain
Hardness	Increased considerably more than proportional to specific gravity increase	10 to 20 times that of normal wood	10 to 18 times that of normal wood
Impact strength			
Toughness	About 1/2 of value for normal wood, but very susceptible to the variables of manufacture	1/2 to 3/4 of value for normal wood, but very susceptible to the variables of manufacture	Same to somewhat greater than normal wood
Izod	About 1/5 of value for normal wood	1/3 to 3/4 of value for normal wood	Same to somewhat greater than normal wood
Abrasion resistance (tangential)	About 1/2 of value for normal wood	Increased about in proportion to specific gravity increase	Increased about in proportion to specific gravity increase
Machinability	Cuts cleaner than normal wood, but dulls tools more	Requires metalworking tools and metalworking tool speeds	Requires metalworking tools and metalworking tool speeds
Moldability	Cannot be molded but can be formed to single curvatures at time of assembly	Can be molded by compression and expansion molding methods	Cannot be molded
Gluability	Same as normal wood	Same as normal wood after light sanding or in the case of thick stock, machining surfaces plane	Same as normal wood after light sanding, or in the case of thick stock, machining surfaces plane

Table 19–2. Strength properties of normal and modified laminates^a of yellow birch and a laminated paper plastic

Property	Normal laminated wood ^b	Impreg (impregnated, uncompressed) ^c	Compreg (impregnated, highly compressed) ^c	Staypak (unimpregnated, highly compressed) ^b	Paper laminate (impregnated, highly compressed) ^d
Thickness of laminate (mm (in.))	23.9 (0.94)	26.2 (1.03)	16.0 (0.63)	12.2 (0.48)	3.2 (0.126) 13.0 (0.512)
Moisture content at time of test (%)	9.2	5.0	5.0	4.0	—
Specific gravity (based on weight and volume at test)	0.7	0.8	1.3	1.4	1.4
Parallel laminates					
Flexure—grain parallel to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	79.3 (11,500)	109.6 (15,900)	184.1 (26,700)	138.6 (20,100)	109.6 (15,900)
Modulus of rupture (MPa (lb in ⁻²))	140.6 (20,400)	129.6 (18,800)	250.3 (36,300)	271.6 (39,400)	252.3 (36,600)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	16.0 (2,320)	16.4 (2,380)	25.4 (3,690)	30.7 (4,450)	20.8 (3,010)
Flexure—grain perpendicular to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	6.9 (1,000)	9.0 (1,300)	29.0 (4,200)	22.1 (3,200)	72.4 (10,500)
Modulus of rupture (MPa (lb in ⁻²))	13.1 (1,900)	11.7 (1,700)	31.7 (4,600)	34.5 (5,000)	167.5 (24,300)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.0 (153)	1.5 (220)	4.3 (626)	4.2 (602)	10.2 (1,480)
Compression parallel to grain (edgewise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	44.1 (6,400)	70.3 (10,200)	113.1 (16,400)	66.9 (9,700)	49.6 (7,200)
Ultimate strength (MPa (lb in ⁻²))	65.5 (9,500)	106.2 (15,400)	180.0 (26,100)	131.7 (19,100)	144.1 (20,900)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	15.8 (2,300)	17.0 (2,470)	26.1 (3,790)	32.2 (4,670)	21.5 (3,120)
Compression perpendicular to grain (edgewise) ^f					
Proportional limit stress (MPa (lb in ⁻²))	4.6 (670)	6.9 (1,000)	33.1 (4,800)	17.9 (2,600)	29.0 (4,200)
Ultimate strength (MPa (lb in ⁻²))	14.5 (2,100)	24.8 (3,600)	96.5 (14,000)	64.8 (9,400)	125.5 (18,200)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.1 (162)	1.7 (243)	3.9 (571)	4.0 (583)	11.0 (1,600)
Compression perpendicular to grain (flatwise) ^e					
Maximum crushing strength (MPa (lb in ⁻²))	—	29.5 (4,280)	115.1 (16,700)	91.0 (13,200)	291.0 (42,200)
Tension parallel to grain (lengthwise)					
Ultimate strength (MPa (lb in ⁻²))	153.1 (22,200)	108.9 (15,800)	255.1 (37,000)	310.3 (45,000)	245.4 (35,600)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	15.8 (2,300)	17.3 (2,510)	27.2 (3,950)	31.8 (4,610)	25.1 (3,640)
Tension perpendicular to grain (edgewise)					
Ultimate strength (MPa (lb in ⁻²))	9.6 (1,400)	9.6 (1,400)	22.1 (3,200)	22.8 (3,300)	137.9 (20,000)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.1 (166)	1.6 (227)	4.3 (622)	4.0 (575)	11.8 (1,710)
Shear strength parallel to grain (edgewise) ^f					
Johnson double shear across laminations (MPa (lb in ⁻²))	20.5 (2,980)	23.8 (3,460)	50.8 (7,370)	43.9 (6,370)	122.7 (17,800)
Cylindrical double shear parallel to laminations (MPa (lb in ⁻²))	20.8 (3,020)	24.5 (3,560)	39.2 (5,690)	21.2 (3,080)	20.7 (3,000)
Shear modulus					
Tension method (GPa (1,000 lb in ⁻²))	1.2 (182)	1.8 (255)	3.1 (454)	—	—
Plate shear method (FPL test) (GPa (1,000 lb in ⁻²))	—	—	—	2.6 (385)	6.3 (909)
Toughness (FPL test edgewise) ^f (J (in-lb))	26.6 (235)	14.1 (125)	16.4 (145)	28.2 (250)	—
Toughness (FPL test edgewise) ^f (J mm ⁻¹ of width (in-lb in ⁻¹ of width))	1.1 (250)	0.53 (120)	1.0 (230)	2.3 (515)	—
Impact strength (Izod)—grain lengthwise					
Flatwise (notch in face) (J mm ⁻¹ of notch (ft-lb in ⁻¹ of notch))	0.75 (14.0)	0.12 (2.3)	0.23 (4.3)	0.68 (12.7)	0.25 (4.7)
Edgewise (notch in face) (J mm ⁻¹ of notch (ft-lb in ⁻¹ of notch))	0.60 (11.3)	0.10 (1.9)	0.17 (3.2) ^g	—	0.036 (0.67)
Hardness					
Rockwell flatwise ^e (M–numbers)					
Load to embed 11.3-mm (0.444-in.) steel ball to 1/2 its diameter (kN (lb))	7.1 (1,600)	10.7 (2,400)	—	—	—
Hardness modulus (H_M) ^h (MPa (lb in ⁻²))	37.2 (5,400)	63.4 (9,200)	284.8 (41,300)	302.0 (43,800)	245.4 (35,600)
Abrasion—Navy wear-test machine (flatwise) ^e wear per 1,000 revolutions (mm (in.))					
	0.76 (0.030)	1.45 (0.057)	0.46 (0.018)	0.38 (0.015)	0.46 (0.018)

Table 19–2. Strength properties of normal and modified laminates^a of yellow birch and a laminated paper plastic—con.

Property	Normal laminated wood ^b	Impreg (impregnated, uncompressed) ^c	Compreg (impregnated, highly compressed) ^c	Staypak (unimpregnated, highly compressed) ^b	Paper laminate (impregnated, highly compressed) ^d
Water absorption (24-h immersion) increase in weight (%)	43.6	13.7	2.7	4.3	2.2
Dimensional stability in thickness direction					
Equilibrium swelling (%)	9.9	2.8	8.0	29	—
Recovery from compression (%)	—	0	0	4	—
Crossband laminates					
Flexure—face grain parallel to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	47.6 (6,900)	55.8 (8,100)	99.3 (14,400)	78.6 (11,400)	86.9 (12,600)
Modulus of rupture (MPa (lb in ⁻²))	90.3 (13,100)	78.6 (11,400)	157.2 (22,800)	173.0 (25,100)	215.8 (31,300)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	9.0 (1,310)	11.5 (1,670)	17.1 (2,480)	20.0 (2,900)	15.4 (2,240)
Compression parallel to face grain (edgewise) ^f					
Proportional limit stress (MPa (lb in ⁻²))	22.8 (3,300)	35.8 (5,200)	60.0 (8,700)	35.8 (5,200)	34.5 (5,000)
Ultimate strength (MPa (lb in ⁻²))	40.0 (5,800)	78.6 (11,400)	164.8 (23,900)	96.5 (14,000)	130.3 (18,900)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	9.4 (1,360)	10.3 (1,500)	15.8 (2,300)	18.6 (2,700)	16.3 (2,370)
Tension parallel to face grain (lengthwise)					
Ultimate strength (MPa (lb in ⁻²))	84.8 (12,300)	54.5 (7,900)	113.8 (16,500)	168.9 (24,500)	187.5 (27,200)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	8.9 (1,290)	10.1 (1,460)	15.1 (2,190)	17.7 (2,570)	18.6 (2,700)
Toughness (FPL test edgewise) ^f (J mm ⁻¹ of width (in-lb in ⁻¹ of width))	0.47 (105)	0.18 (40)	0.51 (115)	1.4 (320)	—

^aLaminates made from 17 plies of 1.6-mm (1/16-in.) rotary-cut yellow birch veneer.

^bVeneer conditioned at 27 °C (80 °F) and 65% relative humidity before assembly with phenol resin film adhesive.

^cImpregnation, 25% to 30% of water-soluble phenol-formaldehyde resin based on the dry weight of untreated veneer.

^dHigh-strength paper (0.076-mm (0.003-in.) thickness) made from commercial unbleached black spruce pulp (*Mitscherlich subtilis*), phenol resin content 36.3% based on weight of treated paper, Izod impact abrasion, flatwise compression, and shear specimens, all on 12.7-mm- (1/2-in.-) thick laminate.

^eLoad applied to the surface of the original material (parallel to laminating pressure direction).

^fForest Products Laboratory (FPL) test procedure: load applied to edge of laminations (perpendicular to laminating pressure direction).

^gValues as high as 0.53 J mm⁻¹ (10.0 ft-lb in⁻¹) of notch have been reported for compreg made with alcohol-soluble resins and 0.37 J mm⁻¹ (7.0 ft-lb in⁻¹) with water-soluble resins.

^hValues based on the average slope of load–penetration plots where H_M is an expression for load per unit of spherical area of penetration of the 11.3-mm (0.444-in.) steel ball expressed in MPa (lb in⁻²).

Table 19–3. Coefficients of linear thermal expansion per degree Celsius of wood, hydrolyzed wood, and paper products^a

Material ^b	Specific gravity of product	Resin content ^c (%)	Fiber or machine direction	Linear expansion per °C (values multiplied by 10 ⁶)		
				Perpendicular to fiber or machine direction in plane of laminations	Pressing direction	Cubical expansion per °C (values multiplied by 10 ⁶)
Yellow birch laminate	0.72	3.1	3.254	40.29	36.64	80.18
Yellow birch staypak laminate	1.30	4.7	3.406	37.88	65.34	106.63
Yellow birch impreg laminate	0.86	33.2	4.648	35.11	37.05	76.81
Yellow birch compreg laminate	1.30	24.8	4.251	39.47	59.14	102.86
	1.31	34.3	4.931	39.32	54.83	99.08
Sitka spruce laminate	0.53	6.0 ^d	3.887	37.14	27.67	68.65
Parallel-laminated paper laminate	1.40	36.5	5.73	15.14	65.10	85.97
Crossbanded paper laminate	1.40	36.5	10.89	11.0 ^e	62.2	84.09
Molded hydrolyzed-wood plastic	1.33	25	42.69	42.69	42.69	128.07
Hydrolyzed-wood sheet laminate	1.39	18	13.49	224.68	77.41	115.58

^aThese coefficients refer to bone-dry material. Generally, air-dry material has a negative thermal coefficient, because the shrinkage resulting from the loss in moisture is greater than the normal thermal expansion.

^bAll wood laminates made from rotary-cut veneer, annual rings in plane of sheet.

^cOn basis of dry weight of product.

^dApproximate.

^eCalculated value.

Table 19–4. Comparison of wood treatments and the degree of dimensional stability achieved

Treatment	Antishrink efficiency (%)
Simple wax dip	2 to 5
Wood–plastic combination	10 to 15
Staypak/Staybwood	30 to 40
Impreg	65 to 70
Chemical modification	65 to 75
Polyethylene glycol	80 to 85
Formaldehyde	82 to 87
Compreg	90 to 95

use in handles for knives and other cutlery. The expansion-molding techniques of forming and curing of the compreg around the metal parts of the handle as well as attaching previously made compreg with rivets are two methods used. Compreg is currently manufactured worldwide, including the United States, United Kingdom, Pakistan, and India.

Veneer of any nonresinous species can be used for making compreg. Most properties depend upon the specific gravity to which the wood is compressed rather than the species used.

Heat Treatments

Heating wood changes the properties of wood. It can decrease the hygroscopicity and improve the dimensional stability and decay resistance. Yet, at the same time, the increase in stability and durability also increases the brittleness and loss in some strength properties, including impact toughness, modulus of rupture, and work to failure. The treatments usually cause a darkening of the wood and the wood has a tendency to crack and split.

Wood can be heated various ways: heating in the presence of moisture, heating in the presence of moisture followed by compression, heating dry wood, and heating dry wood followed by compression. The effect of the heating process on wood properties depends on the process itself. As the wood is heated, the first weight loss is due to the loss of water, followed by a variety of chemistries that produce degradation products and volatile gasses. As the temperature increases, wood cell wall polymers start to degrade. Pyrolysis of the hemicelluloses takes place about 270 °C followed closely by cellulose. Lignin is much more stable to high temperature.

Many of the commercial heat treating processes take place in the absence of air at temperatures ranging from 180 to 260 °C for times ranging from a few minutes to several hours. Temperatures lower than 140 °C result in less change in physical properties, and heating above 300 °C results in severe wood degradation. Wood has been heated in steam, in an inert gas, below molten metal, and in hot oil baths. Improved dimensional stability and durability are thought to be due to a loss of hydroscopic hemicellulose sugars and their conversion to furan-based polymers that are much less

hydroscopic, and the lost sugars decrease the ability of fungi to attack the heated wood. The weight loss is proportional to the square of the reduction in swelling.

A variety of thermal modification processes have been developed. The results of the process depend on several variables, including time and temperature, treatment atmosphere, wood species, moisture content, wood dimensions, and the use of a catalyst. Temperature and time of treatment are the most critical elements. Treatments done in air result in oxidation reactions not leading to the desired properties of the treated wood. Generally, weight loss occurs to a greater extent in hardwoods than in softwoods.

Several names have been given to the various heat-treated products and treatments for wood, including Staypak and Staybwood in the United States, Lignostone and Lignofol in Germany, Jicwood and Jablo in the United Kingdom, ThermoWood in Finland, Plato in the Netherlands, and Perdure and Retification in France.

Heating wood under a variety of conditions is an environmentally benign process requiring no added chemicals and gives rise to a variety of products with decreased moisture contents and some durability against biological degradation. However, it is not recommended to be used in ground contact. Most physical properties are decreased, especially abrasion resistance and toughness, and it is therefore not suitable for load-bearing applications.

Heating Wet Wood

Wood with moisture content close to its equilibrium moisture content (EMC) that is heated to 180 to 200 °C results in a wood with greatly decreased moisture content. The high temperature degrades the hemicellulose sugars to furan-based intermediates and volatile gasses. The furan intermediates have a lower EMC than the sugars and increase bonding of the wood structure. At a weight loss of approximately 25%, the EMC is lowered by almost the same percentage. Dimensional stability is also increased but not as much as heating followed by compression (discussed in the following section).

Two current processes are based on heating wet wood for stability and increased biological resistance. ThermoWood was developed by VTT in Finland and is a three-stage process done in the presence of steam, which helps protect the wood from oxidative reactions. In the first stage, the wood is heated to 100 °C for almost 20 h. In the second stage, the wood is heated to 185 to 230 °C for 10 h, followed by the lowering of the temperature in the presence of a water spray.

Plato (Proving Lasting Advanced Timber Option) wood was developed by Royal Dutch Shell in The Netherlands and involves a four-stage process. The first stage involves heating the wood to 150 to 180 °C under high-pressure steam for 4 to 5 h. The wood is then dried to a moisture content of 8% to 10% and then heated again at 150 to 190 °C for 12 to

16 h, resulting in a drop in moisture content to less than 1%. The wood is then conditioned to 4% to 6% moisture over a 3-day period. The wood is dark brown in color but will weather to the normal gray color in time. It has a 5% to 20% decrease in modulus of rupture but a slightly higher modulus of elasticity.

The Le Bois Perdure process was developed by the French company BCI in the mid-1990s and has been commercialized by PCI Industries, Inc., based in Quebec. The process involves drying and heating the wood at 200 to 230 °C in steam.

All heat-treated wood is gluable and paintable and can be used for furniture, flooring, decking, door and window components, and exterior joinery.

Heating Wet Wood Followed by Compression

When wet wood is heated to 180 to 220 °C and compressed, the wood structure is compressed and remains in this compressed state when dried. The compressed wood is much harder and has a much higher modulus of rupture and elongation. Re-wetting the compressed wood reverses the process and it swells back to its original thickness.

Heating Dry Wood

Heating wood under drying conditions at higher temperatures (95 to 320 °C (200 to 600 °F)) than those normally used in kiln drying produces a product known as Staybwood that decreases the hygroscopicity and subsequent swelling and shrinking of the wood appreciably. However, the stabilization is always accompanied by loss of mechanical properties. Toughness and resistance to abrasion are most seriously affected.

Under conditions that cause a reduction of 40% in shrinking and swelling, the toughness is decreased to less than half that of the original wood. Extensive research to minimize this loss was not successful. Because of the reduction in strength properties from heating at such high temperatures, wood that is dimensionally stabilized in this manner was never commercialized.

One commercial process produces dry-heated wood products. Retification is a process developed in France by École des Mines de St. Etienne and involves heating wood in a nitrogen atmosphere to 180 to 250 °C for several hours.

Heating Dry Wood Followed by Compression

To meet the demand for a tougher compressed product than compreg, a compressed wood containing no resin (staypak) was developed. A temperature range of 150 to 170 °C is used, and the wood is compressed while heated. It does not lose its compression under swelling conditions as does untreated compressed wood. In making staypak, the compressing conditions are modified so that the lignin-cementing material between the cellulose fibers flows sufficiently to eliminate internal stresses.

Staypak is not as water resistant as compreg, but it is about twice as tough and has higher tensile and flexural strength properties (Tables 19–1 and 19–2). The natural finish of staypak is almost equal to that of compreg. Under weathering conditions, however, it is definitely inferior to compreg. For outdoor use, a good synthetic resin varnish or paint finish should be applied to staypak.

Staypak can be used in the same way as compreg where extremely high water resistance is not needed. It shows promise in tool handles, forming dies, connector plates, propellers, and picker sticks and shuttles for weaving, where high impact strength is needed. Staypak is not impregnated; therefore, it can be made from solid wood as well as from veneer. The cost of staypak is less than that of compreg.

A material similar to staypak was produced in Germany prior to World War II. It was a compressed solid wood with much less dimensional stability than staypak and was known as lignostone. Another similar German product was a laminated compressed wood known as lignofol.

Wood Treated with Polyethylene Glycol (PEG)

The dimensional stabilization of wood with polyethylene glycol-1000 (PEG), also known as Carbowax, is accomplished by bulking the fiber to keep the wood in a partially swollen condition. PEG acts in the same manner as does the previously described phenolic resin. It cannot be further cured. The only reason for heating the wood after treatment is to drive off water. PEG remains water soluble in the wood. Above 60% relative humidity, it is a strong humectant and, unless used with care and properly protected, PEG-treated wood can become sticky at high levels of relative humidity. Because of this, PEG-treated wood is usually finished with a polyurethane varnish.

Treatment with PEG is facilitated by using green wood. Here, pressure is not applied because the treatment is based on diffusion. Treating times are such that uniform uptakes of 25% to 30% of chemical are achieved (based on dry weight of wood). The time necessary for this uptake depends on the thickness of the wood and may require weeks. The PEG treatment is being effectively used for cross-sectional wood plaques and other decorative items. Table tops of high quality furniture stay remarkably flat and dimensionally stable when made from PEG-treated wood.

Another application of this chemical is to decrease the checking of green wood during drying. For this application, a high degree of PEG penetration is not required. This method of treatment has been used to decrease checking during drying of small wood blanks or turnings.

Cracking and distortion that old, waterlogged wood undergoes when it is dried can be substantially decreased by treating the wood with PEG. The process was used to dry 200-year-old waterlogged wooden boats raised from Lake George, New York. The “Vasa,” a Swedish ship that sank

Table 19–5. Strength properties of wood–polymer composites^a

Strength property	Unit	Untreated ^b	Treated ^b
Static bending			
Modulus of elasticity	MPa ($\times 10^3$ lb in ⁻²)	9.3 (1,356)	11.6 (1,691)
Fiber stress at proportional limit	MPa (lb in ⁻²)	44.0 (6,387)	79.8 (11,582)
Modulus of rupture	MPa (lb in ⁻²)	73.4 (10,649)	130.6 (18,944)
Work to proportional limit	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	11.4 (1.66)	29.1 (4.22)
Work to maximum load	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	69.4 (10.06)	122.8 (17.81)
Compression parallel to grain			
Modulus of elasticity	GPa ($\times 10^6$ lb in ⁻²)	7.7 (1,113)	11.4 (1,650)
Fiber stress at proportional limit	MPa (lb in ⁻²)	29.6 (4,295)	52.0 (7,543)
Maximum crushing strength	MPa (lb in ⁻²)	44.8 (6,505)	68.0 (9,864)
Work to proportional limit	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	77.8 (11.28)	147.6 (21.41)
Toughness	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	288.2 (41.8)	431.6 (62.6)

^aMethyl methacrylate impregnated basswood.

^bMoisture content 7.2%.

on its initial trial voyage in 1628, was also treated after it was raised. There have been many applications of PEG treatment for the restoration of waterlogged wood from archeological sites.

Wood–Polymer Composites

In the modified wood products previously discussed, most of the chemical resides in cell walls; the lumens are essentially empty. If wood is vacuum impregnated with certain liquid vinyl monomers that do not swell wood and are later polymerized *in situ* by gamma radiation or chemical catalyst-heat systems, the resulting polymer resides almost exclusively in the lumens. Methyl methacrylate is a common monomer used for wood–polymer composites. It is converted to polymethyl methacrylate. The hygroscopic characteristics of the wood substance are not altered because little, if any, polymer penetrates the cell walls. However, because of the high polymer content (70% to 100% based on the dry weight of wood), the normally high void volume of wood is greatly decreased. With the elimination of this very important pathway for vapor or liquid water diffusion, the response of the wood substance to changes in relative humidity or water is very slow, and moisture resistance or water-repellent effectiveness (WRE) is greatly improved. Water-repellent effectiveness is measured as follows:

$$\text{WRE} = \frac{S_1}{S_2} \times 100 \quad (19-1)$$

where S_1 is the swelling or moisture uptake of the control specimen during exposure to water for t minutes, and S_2 is the swelling or moisture uptake of the treated specimen during exposure to water also for t minutes.

Wood–polymer composite materials offer desirable aesthetic appearance, high compression strength and abrasion resistance, and increase in hardness and are much stronger than untreated wood (Table 19–5). Commercial application of these products is largely based on increased strength and hardness properties. Improvements in physical properties

of wood–polymer composites are related to polymer loading. This, in turn, depends not only on the permeability of the wood species but also on the particular piece of wood being treated. Sapwood is filled to a much greater extent than heartwood for most species. The most commonly used monomers include styrene, methyl methacrylate, vinyl acetate, and acrylonitrile. Industrial applications include certain sporting equipment, musical instruments, decorative objects, and high-performance flooring.

At present, the main commercial use of wood–polymer composites is hardwood flooring. Comparative tests with conventional wood flooring indicate that wood–polymer materials resisted indentation from rolling, concentrated, and impact loads better than did white oak. This is largely attributed to improved hardness. Abrasion resistance is also increased. A finish is usually used on these products to increase hardness and wear resistance even more. Wood–polymer composites are also being used for sporting goods, musical instruments, and novelty items.

In addition to the use of vinyl monomers for wood–polymer composites, polysaccharides from renewable resources are also used. Examples include the use of furfuryl alcohol from primarily corn cobs and the use of modified polysaccharides primarily from soy and corn starch. The process (Indurite) involves the impregnation of wood with a water-soluble polysaccharide solution made from soy and corn starch, followed by a curing step at 70 °C. The treatment improves the dimensional stability and hardness of wood and is used in production of flooring materials.

Modification of wood with furfuryl alcohol is called furfurylation. Stamm started research on furfurylation at the Forest Products Laboratory in the 1950s. The process was industrialized in the mid-1960s in the United States, and furfurylated wood products included knife handles, bench tops, and rotor blades, but production ceased by the 1970s. Interest renewed in the late 1980s, and now products are marketed in the United States and Europe. Furfurylation

involves a full cell impregnation step of the treatment solution, an intermediate drying step, a reaction curing step, and a final kiln-drying step. Products are available for decking, marine application, cladding, window joinery, poles, roofs, garden furniture, building materials, and flooring. Impact strength is strongly decreased (from –25% at 15% WPG to –65% at 125% WPG). Stiffness increases from 30% to 80%. The ASE ranges from 30% to 80%. Fungal durability and insect resistance are high at high weight gains.

Chemical Modification

Through chemical reactions, it is possible to add an organic chemical to the hydroxyl groups on wood cell wall components. This type of treatment bulks the cell wall with a permanently bonded chemical. Many reactive chemicals have been used experimentally to chemically modify wood. For best results, chemicals used should be capable of reacting with wood hydroxyls under neutral or mildly alkaline conditions at temperatures less than 120 °C. The chemical system should be simple and must be capable of swelling the wood structure to facilitate penetration. The complete molecule should react quickly with wood components to yield stable chemical bonds while the treated wood retains the desirable properties of untreated wood. Reaction of wood with chemicals such as anhydrides, epoxides, isocyanates, acid chlorides, carboxylic acids, lactones, alkyl chlorides, and nitriles result in antishrink efficiency (ASE) values (Table 19–4) of 65% to 75% at chemical weight gains of 20% to 30%. Antishrink efficiency is determined as follows:

$$S = \frac{V_2 - V_1}{V_1} \times 100 \quad (19-2)$$

where S is volumetric swelling coefficient, V_2 is wood volume after humidity conditioning or wetting with water, and V_1 is wood volume of oven-dried sample before conditioning or wetting. Then,

$$ASE = \frac{S_2 - S_1}{S_1} \times 100 \quad (19-3)$$

where ASE is reduction in swelling or antishrink efficiency resulting from a treatment, S_2 is treated volumetric swelling coefficient, and S_1 is untreated volumetric swelling coefficient.

Reaction of these chemicals with wood yields a modified wood with increased dimensional stability and improved resistance to termites, decay, and marine organisms.

Mechanical properties of chemically modified wood are essentially unchanged compared with untreated wood.

Modification of wood with acetic anhydride has been researched extensively. The acetylation process involves impregnation of acetic anhydride followed by heat to start the reaction. The last step is to remove the acetic acid by-product and any remaining acetic anhydride. The hydroxyl groups of the cell wall polymers are converted to acetyl

groups, making the wood hydrophobic. As a result, biological durability and dimensional stability increase significantly compared with unmodified wood. Acetylated wood is now commercially available.

The reaction of formaldehyde with wood hydroxyl groups is an interesting variation of chemical modification. At weight gains as low as 2%, formaldehyde-treated wood is not attacked by wood-destroying fungi. An antishrink efficiency (Table 19–4) of 47% is achieved at a weight gain of 3.1%, 55% at 4.1%, 60% at 5.5%, and 90% at 7%. The mechanical properties of formaldehyde-treated wood are all decreased from those of untreated wood. A definite embrittlement is observed, toughness and abrasion resistance are greatly decreased, crushing strength and bending strength are decreased about 20%, and impact bending strength is decreased up to 50%.

Paper-Based Plastic Laminates

Commercially, paper-based plastic laminates are of two types: industrial and decorative. Total annual production is equally divided between the two types. They are made by superimposing layers of paper that have been impregnated with a resinous binder and curing the assembly under heat and pressure.

Industrial Laminates

Industrial laminates are produced to perform specific functions requiring materials with predetermined balances of mechanical, electrical, and chemical properties. The most common use of such laminates is electrical insulation. The paper reinforcements used in the laminates are kraft pulp, alpha pulp, cotton linters, or blends of these. Kraft paper emphasizes mechanical strength and dielectric strength perpendicular to laminations. Alpha paper is used for its electric and electronic properties, machineability, and dimensional stability. Cotton linter paper combines greater strength than alpha paper with excellent moisture resistance.

Phenolic resins are the most suitable resins for impregnating the paper from the standpoint of high water resistance, low swelling and shrinking, and high strength properties (except for impact). Phenolics also cost less than do other resins that give comparable properties. Water-soluble resins of the type used for impreg impart the highest water resistance and compressive strength properties to the product, but they make the product brittle (low impact strength). Alcohol-soluble phenolic resins produce a considerably tougher product, but the resins fail to penetrate the fibers as well as water-soluble resins, thus imparting less water resistance and dimensional stability to the product. In practice, alcohol-soluble phenolic resins are generally used.

Paper-based plastic laminates inherit their final properties from the paper from which they are made. High-strength papers yield higher strength plastic laminates than do low-strength papers. Papers with definite directional properties

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result in plastic laminates with definite directional properties unless they are cross laminated (alternate sheets oriented with the machine direction at 90° to each other).

The use of higher strength paper has helped in the development of paper-based laminates suitable for structural use. Pulping under milder conditions and operating the paper machines to give optimum orientation of the fibers in one direction, together with the desired absorbency, contribute markedly to improvements in strength.

Strength and other properties of a paper-plastic laminate are shown in Table 19-2. The National Electrical Manufacturers Association L1-1 specification has additional information on industrial laminates. Paper is considerably less expensive than glass fabric or other woven fabric mats and can be molded at considerably lower pressures; therefore, the paper-based laminates generally have an appreciable price advantage over fabric laminates. However, some fabric laminates give superior electrical properties and higher impact properties. Glass fabric laminates can be molded to greater double curvatures than can paper laminates.

During World War II, a high-strength paper plastic known as papreg was used for molding nonstructural and semistructural airplane parts such as gunner's seats and turrets, ammunition boxes, wing tabs, and the surfaces of cargo aircraft flooring and catwalks. Papreg was used to a limited extent for the skin surface of airplane structural parts, such as wing tips. One major objection to its use for such parts is that it is more brittle than aluminum and requires special fittings. Papreg has been used to some extent for heavy-duty truck floors and industrial processing trays for nonedible materials. Because it can be molded at low pressures and is made from thin paper, papreg is advantageous for use where accurate control of panel thickness is required.

Decorative Laminates

Although made by the same process as industrial laminates, decorative laminates are used for different purposes and bear little outward resemblance to industrial laminate. They are used as facings for doors and walls and tops of counters, flooring, tables, desks, and other furniture.

These decorative laminates are usually composed of a combination of phenolic- and melamine-impregnated sheets of paper. Phenolic-impregnated sheets are brown because of the impregnating resins and make up most of the built-up thickness of the laminate. Phenolic sheets are overlaid with paper impregnated with melamine resin. One sheet of the overlay is usually a relatively thick one of high opacity and has the color or design printed on it. Then, one or more tissue-thin sheets, which become transparent after the resin is cured, are overlaid on the printed sheet to protect it in service. The thin sheets generally contain more melamine resin than do the printed sheets, providing stain and abrasion resistance as well as resistance to cigarette burns, boiling water, and common household solvents.

The resin-impregnated sheets of paper are hot pressed, cured, and then bonded to a wood-based core, usually plywood, hardboard, or particleboard. The thin transparent (when cured) papers impregnated with melamine resin can be used alone as a covering for decorative veneers in furniture to provide a permanent finish. In this use, the impregnated sheet is bonded to the wood surface in hot presses at the same time the resin is cured. The heat and stain resistance and the strength of this kind of film make it a superior finish.

The overall thickness of a laminate may obviously be varied by the number of sheets of kraft-phenolic used in the core assembly. Some years ago, a 2-mm (0.08-in.) thickness was used with little exception because of its high impact strength and resistance to substrate show through. Recently, a 1-mm (0.04-in.) thickness has become popular on vertical surfaces such as walls, cabinet doors, and vertical furniture faces. This results in better economy, and the greater strength of the heavier laminate is not necessary. As applications have proliferated, a series of thicknesses have been offered, from 20 to 60 mm (0.8 to 2.4 in.), even up to 150 mm (6 in.) when self-supportive types are needed. These laminates may have decorative faces on both sides if desired, especially in the heavier thicknesses. Replacement bowling lanes made from high-density fiberboard core and phenolic-melamine, high-pressure laminated paper on the face and back are commercially used.

The phenolic sheets may also contain special postforming-type phenolic resins or extensible papers that make it possible to postform the laminate. By heating to 160 °C (320 °F) for a short time, the structure can readily undergo simple bending to a radius of 10 mm (0.4 in.), and 5 to 6 mm (0.20 to 0.24 in.) with careful control. Rolled furniture edges, decorative moldings, curved counter tops, shower enclosures, and many other applications are served by this technique. Finally, the core composition may be modified to yield a fire-retardant, low-smoking laminate to comply with fire codes. These high-pressure decorative laminates are covered by the National Electrical Manufacturers Association Specification LD-3.

Paper will absorb or give off moisture, depending upon conditions of exposure. This moisture change causes paper to shrink and swell, usually more across the machine direction than along it. In the same manner, the laminated paper plastics shrink and swell, although at a much slower rate. Cross laminating minimizes the amount of this shrinking and swelling. In many furniture uses where laminates are bonded to cores, the changes in dimension as a result of moisture fluctuating with the seasons are different than those of the core material. To balance the construction, a paper plastic with similar properties may be glued to the opposite face of the core to prevent bowing or cupping caused by moisture variation.

Lignin-Filled Laminates

The cost of phenolic resins at one time resulted in considerable effort to find impregnating and bonding agents that were less expensive and yet readily available. Lignin-filled laminates made with lignin recovered from the spent liquor of the soda pulping process were developed as a result of this search. Lignin is precipitated from solution within the pulp or added in a pre-precipitated form before the paper is made. The lignin-filled sheets of paper can be laminated without the addition of other resins, but their water resistance is considerably enhanced when some phenolic resin is applied to the paper in a second operation. The water resistance can also be improved by impregnating only the surface sheet with phenolic resin. It is also possible to introduce lignin, together with phenolic resin, into untreated paper sheets. The lignin-filled laminates are always dark brown or black. They have better toughness than phenolic laminates; in most other strength properties, they are comparable or lower.

Reduction in cost of phenolic resins has virtually eliminated the lignin-filled laminates from U.S. commerce. These laminates have several potential applications, however, where a cheaper laminate with less critical properties than phenolic laminates can be used.

Paper-Face Overlays

Paper has found considerable use as an overlay material for veneer or plywood. Overlays can be classified into three different types according to their use—masking, structural, and decorative. Masking overlays are used to cover minor defects in plywood, such as face checks and patches, minimize grain raising, and provide a more uniform paintable surface, thus making possible the use of lower grade veneer. Paper for this purpose need not be of high strength, because the overlays do not need to add strength to the product. For adequate masking, a single surface sheet with a thickness of 0.5 to 1 mm (0.02 to 0.04 in.) is desirable. Paper impregnated with phenolic resins at 17% to 25% of the weight of the paper gives the best all-around product. Higher resin content makes the product too costly and tends to make the overlay more transparent. Appreciably lower resin content gives a product with low scratch and abrasion resistance, especially when the panels are wet or exposed to high relative humidities.

The paper faces can be applied at the same time that the veneer is assembled into plywood in a hot press. Thermal stresses that might result in checking are not set up if the machine direction of the paper overlays is at right angles to the grain direction of the face plies of the plywood.

The masking-paper-based overlays or vulcanized fiber sheets have been used for such applications as wood house siding that is to be painted. These overlays mask defects in the wood, prevent bleed-through of resins and extractives in the wood, and provide a better substrate for paint. The

paper-based overlays improve the across-the-board stability from changes in dimension as a result of changes in moisture content.

The structural overlay, also known as the high-density overlay, contains no less than 45% thermosetting resins, generally phenolic. It consists of one or more plies of paper similar to that used in the industrial laminates described previously. The resin-impregnated papers can be bonded directly to the surface of a wood substrate during cure of the sheet, thus requiring only a single pressing operation.

The decorative-type overlay is described in the Decorative Laminates section.

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Heat Sterilization of Wood

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Insects and other pests can travel between countries in pallets and other wood packaging materials through international trade. Because these pests can cause significant ecological damage, their invasion into non-native countries is undesirable. Heat sterilization is currently the most practical and environmentally friendly treatment to kill pests in solid wood materials and prevent their transfer between continents and regions. Consequently, regulations requiring heat sterilization are becoming more and more common.

Two important questions should be considered in heat sterilizing solid wood materials: First, what temperature–time regime is required to kill a particular pest? Second, how much time is required to heat the center of any wood configuration to the kill temperature? The entomology research on the first question has facilitated the development of international standards for heat sterilization of various solid wood materials. This chapter primarily addresses the second question. It focuses on various factors that should be considered when planning and implementing a heat treatment process, discusses experimentally derived heating times for commonly used wood products, and presents analytical and empirical methods for estimating heating times that can be used as starting points in the development of heat treatment schedules. Current wood packaging material enforcement regulations and several additional practical considerations for heat treatment operations are also presented.

The preferred units of measure for this chapter are in the in–lb system because of the current high demand for this information in the United States. Metric units or conversion factors are also provided.

Heat Treatment Standards

The current international standard for heat sterilization of solid wood packaging materials is the International Standard for Phytosanitary Measures (ISPM) Pub. No. 15, “Guidelines for Regulating Wood Packaging Material in International Trade,” which requires heating wood to a minimum core temperature of 133 °F (56 °C) for a minimum of 30 min (IPPC 2002, APHIS 2004). These guidelines are for all forms of wood packaging material that may serve as a pathway for plant pests posing a threat mainly to living trees. This temperature–time regime is chosen in consideration of the wide range of pests for which this combination is documented to be lethal and a commercially feasible treatment. Table 20–1 lists the pest groups associated with wood packaging material that can be practically eliminated by heat treatment under ISPM 15 standard. Although some pests are known to have a higher thermal tolerance, quarantine

Table 20–1. Pest groups that are practically eliminated by heat treatment under ISPM 15 standard

Insects
Anobiidae
Bostrichidae
Buprestidae
Cerambycidae
Curculionidae
Isoptera
Lyctidae (with some exceptions for HT)
Oedemeridae
Scolytidae
Siricidae
Nematodes
<i>Bursaphelenchus xylophilus</i>

pests in this category are managed by the National Plant Protection Organizations (NPPOs) on a case-by-case basis (IPPC 2002). Future development may identify other temperature–time regimes required to kill specific insects or fungi.

Factors Affecting Heating Times

From a practical standpoint, the time required for the center of solid wood material to reach the kill temperature depends on many factors, including the type of energy source used to generate the heat, the medium used to transfer the heat (for example, wet or dry heat), the effectiveness of the air circulation in the heating facility, the species and physical properties (configurations, specific gravity, moisture content, initial wood temperature) of the wood and wood products being sterilized, and the stacking methods used in the heat treatment process.

Energy Source

Energy is the amount of heat supplied during the heat treatment process. Heat-treating chambers typically employ systems that utilize steam, hot air (direct fire), electricity, and hot water or hot oil as mechanisms to generate the heat necessary to sterilize the wood. The choice of heat energy primarily depends on the heat treatment method, energy resources available, and the cost of the energy.

Heating Medium

The temperature and humidity of the heating medium significantly affect heating times. Higher heating temperatures obviously yield shorter heating times, and heating wood in saturated steam (wet heat) results in the shortest heating times. When the heating medium is air that is not saturated with steam, the relative humidity is less than 100% (wet-bulb depression > 0 °F), and drying occurs as water evaporates from the wood surface. As the heating medium changes from wet to dry heat, the time needed to reach the required temperature increases. This is illustrated in Figure 20–1, which shows experimentally derived heating times as a function of wet-bulb depression for a series of lumber and timber products.

When the wet-bulb temperature in the heating medium approaches or falls below the target center temperature, heating time becomes much longer than with wet heat (Simpson 2002, Simpson and others 2003) because evaporation of water from the wood surface with dry heat cools the surface and lowers its temperature, reducing the surface-to-center temperature gradient that is the driving force for transferring heat. With wet heat there is little or no evaporation of moisture and thus little surface cooling to slow heat transfer.

Air Circulation

Maintaining adequate air circulation is also important in heat sterilization. The circulating air performs two functions, as it does in kiln drying: it carries heat to the wood to effect evaporation, and it removes the evaporated water vapor. Good air circulation ensures uniform heat distribution in the chamber and keeps the wood surface temperature high so that the surface-to-center temperature gradient is as high as possible. This is usually accomplished with fans and baffles in a treatment chamber.

Size and Configuration of Wood

The heat treatment process is affected by wood configuration and size, as would be expected. Heating time increases with size and at a rate that is more than proportional to the configuration. For example, heating time can range from only a few minutes for thin boards to many hours for large timbers. The effect of wood configuration on heating time can be seen in Figure 20–1 for a series of web-bulb depressions.

Species

Studies of five hardwood species (red maple, sugar maple, red oak, basswood, and aspen) at the USDA Forest Service Forest Products Laboratory (FPL) have indicated that the actual effect of species was not large (Simpson and others 2005). In fact, the differences in heating times of different species are of a similar magnitude to the expected natural variability between individual boards and square timbers. In heat treatment operation, there is no practical reason to heat-treat different hardwood species separately. Figure 20–2 illustrates the effects of species on heating times of boards and square timbers for five hardwood species.

No data are currently available to directly assess the effect of species in heat-treating softwood products. However, there are practical reasons to separate species in drying softwood lumber, and heat treatment for softwood products is often accomplished as part of the wood drying process. Detailed information on heating times for softwood products is presented in the sections of stacking methods, heating times for wood in various forms, and methods for estimating heating times.

Stacking Methods

Proper stacking of lumber or timbers is an essential aspect of the heat treatment process because it directly affects heat

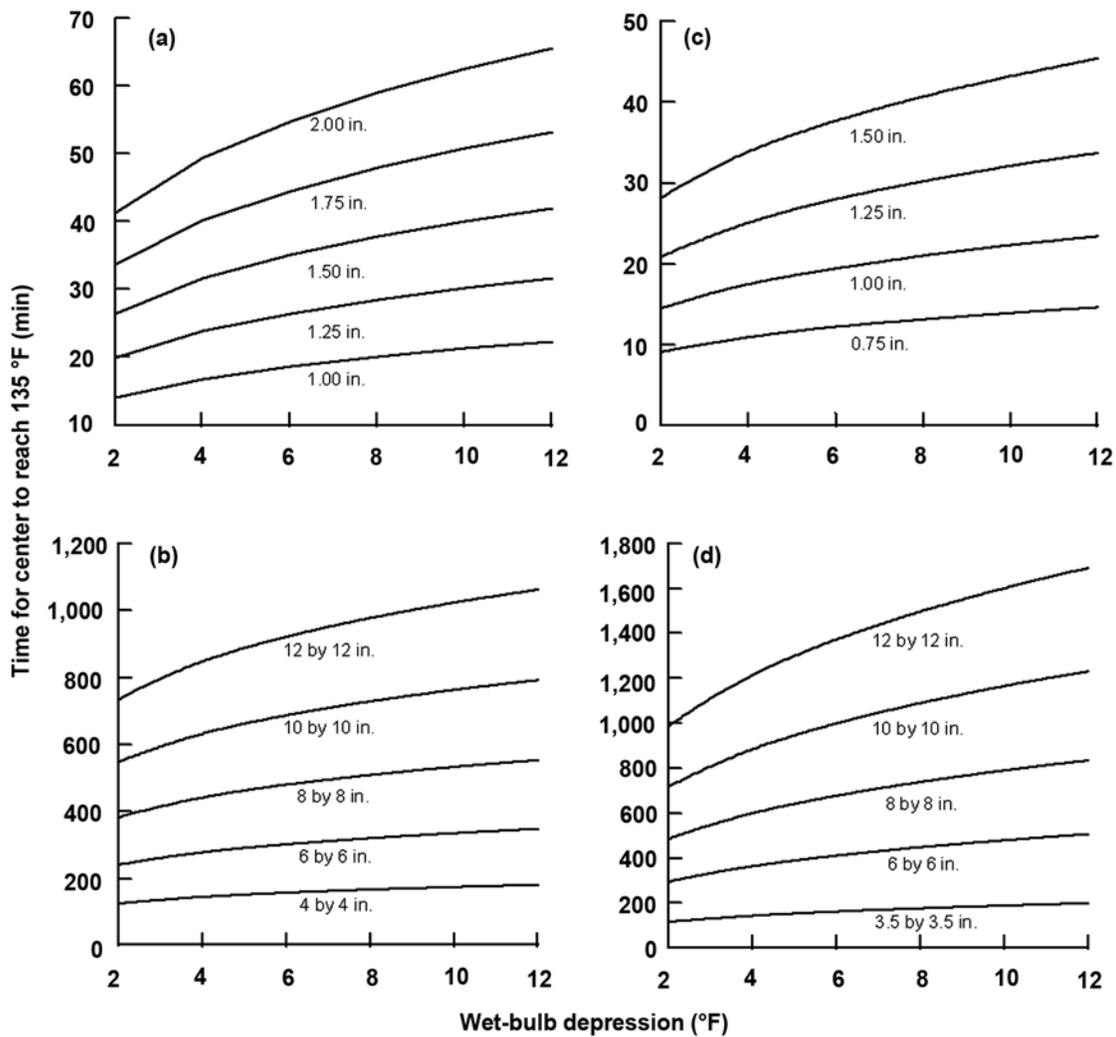


Figure 20-1. Dependence of heating time on wet-bulb depression for (a) 1- to 2-in.-thick ponderosa pine boards; (b) 4- to 12-in. ponderosa pine timbers; (c) 3/4- to 1-1/2-in.-thick Douglas-fir boards; and (d) 3-1/2- by 3-1/2-in. Douglas-fir timbers (initial temperature: 60 °F). ($^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$; 1 in. = 25.4 mm)

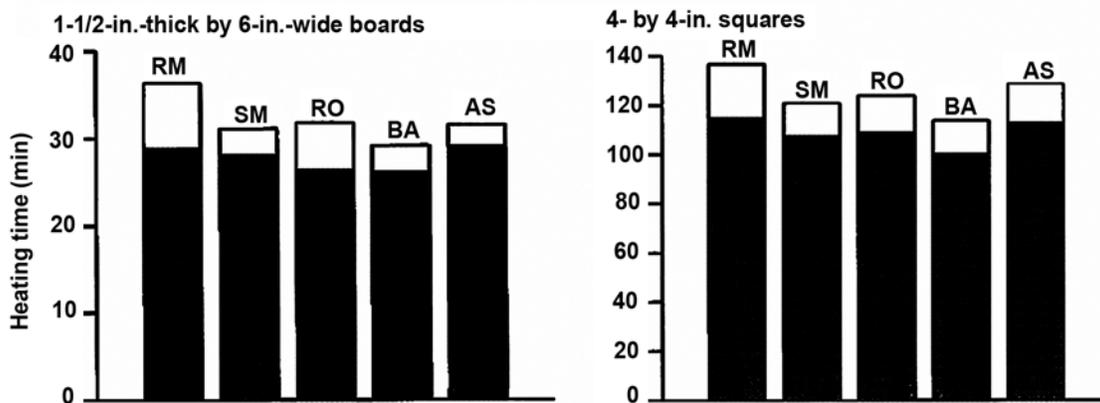


Figure 20-2. Effect of species on heating times of boards and squares. RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen. The solid rectangle represents 2 °F (1.1 °C) wet-bulb depression. The entire rectangle represents 10 °F (5.6 °C) wet-bulb depression.

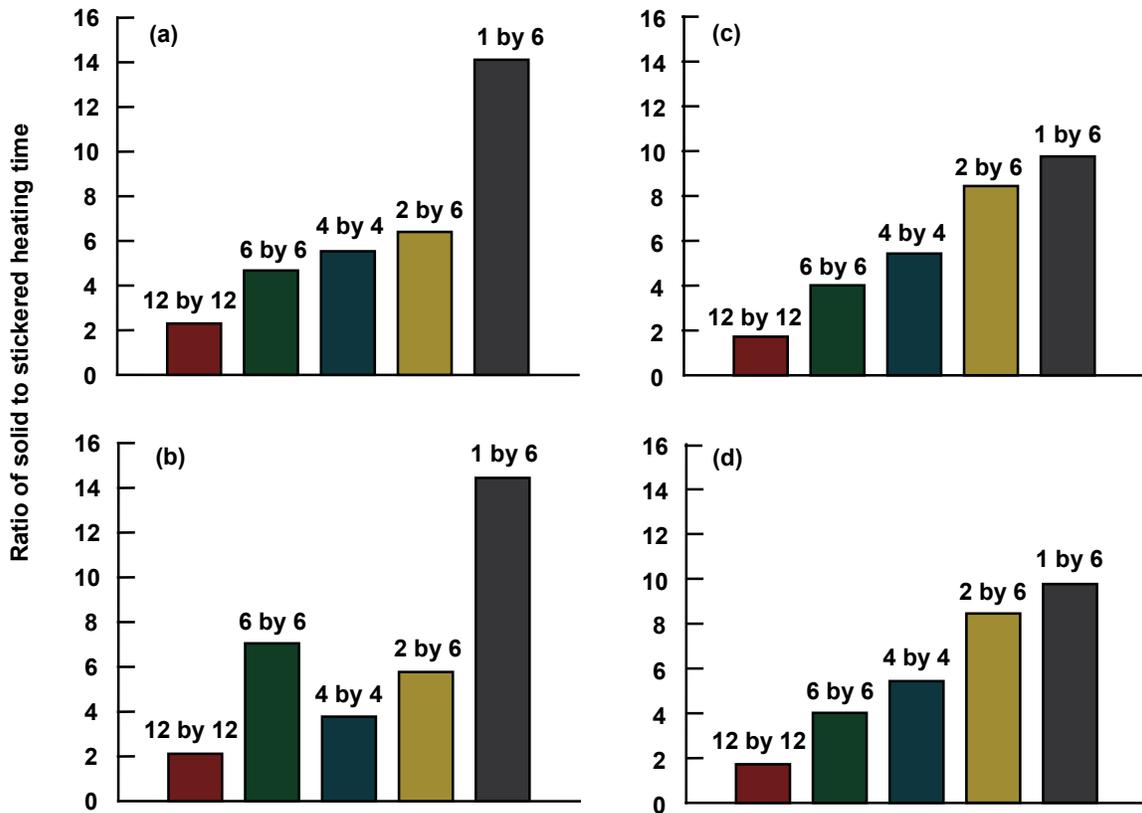


Figure 20–3. Ratio of heating times of solid-piled boards and timbers (4 by 3.2 ft) to stickered boards and timbers for (a) Douglas-fir, 1.5 °F/2.2 °F (0.8 °C/1.2 °C) wet-bulb depression; (b) Douglas-fir, 12.5 °F/13.8 °F (7.0 °C/7.7 °C) wet-bulb depression; (c) ponderosa pine, 2.5 °F/2.8 °F (1.4 °C/1.6 °C) wet-bulb depression; and (d) ponderosa pine, 12.0 °F/13.4 °F (6.7 °C/7.5 °C) wet-bulb depression.

transfer and, consequently, heating times. If a heat treatment facility receives solid-piled bundles of lumber or timbers, it may be desirable to heat-treat in the solid-piled configuration. However, a solid bundle of lumber or timbers requires much longer heating times than a comparable quantity of stickered lumber or timbers. Figure 20–3, for example, shows the ratio of heating times for equal quantities of lumber or timbers, one being heat treated as a solid bundle (4 by 3.2 ft) and the other treated after stickering. Note that the ratio ranges from about 2 for 12- by 12-in. timbers to more than 14 for 1- by 6-in. boards, which indicates that heat-treating stickered materials can result in substantial decreases in heating times. In addition, a higher degree of variation in heating times for solid-piled materials than for stickered materials results from how closely the individual pieces fit together in a stacking bundle (Simpson and others 2003). Gaps between individual pieces allow hot air to penetrate and thus warm the surface more than where adjacent pieces fit tightly together. In commercial practice, this high variability would cause complications in estimating heating times.

Heating Times for Wood in Various Forms

A series of heating experiments were conducted at the FPL (Simpson 2001, 2002; Simpson and others 2003, 2005). Tables 20–2 and 20–3 summarize experimental heating times for ponderosa pine and Douglas-fir boards and square timbers to a center temperature of 133 °F (56 °C) in a heating environment of 160 °F (71 °C) dry-bulb temperature and various wet-bulb depressions. Table 20–4 summarizes average heating times required to reach 133 °F (56 °C) for six sizes of five hardwood species (red maple, sugar maple, red oak, basswood, and aspen) at two wet-bulb depressions (0 and 10 °F (0 and 5.6 °C)). Note that heating times in these tables are for wood in green condition and that these data were obtained through laboratory experiments in a small-scale dry kiln (approximately 1,500 board foot (3.5 m³) capacity) under well-controlled heating conditions. Although the experimental results have not been calibrated to commercial operation, they have served as the bases for developing heat treatment schedules for industrial applications (ALSC 2009).

Table 20–2. Summary of experimental heating times to heat ponderosa pine boards and square timbers to a center temperature of 133 °F (56 °C) in a heating environment of nominal 160 °F (71 °C) dry-bulb temperature and various wet-bulb depressions

Wet-bulb depression (°F (°C))	Experimental heating times (min) ^a				
	1 by 6 ^b	2 by 6	4 by 4	6 by 6	12 by 12
Stickered					
2.5 (1.4)	17 (8.1)	43 (13.1)	153 (8.9)	299 (17.7)	1,006 (15.5)
6.2 (3.4)	16 (5.9)	53 (2.4)	180 (6.0)	271 (6.2)	980 (12.1)
12.0 (6.6)	23 (3.1)	67 (15.0)	207 (17.3)	420 (28.3)	1,428 (8.2)
26.8 (14.9)	188 (45.2)	137 (12.5)	256 (19.0)	568 (7.2)	1,680 (13.9)
47.5 (26.4)	427 (18.1)	361 (30.7)	817 (53.9)	953 (38.1)	2,551 (22.2)
Solid-piled^c					
2.8 (1.6)	166 (70.3)	361 (64.9)	831 (14.0)	1,201 (30.1)	1,736 (26.4)
13.4 (7.4)	201 (22.7)	391 (23.4)	710 (48.1)	1,617 (26.7)	2,889 (22.4)

^aValues in parentheses are coefficients of variation (%).

^bActual sizes are the same as nominal sizes.

^cSolid pile 4 ft wide and 3.2 ft high.

Table 20–3. Summary of experimental heating times to heat Douglas-fir boards and square timbers to a center temperature of 133 °F (56 °C) in a heating environment of nominal 160 °F (71 °C) dry-bulb temperature and various wet-bulb depressions

Wet-bulb depression (°F (°C))	Experimental heating times (min) ^a				
	1 by 6 ^b	2 by 6	4 by 4	6 by 6	12 by 12
Stickered					
2.2 (1.2)	7 (22.2 ^c)	21 (21.3)	78 (12.5)	209 (8.9)	840 (8.8)
6.3 (3.5)	8 (10.3)	25 (21.9)	91 (10.5)	202 (11.6)	914 (13.9)
12.5 (6.9)	10 (6.7)	34 (22.3)	138 (17.8)	262 (7.7)	1,153 (7.0)
27.1 (15.0)	216 (39.9)	157 (23.1)	255 (25.1)	715 (22.8)	1,679 (3.1)
44.2 (24.6)	233 (62.8)	223 (20.3)	362 (28.0)	849 (6.1)	2,005 (23.3)
Solid-piled^c					
1.5 (0.8)	103 (45.2)	137 (46.9)	432 (27.2)	977 (9.3)	1,931 (13.5)
13.8 (7.7)	143 (69.1)	195 (77.4)	521 (54.7)	1,847 (25.7)	1,847 (25.7)

^aValues in parentheses are coefficients of variation (%).

^bNominal sizes.

^cSolid pile 4 ft wide and 3.2 ft high.

Methods for Estimating Heating Times

Many combinations of wood configurations, heating temperatures, wet-bulb depressions, and initial wood temperatures are possible. No one experiment of practical scope would cover them all. Therefore, analytical methods are needed to estimate the heating times for combinations not directly measured experimentally.

MacLean Equations

MacLean (1930, 1932, 1941) developed equations for estimating heating times in steam and showed experimentally that they worked well. The equations are for two-dimensional heat flow (heating is from all four cross-sectional faces) and apply only to heating in a saturated steam environment.

Heat conduction is considered to be about 2.5 times faster in the longitudinal grain direction than across the grain. However, because the length of many typical timbers and rounds is much greater than the cross-sectional dimension, longitudinal conduction is ignored and the equations thus simplified.

Round Cross Section

The heat conduction equations for round cross sections are taken from MacLean (1930), further refined by Ingersoll and Zobel (1948). The temperature T at any point on radius r is given by

$$T = T_s + 2(T_0 - T_s) \sum_{n=1}^{\infty} \frac{J_0(z_n r/R)}{z_n J_1(z_n)} \exp(-\alpha z_n^2 / R^2) \quad (20-1)$$

Table 20-4. Summary of experimental heating times to 133 °F (56 °C) for six sizes of five hardwood species heated at a nominal dry-bulb temperature of 160 °F (71 °C) and two wet-bulb depressions^a

Wet-bulb depression (°F (°C))	Piece size (in.) ^c	Heating time (min) ^b				
		Red maple	Sugar maple	Red oak	Basswood	Aspen
0 (0)	1 by 6	14 (15)	13 (14)	14 (15)	12 (14)	13 (14)
	1-1/2 by 6	29 (31)	28 (30)	26 (28)	26 (28)	29 (32)
	2 by 6	50 (52)	48 (49)	49 (53)	46 (48)	50 (54)
	3 by 3	59 (64)	58 (61)	57 (60)	51 (58)	61 (64)
	4 by 4	115 (119)	107 (113)	109 (112)	100 (108)	113 (117)
	6 by 6	265 (283)	255 (277)	252 (259)	226 (243)	262 (278)
10 (5.6)	1 by 6	17 (18)	14 (15)	15 (16)	15 (17)	15 (16)
	1-1/2 by 6	36 (38)	31 (34)	32 (33)	29 (31)	32 (33)
	2 by 6	59 (62)	53 (56)	56 (59)	54 (58)	57 (62)
	3 by 3	85 (96)	63 (67)	66 (69)	63 (69)	69 (74)
	4 by 4	137 (143)	121 (127)	124 (129)	114 (120)	129 (133)
	6 by 6	294 (304)	284 (299)	284 (298)	262 (284)	285 (195)

^aHeating times were adjusted to a common initial temperature of 60 °F (16 °C) and the overall actual average heating temperature of 157 °F (69 °C).

^bValues in parentheses are 99% upper confidence bounds of heating times.

^cActual sizes.

where

T_s is surface temperature (which must be attained immediately),

T_0 initial temperature,

J_0 zero-order Bessel function,

J_1 first-order Bessel function,

z_n n th root of $J_0(z_n) = 0$,

r any point on radius of cross section,

R radius of cross section,

α thermal diffusivity (dimension²/time), and

t heating time.

$$z_2 = 5.520$$

$$z_3 = 8.654$$

$$z_4 = 11.792$$

$$z_5 = 14.931$$

and the first five values of $J_1(z_n)$ are

$$J_1(2.405) = 0.5191$$

$$J_1(5.520) = -0.3403$$

$$J_1(8.654) = 0.2714$$

$$J_1(11.792) = -0.2325$$

$$J_1(14.931) = 0.2065$$

To calculate the temperature at the center of the cross section, $r = 0$, Equation (20-1) becomes

$$T_c = T_s + 2(T_0 - T_s) \sum_{n=1}^{\infty} \frac{\exp(-\alpha t z_n^2 / R^2)}{z_n J_1(z_n)} \quad (20-2)$$

Equations (20-1) and (20-2) converge quickly, so only the first few terms are necessary. The first few terms of Equation (20-2) are

$$T_c = T_s + 2(T_0 - T_s) \left[\frac{\exp(-\alpha t z_1^2 / R^2)}{z_1 J_1(z_1)} + \frac{\exp(-\alpha t z_2^2 / R^2)}{z_2 J_1(z_2)} + \frac{\exp(-\alpha t z_3^2 / R^2)}{z_3 J_1(z_3)} + \dots \right] \quad (20-3)$$

From Watson (1958), the first five roots of $J_0(z_n) = 0$ are

$$z_1 = 2.405$$

Rectangular Cross Section

The equation for rectangular cross sections is taken from MacLean (1932) and is the solution to the differential equation of heat conduction in the two dimensions of a rectangular cross section. The temperature T at any point x and y is given by

$$T = T_s + (T_0 - T_s) (16/\pi^2) \times \{ \sin(\pi x/a) \sin(\pi y/b) \exp[-\pi^2 t (\alpha_x/a^2 + \alpha_y/b^2)] + (1/3) \sin(3\pi x/a) \sin(\pi y/b) \exp[-\pi^2 t (9\alpha_x/a^2 + \alpha_y/b^2)] + (1/3) \sin(\pi x/a) \sin(3\pi y/b) \exp[-\pi^2 t (\alpha_x/a^2 + 9\alpha_y/b^2)] + (1/5) \sin(5\pi x/a) \sin(\pi y/b) \exp[-\pi^2 t (25\alpha_x/a^2 + \alpha_y/b^2)] + (1/5) \sin(\pi x/a) \sin(5\pi y/b) \exp[-\pi^2 t (\alpha_x/a^2 + 25\alpha_y/b^2)] + (1/7) \sin(7\pi x/a) \sin(\pi y/b) \exp[-\pi^2 t (49\alpha_x/a^2 + \alpha_y/b^2)] + (1/7) \sin(\pi x/a) \sin(7\pi y/b) \exp[-\pi^2 t (\alpha_x/a^2 + 49\alpha_y/b^2)] + \dots \} \quad (20-4)$$

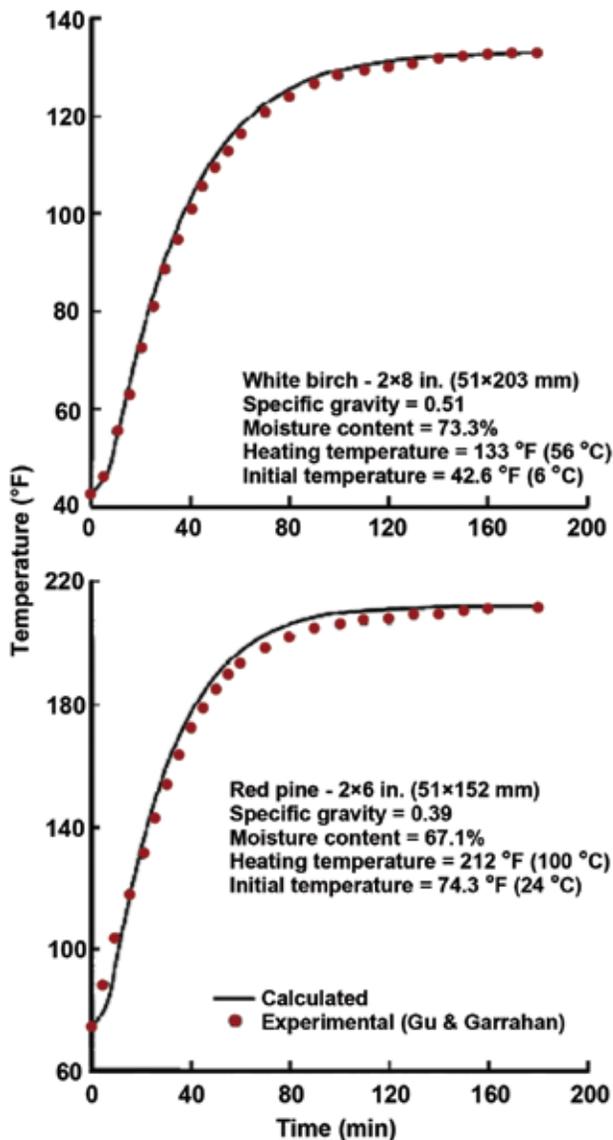


Figure 20–4. Comparison of experimental heating times of Gu and Garrahan (1984) with times calculated using MacLean equations for white birch and red pine.

where

- T_s is surface temperature (which must be attained immediately),
- T_0 initial temperature,
- a one cross-sectional dimension,
- b other cross-sectional dimension,
- α_x thermal diffusivity in the x direction (dimension²/time),
- α_y thermal diffusivity in the y direction, and
- t heating time.

Equation (20–4) converges quickly, so only the first few terms are necessary. Because thermal conductivity and thermal diffusivity do not differ much in the radial and tangen-

tial directions of wood, in Equation (20–4) we can set $\alpha_x = \alpha_y$ (MacLean 1941). Equation (20–4) can easily be converted to calculate the temperature at the center of the cross section by setting $x = a/2$ and $y = b/2$.

Gu and Garrahan (1984) experimentally confirmed that MacLean’s equations were valid for estimating heating times. Figure 20–4 shows close agreement of experimental heating times of Gu and Garrahan (1984) with times calculated using MacLean’s heat conduction equation. Simpson (2001) further confirmed the validity of MacLean’s equations and used them to develop a series of tables of heating times (to the center) of round and rectangular sections. Variables in the tables were wood specific gravity, moisture content, initial temperature, heating temperature, and target center temperature.

Specific gravity and moisture content values were chosen to represent several species that might be subjected to heat sterilization. Target center temperatures other than 133 °F (56 °C) were included because future heat sterilization requirements are not known and might include higher temperatures. As an example, Table 20–5 tabulates the estimated heating times to heat lumber of selected sizes to 133 °F (56 °C) for wood specific gravity of 0.35 (Cheung 2008). Tables for other combinations of variables are presented in Simpson (2001).

Heat experiments at the Forest Products Laboratory indicated that MacLean’s equations are able to estimate heating times in steam to a degree of accuracy that is within about 5% to 15% of measured heating times. The equations offer a powerful way to include the effects of all the variables that affect heating time—specific gravity, moisture content, initial temperature, heating temperature, target center temperature, and cross-sectional dimensions.

MacLean’s approach requires full access of all four faces to the heating medium. This might not be achieved in the close edge-to-edge contact of the stickered configuration or the solid-piled configuration. In practice, his approach will probably require some small level of gapping between adjacent boards or timbers.

Multiple Regression Models

MacLean’s equations apply only to heating in a saturated steam environment. When the heating medium is air that is not saturated with steam, there is a wet-bulb depression (the relative humidity is less than 100%), and drying occurs as water evaporates from the wood surface. The consequence is that heating time increases and MacLean’s equations no longer apply. An alternative method to estimate the heating time when simultaneous drying occurs is to use a strictly empirical approach.

The following multiple regression model proved to have a good ability to predict heating time from size, wet-bulb depression, and initial wood temperature as long as the

Table 20–5. Estimated heating times to heat lumber to 133 °F (56 °C) for wood with a specific gravity of 0.35

Thickness (t) and width (w) (in.)	Heat temp. (°F)	Estimated heating time (min) from four initial wood temperatures and four MC levels															
		30 °F				50 °F				70 °F				90 °F			
		25%	70%	100%	130%	25%	70%	100%	130%	25%	70%	100%	130%	25%	70%	100%	130%
t = 1.0 w = 4.0	140	21	21	20	19	19	19	18	17	17	17	16	15	15	14	13	12
	150	15	15	14	13	14	13	13	12	12	11	11	10	10	9	9	8
	160	13	12	12	11	11	11	10	9	10	9	9	8	8	7	7	6
	170	11	10	10	9	10	9	8	8	8	7	7	7	6	6	6	5
	180	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4
	190	9	8	8	7	7	7	7	6	6	6	5	5	5	4	4	4
	200	8	7	7	6	7	6	6	5	6	5	5	4	4	4	4	3
210	7	7	6	6	6	6	5	5	5	5	4	4	4	4	3	3	
t = 1.0 w = 6.0	140	21	21	20	19	19	19	18	17	17	17	16	15	15	14	13	12
	150	15	15	14	13	14	13	13	12	12	11	11	10	10	9	9	8
	160	13	12	12	11	11	11	10	9	10	9	9	8	8	7	7	6
	170	11	10	10	9	10	9	8	8	8	7	7	7	6	6	6	5
	180	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4
	190	9	8	8	7	7	7	7	6	6	6	5	5	5	4	4	4
	200	8	7	7	6	7	6	6	5	6	5	5	4	4	4	4	3
210	7	7	6	6	6	6	5	5	5	5	4	4	4	4	3	3	
t = 2.0 w = 4.0	140	75	74	70	66	69	67	64	59	62	59	56	53	54	50	48	45
	150	56	55	52	49	51	49	46	43	45	42	40	38	38	35	33	31
	160	46	45	43	40	42	40	38	35	37	34	33	30	30	28	26	25
	170	41	39	37	35	36	34	33	30	32	29	28	26	26	24	22	21
	180	36	35	33	31	32	30	29	27	28	26	24	23	23	21	20	18
	190	33	31	30	28	29	27	26	24	25	23	22	20	21	18	17	16
	200	30	28	27	25	27	25	24	22	23	21	20	19	19	17	16	15
210	28	26	25	23	25	23	22	20	22	19	18	17	18	15	15	14	
t = 2.0 w = 8.0	140	86	85	81	76	79	77	73	68	71	67	64	60	61	57	54	50
	150	63	62	59	55	57	55	52	49	50	47	45	42	41	38	36	34
	160	52	50	48	45	46	44	42	39	40	37	35	33	32	30	28	26
	170	44	43	41	38	39	37	35	33	34	31	30	28	27	25	24	22
	180	39	37	36	33	35	32	31	29	30	27	26	24	24	21	20	19
	190	35	33	32	30	31	29	27	26	27	24	23	21	21	19	18	17
	200	32	30	29	27	29	26	25	23	24	22	21	19	19	17	16	15
210	30	28	26	24	26	24	23	21	22	20	19	18	18	16	15	14	
t = 4.0 w = 4.0	140	188	186	177	166	173	168	160	150	157	149	142	132	136	127	120	112
	150	141	138	131	123	128	123	117	110	114	107	102	95	96	89	85	79
	160	118	114	109	102	107	102	97	90	94	88	83	78	79	72	69	64
	170	103	99	94	88	93	88	83	78	82	76	72	67	68	62	59	55
	180	93	88	84	78	84	78	74	69	73	67	64	59	61	55	52	49
	190	85	80	76	71	76	71	67	63	67	61	58	54	56	50	47	44
	200	79	74	70	65	71	65	62	57	62	56	53	49	52	46	43	40
210	74	68	65	60	66	60	57	53	58	52	49	46	48	43	40	37	
t = 4.0 w = 12.0	140	335	332	316	296	309	300	286	267	278	265	252	235	239	224	213	198
	150	248	243	232	217	225	216	206	192	198	187	178	166	165	153	145	135
	160	205	199	190	177	184	175	167	156	160	150	142	133	131	120	114	106
	170	177	171	162	152	158	149	142	133	136	126	120	112	111	101	95	89
	180	158	150	143	133	140	131	124	116	120	110	105	98	97	87	83	77
	190	143	135	128	119	126	117	111	104	108	98	93	87	87	78	74	69
	200	131	122	116	108	115	106	101	94	98	89	84	78	79	70	67	62
210	121	112	106	99	107	97	92	86	91	81	77	72	73	64	61	57	

Table 20–6. Coefficients for multiple regression models (Eq. (20–5)) for estimating time required to heat stickered ponderosa pine and Douglas-fir boards and timbers to a 133 °F (56 °C) center temperature in a 160 °F (71 °C) heating medium^a

Application	Coefficients				
	$\ln a$	b	c	d	R^2
Ponderosa pine, 1- and 2-in. boards, WBD < 12 °F	5.04	1.55	0.257	0.627	0.978
Ponderosa pine, 4-, 6-, and 12-in. timbers, WBD < 12 °F	4.59	1.61	0.205	-0.521	0.967
Douglas-fir, 1- and 2-in. boards, WBD < 12 °F	8.04	1.63	0.265	-1.35	0.925
Douglas-fir, 4-, 6-, and 12-in. timbers, WBD < 12 °F	15.03	0.455	0.336	-2.70	0.984

^a $T_c = (T_F - 32)/1.8$; °C = °F/1.8; 1 in. = 25.4 mm.

wet-bulb temperature in the heating chamber is greater than the target center temperature:

$$\ln T_{133} = \ln a + b (\ln t)^n + c \ln (\text{WBD}) + d \ln (T_i) \quad (20-5)$$

where

T_{133}	is	time for the center to reach 133 °F (56 °C) (min),
t		thickness of boards or cross-sectional dimension of timbers (in.),
WBD		wet-bulb depression (°F),
T_i		initial wood temperature (°F),
a, b, c, d		regression coefficients,
n		either 1 or 2.

Simpson and others (2003) developed a series of regression models to estimate heating times for ponderosa pine and Douglas-fir boards and timbers. The regression coefficients (a , b , c , and d) and coefficients of determination (R^2) are shown in Table 20–6. The models worked well when the wet-bulb depression was less than or equal to about 12 °F (6.7 °C) and the boards or timbers were stickered. The heating time estimates for a series of sizes, wet-bulb depressions, and initial temperature generated using these equations are presented in Tables 20–7 to 20–10. The estimates for ponderosa pine cover initial temperatures from 40 to 80 °F (4.4 to 26.7 °C) (in 10 °F (5.6 °C) increments). The estimates for Douglas-fir cover only initial temperature of 60 to 80 °F (15.6 to 26.7 °C) because of the seasonal timing of the experiments.

The estimated heating times in Tables 20–7 to 20–10 are average times and give a reasonable general estimate of the time required to heat the center of wood to 133 °F (56 °C). In any group of lumber and timbers, the average time does not ensure that all pieces will achieve the target temperature because some will require more than the average time. Therefore, the upper statistical confidence levels for the heating times need to be considered. Equations for calculating the upper confidence levels of heating times for ponderosa pine and Douglas-fir boards and timbers are provided

in Simpson and others (2003). In Tables 20–7 to 20–10, the heating time values of 99% upper confidence bounds are presented in parentheses.

American Lumber Standard Committee (ALSC) Enforcement Regulations

Heat treatment of wood is typically accomplished in a heat chamber. Heat chamber is defined as any enclosed equipment used to heat-treat lumber or wood packaging material and includes kiln, heat boxes, or any other appropriate apparatus. Depending on the treating schedules used, products from heat treatment processes are of two types:

1. Heat treated (HT)—lumber or used, previously assembled or repaired wood packaging that has been placed in a closed chamber with artificial heat added until the lumber or packaging achieves a minimum core temperature of 133 °F (56 °C) for a minimum of 30 min.
2. Kiln-dried heat-treated (KD HT)—lumber or used, previously assembled or repaired wood packaging that has been placed in a closed chamber with artificial heat added until the lumber or packaging achieves a minimum core temperature of 133 °F (56 °C) for a minimum of 30 min and that is dried to a maximum moisture content of 19% or less.

ALSC enforcement regulations require that a heat treatment facility should be inspected and verified by an accredited third-party agency for initial qualification. Agencies will verify the accuracy of temperature-measuring and recording devices in the heating chamber and require that thermocouples be located to accurately measure the temperature achieved in the heat chamber and that an appropriate number of thermocouples are utilized given the chamber configuration. A thermocouple verification study is needed for any kiln schedule operating in a heat chamber using (1) both dry and wet heat (steam) with wet-bulb temperature of less than 140 °F (60 °C) or (2) only dry heat of less than 160 °F (71 °C). In such a verification study, an appropriate number

Table 20–7. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for ponderosa pine boards estimated by multiple regression models^a

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min) ^b				
		1.00 in. thick	1.25 in. thick	1.50 in. thick	1.75 in. thick	2.00 in. thick
2	40	18 (39)	26 (53)	34 (67)	43 (82)	53 (98)
4	40	22 (45)	31 (60)	41 (76)	52 (93)	64 (112)
6	40	24 (48)	34 (65)	45 (83)	58 (101)	71 (121)
8	40	26 (51)	37 (69)	49 (87)	62 (107)	76 (128)
10	40	28 (54)	39 (72)	52 (92)	66 (112)	81 (134)
12	40	29 (56)	41 (75)	54 (95)	69 (117)	85 (139)
2	50	16 (28)	22 (37)	30 (47)	38 (58)	46 (70)
4	50	19 (31)	27 (42)	36 (54)	45 (66)	55 (80)
6	50	21 (34)	30 (46)	39 (59)	50 (72)	62 (87)
8	50	23 (36)	32 (49)	42 (62)	54 (77)	66 (92)
10	50	24 (38)	34 (51)	45 (65)	57 (80)	70 (97)
12	50	25 (39)	36 (53)	47 (68)	60 (84)	74 (101)
2	60	14 (21)	20 (28)	27 (36)	34 (45)	41 (55)
4	60	17 (24)	24 (33)	32 (42)	40 (52)	49 (63)
6	60	19 (26)	27 (35)	35 (46)	45 (57)	55 (70)
8	60	20 (28)	29 (38)	38 (49)	48 (61)	59 (75)
10	60	21 (29)	30 (40)	40 (52)	51 (65)	63 (79)
12	60	22 (30)	32 (42)	42 (54)	53 (68)	66 (83)
2	70	13 (17)	18 (24)	24 (31)	31 (39)	38 (48)
4	70	15 (20)	22 (27)	29 (36)	37 (46)	45 (57)
6	70	17 (22)	24 (30)	32 (40)	41 (51)	50 (64)
8	70	18 (23)	26 (33)	34 (43)	44 (56)	54 (70)
10	70	19 (25)	27 (35)	36 (46)	46 (59)	57 (74)
12	70	20 (26)	29 (36)	38 (45)	48 (63)	60 (78)
2	80	12 (15)	17 (21)	22 (29)	28 (37)	35 (46)
4	80	14 (18)	20 (26)	26 (35)	34 (45)	41 (56)
6	80	16 (20)	22 (29)	29 (39)	37 (51)	46 (64)
8	80	17 (22)	24 (31)	32 (42)	40 (55)	49 (70)
10	80	18 (23)	25 (33)	33 (45)	43 (59)	52 (75)
12	80	19 (24)	26 (35)	35 (48)	45 (63)	55 (79)

^a $T_c = (T_F - 32)/1.8$; °C = °F/1.8; 1 in. = 25.4 mm.

^bValues in parentheses are 99% upper confidence bounds of heating times.

of thermocouples are used to accurately measure the temperature conditions of the chamber and the wood to ensure that time and temperature requirements for heat treating are met. Any equipment variance of more than ±5 °F (±2.8 °C) requires recalibration or replacement.

Heat treatment facilities are also required to monitor temperatures throughout the heat treatment cycle by any of the following options:

1. Wet- and dry-bulb temperature
2. Dry-bulb only—unless the specific schedule has been verified, required heating times shall be equal to or greater than the time specified for the applicable schedule assuming the maximum wet-bulb depression as provided in either of the following:
 - a. FPL–RP–607, *Heat sterilization time of ponderosa pine and Douglas-fir boards and square timbers* (Simpson and others 2003); or

- b. FPL–RP–604, *Effect of wet-bulb depression on heat sterilization time of slash pine lumber* (Simpson 2002); or
 - c. CFIA PI–07, *The technical heat treatment guidelines and operating conditions manual*, Option C (CFIA 2006).
3. Direct measurement of wood core temperature of the thickest piece(s) by use of thermocouple(s) properly sealed with non-conductive material

Heat treatment facilities are currently required to annually calibrate the temperature-monitoring and recording equipment for each facility heat-treating chamber and requalify a heat-treating chamber any time there is a major change in equipment or remodeling of the chamber. Except in the case of wood core temperature of the thickest piece(s) being directly measured by using thermocouples, when wood moisture content is not determined at the beginning of the heat treatment cycle, facilities are required to select and use

Table 20–8. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for ponderosa pine square timbers estimated by multiple regression models^a

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min) ^b				
		4 by 4	6 by 6	8 by 8	10 by 10	12 by 12
2	40	155 (225)	297 (429)	473 (682)	677 (980)	90 (1,321)
4	40	178 (259)	343 (492)	545 (782)	780 (1,123)	1,04 (1,512)
6	40	194 (282)	372 (535)	592 (850)	848 (1,220)	1,13 (1,643)
8	40	206 (299)	395 (569)	628 (903)	899 (1,296)	1,20 (1,745)
10	40	215 (314)	413 (597)	657 (947)	941 (1,359)	1,26 (1,830)
12	40	223 (327)	429 (621)	682 (986)	977 (1,414)	1,31 (1,904)
2	50	138 (200)	265 (382)	421 (609)	603 (878)	80 (1,185)
4	50	159 (229)	305 (437)	485 (697)	695 (1,003)	93 (1,354)
6	50	173 (249)	332 (475)	527 (756)	755 (1,088)	1,01 (1,468)
8	50	183 (264)	352 (504)	559 (802)	801 (1,155)	1,07 (1,558)
10	50	192 (277)	368 (529)	585 (841)	838 (1,210)	1,12 (1,633)
12	50	199 (288)	382 (550)	607 (875)	870 (1,258)	1,16 (1,697)
2	60	125 (182)	241 (350)	383 (559)	548 (807)	73 (1,091)
4	60	144 (208)	278 (400)	441 (638)	632 (921)	84 (1,245)
6	60	157 (226)	302 (433)	479 (692)	687 (998)	92 (1,349)
8	60	166 (240)	320 (460)	508 (734)	728 (1,058)	97 (1,430)
10	60	174 (251)	335 (482)	532 (769)	762 (1,108)	1,02 (1,497)
12	60	181 (261)	348 (501)	552 (799)	791 (1,151)	1,06 (1,555)
2	70	116 (169)	222 (326)	353 (523)	506 (755)	67 (1,022)
4	70	133 (193)	256 (372)	407 (596)	583 (860)	78 (1,164)
6	70	145 (210)	278 (403)	442 (645)	634 (932)	85 (1,260)
8	70	154 (222)	295 (427)	469 (684)	672 (987)	90 (1,335)
10	70	161 (233)	309 (448)	491 (716)	703 (1,033)	94 (1,398)
12	70	167 (242)	321 (465)	510 (743)	730 (1,073)	97 (1,451)
2	80	108 (160)	207 (308)	330 (494)	472 (715)	63 (968)
4	80	124 (182)	239 (351)	380 (563)	544 (814)	73 (1,102)
6	80	135 (197)	260 (380)	413 (609)	591 (880)	79 (1,192)
8	80	143 (209)	275 (403)	438 (645)	627 (932)	84 (1,262)
10	80	150 (219)	288 (421)	458 (675)	656 (975)	88 (1,321)
12	80	156 (227)	299 (438)	476 (701)	681 (1,013)	91 (1,371)

^a $T_c = (T_F - 32)/1.8$; $^{\circ}C = ^{\circ}F/1.8$; 1 in. = 25.4 mm.

^bValues in parentheses are 99% upper confidence bounds of heating times.

appropriate time–temperature schedules assuming the lowest initial wood moisture content from one of the following publications:

- FPL–GTR–130, *Heating times for round and rectangular cross sections of wood in steam* (Simpson 2001);
- FPL–RP–607, *Heat sterilization time of ponderosa pine and Douglas-fir boards and square timbers* (Simpson and others 2003);
- FPL–RP–604, *Effect of wet-bulb depression on heat sterilization time of slash pine lumber* (Simpson 2002); or
- CFIA PI–07, *The technical heat treatment guidelines and operating conditions manual, Option C* (CFIA 2006).

Quality Mark

ISPM 15 requires that treated packaging must be marked with an official stamp that includes an International Plant

Protection Convention (IPPC) symbol, an International Standards Organization (ISO) two-letter country code, and abbreviation of the type of treatment used (heat treatment is indicated by the mark HT), and a unique number assigned by the country’s national plant protection organization to the producer of the wood packaging material, who is responsible for ensuring that appropriate wood is used and properly marked (Figure 20–5). If wood packaging materials arrive in a member country without this quality mark, officials at the port of arrival have the right to refuse entry or require treatment (such as fumigation) at the port—a costly situation. Recycled, remanufactured, or repaired wood packing material should be recertified and remarked. All components of such material are required to be properly treated.

Other Considerations

Heating capacity—It is critical in heat sterilization that the heating and humidification system be designed to meet the production schedule. Typically, the heating capacity of a

Table 20–9. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for Douglas-fir boards estimated by multiple regression models^a

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min) ^b			
		0.75 in. thick	1.00 in. thick	1.25 in. thick	1.50 in. thick
2	60	9 (25)	14 (37)	21 (53)	28 (70)
4	60	11 (29)	17 (44)	25 (62)	34 (82)
6	60	12 (32)	19 (49)	28 (68)	38 (91)
8	60	13 (34)	21 (52)	30 (74)	41 (98)
10	60	14 (36)	22 (55)	32 (78)	43 (104)
12	60	15 (38)	23 (58)	34 (82)	45 (109)
2	70	7 (15)	12 (22)	17 (32)	23 (42)
4	70	9 (17)	14 (26)	20 (37)	27 (49)
6	70	10 (19)	16 (29)	23 (41)	31 (55)
8	70	11 (20)	17 (31)	24 (44)	33 (59)
10	70	11 (22)	18 (33)	26 (47)	35 (63)
12	70	12 (23)	19 (35)	27 (49)	37 (66)
2	80	6 (10)	10 (16)	14 (23)	19 (31)
4	80	7 (12)	12 (19)	17 (27)	23 (37)
6	80	8 (13)	13 (21)	19 (30)	25 (41)
8	80	9 (15)	14 (23)	20 (32)	28 (44)
10	80	9 (15)	15 (24)	22 (35)	29 (47)
12	80	10 (16)	16 (25)	23 (36)	31 (49)

^a $T_c = (T_F - 32)/1.8$; °C = °F/1.8; 1 in. = 25.4 mm.

^bValues in parentheses are 99% upper confidence bounds of heating times.

Table 20–10. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for Douglas-fir square timbers estimated by multiple regression models^a

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min) ^b				
		4 by 4	6 by 6	8 by 8	10 by 10	12 by 12
2	60	159 (229)	285 (406)	473 (667)	738 (1,034)	1,098 (1,534)
4	60	200 (298)	360 (526)	597 (862)	932 (1,334)	1,386 (1,974)
6	60	229 (349)	412 (615)	684 (1,007)	1,068 (1,556)	1,588 (2,299)
8	60	253 (391)	454 (689)	754 (1,126)	1,176 (1,739)	1,749 (2,567)
10	60	272 (427)	489 (752)	812 (1,229)	1,267 (1,897)	1,885 (2,799)
12	60	289 (459)	520 (809)	863 (1,321)	1,347 (2,038)	2,004 (3,006)
2	70	105 (143)	188 (256)	312 (426)	487 (669)	724 (1,003)
4	70	132 (181)	237 (323)	394 (535)	614 (836)	914 (1,251)
6	70	151 (209)	272 (372)	451 (615)	704 (959)	1,047 (1,432)
8	70	167 (232)	299 (412)	497 (680)	775 (1,061)	1,153 (1,580)
10	70	179 (252)	323 (447)	535 (737)	835 (1,148)	1,243 (1,709)
12	70	191 (270)	343 (478)	569 (788)	888 (1,226)	1,321 (1,824)
2	80	73 (103)	131 (188)	217 (315)	339 (499)	505 (753)
4	80	92 (127)	165 (230)	274 (386)	428 (609)	637 (918)
6	80	105 (144)	189 (261)	314 (436)	491 (688)	730 (1,036)
8	80	116 (159)	209 (286)	346 (477)	540 (752)	804 (1,130)
10	80	125 (171)	225 (307)	373 (513)	582 (807)	866 (1,212)
12	80	133 (182)	239 (326)	397 (544)	619 (855)	921 (1,283)

^a $T_c = (T_F - 32)/1.8$; °C = °F/1.8; 1 in. = 25.4 mm.

^bValues in parentheses are 99% upper confidence bounds of heating times.

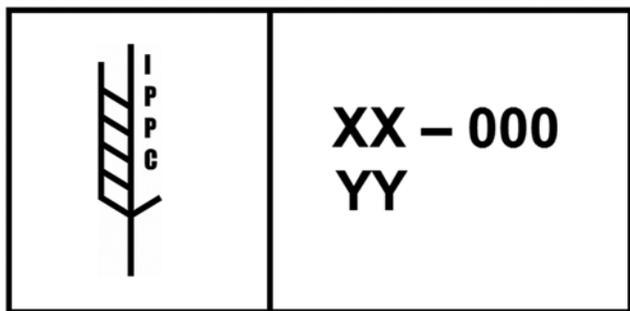


Figure 20–5. ISPM 15 requires the use of a quality mark on wood packaging materials to certify that proper treatment has occurred.

hardwood kiln ranges from 0.5 to 1.5 boiler horsepower per thousand board feet of lumber (7,100 to 21,300 Btu/h per cubic meter of lumber). To get the rapid heating needed, the boiler horsepower needs to be sized from 6.0 to 12.5 boiler horsepower per thousand board feet (85,100 to 177,300 Btu/h per cubic meter), depending on the lumber used and starting temperature (Denig and Bond 2003).

Structure damage—The environment used for heat sterilization of wood can be extremely corrosive and damaging to some structures. In addition to using the proper materials, a floor drain system should be used, especially when using the high-humidity schedules.

Mold prevention—Heat sterilization kills only mold, fungus, and insects that are present when the material is sterilized. In certain cases, mold and fungus have rapidly infested heat-sterilized lumber that was not dry (Denig and Bond 2003). It is critical for the pallet operator and user to keep their production facility free of waste wood, minimize pallet inventory of heat-treated pallets, and ensure some air movement around green pallets that have been heat-treated.

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Adherend. A body that is held to another body by an adhesive.

Adhesion. The state in which two surfaces are held together by interfacial forces, which may consist of valence forces or interlocking action or both.

Adhesive. A substance capable of holding materials together by surface attachment. It is a general term and includes cements, mucilage, and paste, as well as glue.

Assembly Adhesive—An adhesive that can be used for bonding parts together, such as in the manufacture of a boat, airplane, furniture, and the like.

Cold-Setting Adhesive—An adhesive that sets at temperatures below 20 °C (68 °F).

Construction Adhesive—Any adhesive used to assemble primary building materials into components during building construction—most commonly applied to elastomer-based mastic-type adhesives.

Contact Adhesive—An adhesive that is apparently dry to the touch and that will adhere to itself instantaneously upon contact; also called contact bond adhesive or dry bond adhesive.

Gap-Filling Adhesive—An adhesive capable of forming and maintaining a bond between surfaces that are not close fitting.

Hot-Melt Adhesive—An adhesive that is applied in a molten state and forms a bond on cooling to a solid state.

Hot-Setting Adhesive—An adhesive that requires a temperature at or above 100 °C (212 °F) to set it.

Room-Temperature-Curing Adhesive—An adhesive that sets in the temperature range of 20 to 30 °C (68 to 86 °F), in accordance with the limits for Standard Room Temperature specified in the Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing (ASTM D 618).

Solvent Adhesive—An adhesive having a volatile organic liquid as a vehicle. (This term excludes water-based adhesives.)

Structural Adhesive—A bonding agent used for transferring required loads between adherends exposed to service environments typical for the structure involved.

Air-Dried. (See **Seasoning.**)

Allowable Property. The value of a property normally published for design use. Allowable properties are identified with grade descriptions and standards, reflect the orthotropic structure of wood, and anticipate certain end uses.

Allowable Stress. (See **Allowable Property.**)

American Lumber Standard. The American Softwood Lumber Standard, Voluntary Product Standard PS-20 (National Institute of Standards and Technology), establishes standard sizes and requirements for the development and coordination of lumber grades of various species, the assignment of design values when called for, and the preparation of grading rules applicable to each species. It provides for implementation of the standard through an accreditation and certification program to assure uniform industry-wide marking and inspection. A purchaser must, however, make use of grading association rules because the basic standards are not in themselves commercial rules.

Anisotropic. Exhibiting different properties when measured along different axes. In general, fibrous materials such as wood are anisotropic.

Assembly Joint. (See **Joint.**)

Assembly Time. (See **Time, Assembly.**)

Balanced Construction. A construction such that the forces induced by uniformly distributed changes in moisture content will not cause warping. Symmetrical construction of plywood in which the grain direction of each ply is perpendicular to that of adjacent plies is balanced construction.

Bark Pocket. An opening between annual growth rings that contains bark. Bark pockets appear as dark streaks on radial surfaces and as rounded areas on tangential surfaces.

Bastard Sawn. Lumber (primarily hardwoods) in which the annual rings make angles of 30° to 60° with the surface of the piece.

Beam. A structural member supporting a load applied transversely to it.

Bending, Steam. The process of forming curved wood members by steaming or boiling the wood and bending it to a form.

Bent Wood. (See **Bending, Steam.**)

Bird Peck. A small hole or patch of distorted grain resulting from birds pecking through the growing cells in the tree. The shape of bird peck usually resembles a carpet tack with the point towards the bark; bird peck is usually accompanied by discoloration extending for considerable distance along the grain and to a much lesser extent across the grain.

Birdseye. Small localized areas in wood with the fibers indented and otherwise contorted to form few to many small circular or elliptical figures remotely resembling birds' eyes on the tangential surface. Sometimes found in sugar maple and used for decorative purposes; rare in other hardwood species.

Blister. An elevation of the surface of an adherend, somewhat resembling in shape a blister on human skin; its bound-

aries may be indefinitely outlined, and it may have burst and become flattened. (A blister may be caused by insufficient adhesive; inadequate curing time, temperature, or pressure; or trapped air, water, or solvent vapor.)

Bloom. Crystals formed on the surface of treated wood by exudation and evaporation of the solvent in preservative solutions.

Blow. In plywood and particleboard especially, the development of steam pockets during hot pressing of the panel, resulting in an internal separation or rupture when pressure is released, sometimes with an audible report.

Blue Stain. (See **Stain.**)

Board. (See **Lumber.**)

Board Foot. A unit of measurement of lumber represented by a board 12 in. long, 12 in. wide, and 1 in. thick or its cubic equivalent. In practice, the board foot calculation for lumber 1 in. or more in thickness is based on its nominal thickness and width and the actual length. Lumber with a nominal thickness of less than 1 in. is calculated as 1 in.

Bole. The main stem of a tree of substantial diameter—roughly, capable of yielding sawtimber, veneer logs, or large poles. Seedlings, saplings, and small-diameter trees have stems, not boles.

Bolt. (1) A short section of a tree trunk. (2) In veneer production, a short log of a length suitable for peeling in a lathe.

Bond. (1) The union of materials by adhesives. (2) To unite materials by means of an adhesive.

Bondability. Term indicating ease or difficulty in bonding a material with adhesive.

Bond Failure. Rupture of adhesive bond.

Bondline. The layer of adhesive that attaches two adherends.

Bondline Slip. Movement within and parallel to the bondline during shear.

Bond Strength. The unit load applied in tension, compression, flexure, peel impact, cleavage, or shear required to break an adhesive assembly, with failure occurring in or near the plane of the bond.

Bow. The distortion of lumber in which there is a deviation, in a direction perpendicular to the flat face, from a straight line from end-to-end of the piece.

Box Beam. A built-up beam with solid wood flanges and plywood or wood-based panel product webs.

Boxed Heart. The term used when the pith falls entirely within the four faces of a piece of wood anywhere in its length. Also called boxed pith.

Brashness. A condition that causes some pieces of wood to be relatively low in shock resistance for the species and, when broken in bending, to fail abruptly without splintering at comparatively small deflections.

Breaking Radius. The limiting radius of curvature to which wood or plywood can be bent without breaking.

Bright. Free from discoloration.

Broad-Leaved Trees. (See **Hardwoods.**)

Brown Rot. (See **Decay.**)

Brown Stain. (See **Stain.**)

Built-Up Timbers. An assembly made by joining layers of lumber together with mechanical fastenings so that the grain of all laminations is essentially parallel.

Burl. (1) A hard, woody outgrowth on a tree, more or less rounded in form, usually resulting from the entwined growth of a cluster of adventitious buds. Such burls are the source of the highly figured burl veneers used for purely ornamental purposes. (2) In lumber or veneer, a localized severe distortion of the grain generally rounded in outline, usually resulting from overgrowth of dead branch stubs, varying from one to several centimeters (one-half to several inches) in diameter; frequently includes one or more clusters of several small contiguous conical protuberances, each usually having a core or pith but no appreciable amount of end grain (in tangential view) surrounding it.

Butt Joint. (See **Joint.**)

Buttress. A ridge of wood developed in the angle between a lateral root and the butt of a tree, which may extend up the stem to a considerable height.

Cambium. A thin layer of tissue between the bark and wood that repeatedly subdivides to form new wood and bark cells.

Cant. A log that has been slabbed on one or more sides. Ordinarily, cants are intended for resawing at right angles to their widest sawn face. The term is loosely used. (See **Fitch.**)

Casehardening. A condition of stress and set in dry lumber characterized by compressive stress in the outer layers and tensile stress in the center or core.

Catalyst. A substance that initiates or changes the rate of chemical reaction but is not consumed or changed by the reaction.

Cell. A general term for the anatomical units of plant tissue, including wood fibers, vessel members, and other elements of diverse structure and function.

Cellulose. The carbohydrate that is the principal constituent of wood and forms the framework of the wood cells.

Cellulosic Fiberboard. (See **Wood-Based Composite Panel.**)

Glossary

Check. A lengthwise separation of the wood that usually extends across the rings of annual growth and commonly results from stresses set up in wood during seasoning.

Chemical Brown Stain. (See **Stain.**)

Chipboard. A paperboard used for many purposes that may or may not have specifications for strength, color, or other characteristics. It is normally made from paper stock with a relatively low density in the thickness of 0.1524 mm (0.006 in.) and up.

Cleavage. In an adhesively bonded joint, a separation in the joint caused by a wedge or other crack-opening-type action.

Close Grained. (See **Grain.**)

Coarse Grained. (See **Grain.**)

Cohesion. The state in which the constituents of a mass of material are held together by chemical and physical forces.

Cold Pressing. A bonding operation in which an assembly is subjected to pressure without the application of heat.

Collapse. The flattening of single cells or rows of cells in heartwood during the drying or pressure treatment of wood. Often characterized by a caved-in or corrugated appearance of the wood surface.

Compartment Kiln. (See **Kiln.**)

Composite Assembly. A combination of two or more materials bonded together that perform as a single unit.

Composite Panel. (See **Wood-Based Composite Panel.**)

Compound Curvature. Wood bent to a compound curvature, no element of which is a straight line.

Compreg. Wood in which the cell walls have been impregnated with synthetic resin and compressed to give it reduced swelling and shrinking characteristics and increased density and strength properties.

Compression Failure. Deformation of the wood fibers resulting from excessive compression along the grain either in direct end compression or in bending. It may develop in standing trees due to bending by wind or snow or to internal longitudinal stresses developed in growth, or it may result from stresses imposed after the tree is cut. In surfaced lumber, compression failures may appear as fine wrinkles across the face of the piece.

Compression Wood. Abnormal wood formed on the lower side of branches and inclined trunks of softwood trees. Compression wood is identified by its relatively wide annual rings (usually eccentric when viewed on cross section of branch or trunk), relatively large amount of latewood (sometimes more than 50% of the width of the annual rings in which it occurs), and its lack of demarcation between earlywood and latewood in the same annual rings. Compression wood shrinks excessively longitudinally, compared with normal wood.

Conditioning (pre and post). The exposure of a material to the influence of a prescribed atmosphere for a stipulated period of time or until a stipulated relation is reached between material and atmosphere.

Conifer. (See **Softwoods.**)

Connector, Timber. Metal rings, plates, or grids that are embedded in the wood of adjacent members, as at the bolted points of a truss, to increase the strength of the joint.

Consistency. That property of a liquid adhesive by virtue of which it tends to resist deformation. (Consistency is not a fundamental property but is composed of rheological properties such as viscosity, plasticity, and other phenomena.)

Construction Adhesive. (See **Adhesive.**)

Contact Angle. The angle between a substrate plane and the free surface of a liquid droplet at the line of contact with the substrate.

Cooperage. Containers consisting of two round heads and a body composed of staves held together with hoops, such as barrels and kegs.

Slack Cooperage—Cooperage used as containers for dry, semidry, or solid products. The staves are usually not closely fitted and are held together with beaded steel, wire, or wood hoops.

Tight Cooperage—Cooperage used as containers for liquids, semisolids, or heavy solids. Staves are well fitted and held tightly with cooperage-grade steel hoops.

Copolymer. Substance obtained when two or more types of monomers polymerize.

Corbel. A projection from the face of a wall or column supporting a weight.

Core Stock. A solid or discontinuous center ply used in panel-type glued structures (such as furniture panels and solid or hollowcore doors).

Coupling Agent. A molecule with different or like functional groups that is capable of reacting with surface molecules of two different substances, thereby chemically bridging the substances.

Covalent Bond. A chemical bond that results when electrons are shared by two atomic nuclei.

Creep. (1) Time-dependent deformation of a wood member under sustained wood. (2) In an adhesive, the time-dependent increase in strain resulting from a sustained stress.

Crook. The distortion of lumber in which there is a deviation, in a direction perpendicular to the edge, from a straight line from end-to-end of the piece.

Crossband. To place the grain of layers of wood at right angles in order to minimize shrinking and swelling; also, in plywood of three or more plies, a layer of veneer whose grain direction is at right angles to that of the face plies.

Cross Break. A separation of the wood cells across the grain. Such breaks may be due to internal stress resulting from unequal longitudinal shrinkage or to external forces.

Cross Grained. (See **Grain.**)

Cross-Link. An atom or group connecting adjacent molecules in a complex molecular structure.

Cup. A distortion of a board in which there is a deviation flatwise from a straight line across the width of the board.

Cure. To change the properties of an adhesive by chemical reaction (which may be condensation, polymerization, or vulcanization) and thereby develop maximum strength. Generally accomplished by the action of heat or a catalyst, with or without pressure.

Curing Agent. (See **Hardener.**)

Curing Temperature. (See **Temperature, Curing.**)

Curing Time. (See **Time, Curing.**)

Curly Grained. (See **Grain.**)

Curtain Coating. Applying liquid adhesive to an adherend by passing the adherend under a thin curtain of liquid falling by gravity or pressure.

Cut Stock. (See **Lumber for Dimension.**)

Cuttings. In hardwoods, portions of a board or plank having the quality required by a specific grade or for a particular use. Obtained from a board by crosscutting or ripping.

Decay. The decomposition of wood substance by fungi.

Advanced (Typical) Decay—The older stage of decay in which the destruction is readily recognized because the wood has become punky, soft and spongy, stringy, ringshaked, pitted, or crumbly. Decided discoloration or bleaching of the rotted wood is often apparent.

Brown Rot—In wood, any decay in which the attack concentrates on the cellulose and associated carbohydrates rather than on the lignin, producing a light to dark brown friable residue—hence loosely termed “dry rot.” An advanced stage where the wood splits along rectangular planes, in shrinking, is termed “cubical rot.”

Dry Rot—A term loosely applied to any dry, crumbly rot but especially to that which, when in an advanced stage, permits the wood to be crushed easily to a dry powder. The term is actually a misnomer for any decay, since all fungi require considerable moisture for growth.

Incipient Decay—The early stage of decay that has not proceeded far enough to soften or otherwise perceptibly impair the hardness of the wood. It is usually accompanied by a slight discoloration or bleaching of the wood.

Heart Rot—Any rot characteristically confined to the heartwood. It generally originates in the living tree.

Pocket Rot—Advanced decay that appears in the form of a hole or pocket, usually surrounded by apparently sound wood.

Soft Rot—A special type of decay developing under very wet conditions (as in cooling towers and boat timbers) in the outer wood layers, caused by cellulose-destroying microfungi that attack the secondary cell walls and not the intercellular layer.

White-Rot—In wood, any decay or rot attacking both the cellulose and the lignin, producing a generally whitish residue that may be spongy or stringy rot, or occur as pocket rot.

Delamination. The separation of layers in laminated wood or plywood because of failure of the adhesive, either within the adhesive itself or at the interface between the adhesive and the adherend.

Delignification. Removal of part or all of the lignin from wood by chemical treatment.

Density. As usually applied to wood of normal cellular form, density is the mass per unit volume of wood substance enclosed within the boundary surfaces of a wood-plus-voids complex. It is variously expressed as pounds per cubic foot, kilograms per cubic meter, or grams per cubic centimeter at a specified moisture content.

Density Rules. A procedure for segregating wood according to density, based on percentage of latewood and number of growth rings per inch of radius.

Dew Point. The temperature at which a vapor begins to deposit as a liquid. Applies especially to water in the atmosphere.

Diagonal Grained. (See **Grain.**)

Diffuse-Porous Wood. Certain hardwoods in which the pores tend to be uniform in size and distribution throughout each annual ring or to decrease in size slightly and gradually toward the outer border of the ring.

Dimension. (See **Lumber for Dimension.**)

Dipole–Dipole Forces. Intermolecular attraction forces between polar molecules that result when positive and negative poles of molecules are attracted to one another.

Dote. “Dote,” “doze,” and “rot” are synonymous with “decay” and are any form of decay that may be evident as either a discoloration or a softening of the wood.

Double Spread. (See **Spread.**)

Dry-Bulb Temperature. The temperature of air as indicated by a standard thermometer. (See **Psychrometer.**)

Dry Kiln. (See **Kiln.**)

Dry Rot. (See **Decay.**)

Glossary

Dry Strength. The strength of an adhesive joint determined immediately after drying under specified conditions or after a period of conditioning in a standard laboratory atmosphere.

Drywall. Panel product used as an interior wall and ceiling covering made of gypsum plaster with paper facings. The gypsum plaster may be reinforced with recycled fiber.

Durability. A general term for permanence or resistance to deterioration. Frequently used to refer to the degree of resistance of a species of wood to attack by wood-destroying fungi under conditions that favor such attack. In this connection, the term “decay resistance” is more specific. As applied to bondlines, the life expectancy of the structural qualities of the adhesive under the anticipated service conditions of the structure.

Earlywood. The portion of the growth ring that is formed during the early part of the growing season. It is usually less dense and weaker mechanically than latewood.

Edge Grained. (See **Grain.**)

Edge Joint. (See **Joint.**)

Elastomer. A macromolecular material that, at room temperature, is deformed by application of a relatively low force and is capable of recovering substantially in size and shape after removal of the force.

Embrittlement. A loss in strength or energy absorption without a corresponding loss in stiffness. Clear, straight-grained wood is generally considered a ductile material; chemical treatments and elevated temperatures can alter the original chemical composition of wood, thereby embrittling the wood.

Encased Knot. (See **Knot.**)

End Grained. (See **Grain.**)

End Joint. (See **Joint.**)

Equilibrium Moisture Content. The moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature.

Excelsior. (See **Wood Wool.**)

Extender. A substance, generally having some adhesive action, added to an adhesive to reduce the amount of the primary binder required per unit area.

Exterior Plywood. (See **Wood-Based Composite Panel.**)

Extractive. Substances in wood, not an integral part of the cellular structure, that can be removed by solution in hot or cold water, ether, benzene, or other solvents that do not react chemically with wood components.

Extrusion Spreading. A method of adhesive application in which adhesive is forced through small openings in the spreader head.

Factory and Shop Lumber. (See **Lumber.**)

Failure, Adherend. Rupture of an adhesive joint, such that the separation appears to be within the adherend.

Failure, Adhesive. Rupture of an adhesive joint, such that the plane of separation appears to be at the adhesive–adherend interface.

Failure, Cohesive. Rupture of an adhesive joint, such that the separation appears to be within the adhesive.

Feed Rate. The distance that the stock being processed moves during a given interval of time or operational cycle.

Fiber, Wood. A wood cell comparatively long (≤ 40 to 300 mm, ≤ 1.5 to 12 in.), narrow, tapering, and closed at both ends.

Fiberboard. (See **Wood-Based Composite Panel.**)

Fiber Saturation Point. The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. It applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30% moisture content, based on oven-dry weight.

Fibril. A threadlike component of cell walls, invisible under a light microscope.

Figure. The pattern produced in a wood surface by annual growth rings, rays, knots, deviations from regular grain such as interlocked and wavy grain, and irregular coloration.

Filler. In woodworking, any substance used to fill the holes and irregularities in planed or sanded surfaces to decrease the porosity of the surface before applying finish coatings. As applied to adhesives, a relatively nonadhesive substance added to an adhesive to improve its working properties, strength, or other qualities.

Fine Grained. (See **Grain.**)

Fingerjoint. (See **Joint.**)

Finish (Finishing). (1) Wood products such as doors, stairs, and other fine work required to complete a building, especially the interior. (2) Coatings of paint, varnish, lacquer, wax, or other similar materials applied to wood surfaces to protect and enhance their durability or appearance.

Fire Endurance. A measure of the time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance.

Fire Resistance. The property of a material or assembly to withstand fire or give protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a given structural function, or both.

Fire Retardant. (See **Flame Retardant.**)

Fire-Retardant-Treated Wood. As specified in building codes, a wood product that has been treated with chemicals by a pressure process or treated during the manufacturing process for the purpose of reducing its flame spread performance in an ASTM E 84 test conducted for 30 min to performance levels specified in the codes.

Flake. A small flat wood particle of predetermined dimensions, uniform thickness, with fiber direction essentially in the plane of the flake; in overall character resembling a small piece of veneer. Produced by special equipment for use in the manufacture of flakeboard.

Flakeboard. (See **Wood-Based Composite Panel.**)

Flame Retardant. A treatment, coating, or chemicals that when applied to wood products delays ignition and reduces the flame spread of the product.

Flame Spread. The propagation of a flame away from the source of ignition across the surface of a liquid or a solid, or through the volume of a gaseous mixture.

Flat Grained. (See **Grain.**)

Flat Sawn. (See **Grain.**)

Flecks. (See **Rays, Wood.**)

Flich. A portion of a log sawn on two or more faces—commonly on opposite faces leaving two waney edges. When intended for resawing into lumber, it is resawn parallel to its original wide faces. Or, it may be sliced or sawn into veneer, in which case the resulting sheets of veneer laid together in the sequence of cutting are called a flich. The term is loosely used. (See **Cant.**)

Framing. Lumber used for the structural member of a building, such as studs and joists.

Full-Cell Process. Any process for impregnating wood with preservatives or chemicals in which a vacuum is drawn to remove air from the wood before admitting the preservative. This favors heavy adsorption and retention of preservative in the treated portions.

Furnish. Wood material that has been reduced for incorporation into conventional wood-based composites; including flakes, particles, and fiber.

Gelatinous Fibers. Modified fibers that are associated with tension wood in hardwoods.

Girder. A large or principal beam used to support concentrated loads at isolated points along its length.

Gluability. (See **Bondability.**)

Glue. Originally, a hard gelatin obtained from hides, tendons, cartilage, bones, etc., of animals. Also, an adhesive prepared from this substance by heating with water. Through general use, the term is now synonymous with the term “adhesive.”

Glue Laminating. Production of structural or nonstructural wood members by bonding two or more layers of wood together with adhesive.

Glued Laminated Timber (Glulam). A manufactured structural timber product composed of layers of dimensional lumber glued together.

Glueline. (See **Bondline.**)

Grade. The designation of the quality of a manufactured piece of wood or of logs.

Grain. The direction, size, arrangement, appearance, or quality of the fibers in wood or lumber. To have a specific meaning the term must be qualified.

Close-Grained (Fine-Grained) Wood—Wood with narrow, inconspicuous annual rings. The term is sometimes used to designate wood having small and closely spaced pores, but in this sense the term “fine textured” is more often used.

Coarse-Grained Wood—Wood with wide conspicuous annual rings in which there is considerable difference between earlywood and latewood. The term is sometimes used to designate wood with large pores, such as oak, keruing, meranti, and walnut, but in this sense, the term “open-grained” is more often used.

Cross-Grained Wood—Wood in which the fibers deviate from a line parallel to the sides of the piece. Cross grain may be either diagonal or spiral grain or a combination of the two.

Curly-Grained Wood—Wood in which the fibers are distorted so that they have a curled appearance, as in “birds-eye” wood. The areas showing curly grain may vary up to several inches in diameter.

Diagonal-Grained Wood—Wood in which the annual rings are at an angle with the axis of a piece as a result of sawing at an angle with the bark of the tree or log. A form of cross-grain.

Edge-Grained Lumber—Lumber that has been sawed so that the wide surfaces extend approximately at right angles to the annual growth rings. Lumber is considered edge grained when the rings form an angle of 45° to 90° with the wide surface of the piece.

End-Grained Wood—The grain as seen on a cut made at a right angle to the direction of the fibers (such as on a cross section of a tree).

Fiddleback-Grained Wood—Figure produced by a type of fine wavy grain found, for example, in species of maple; such wood being traditionally used for the backs of violins.

Flat-Grained (Flat-Sawn) Lumber—Lumber that has been sawn parallel to the pith and approximately tangent

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to the growth rings. Lumber is considered flat grained when the annual growth rings make an angle of less than 45° with the surface of the piece.

Interlocked-Grained Wood—Grain in which the fibers put on for several years may slope in a right-handed direction, and then for a number of years the slope reverses to a left-handed direction, and later changes back to a right-handed pitch, and so on. Such wood is exceedingly difficult to split radially, though tangentially it may split fairly easily.

Open-Grained Wood—Common classification for woods with large pores such as oak, keruing, meranti, and walnut. Also known as “coarse textured.”

Plainsawn Lumber—Another term for flat-grained lumber.

Quartersawn Lumber—Another term for edge-grained lumber.

Side-Grained Wood—Another term for flat-grained lumber.

Slash-Grained Wood—Another term for flat-grained lumber.

Spiral-Grained Wood—Wood in which the fibers take a spiral course about the trunk of a tree instead of the normal vertical course. The spiral may extend in a right-handed or left-handed direction around the tree trunk. Spiral grain is a form of cross grain.

Straight-Grained Wood—Wood in which the fibers run parallel to the axis of a piece.

Vertical-Grained Lumber—Another term for edge-grained lumber.

Wavy-Grained Wood—Wood in which the fibers collectively take the form of waves or undulations.

Green. Freshly sawed or undried wood. Wood that has become completely wet after immersion in water would not be considered green but may be said to be in the “green condition.”

Growth Ring. The layer of wood growth put on a tree during a single growing season. In the temperate zone, the annual growth rings of many species (for example, oaks and pines) are readily distinguished because of differences in the cells formed during the early and late parts of the season. In some temperate zone species (black gum and sweetgum) and many tropical species, annual growth rings are not easily recognized.

Gum. A comprehensive term for nonvolatile viscous plant exudates, which either dissolve or swell up in contact with water. Many substances referred to as gums such as pine and spruce gum are actually oleoresins.

Hardboard. (See **Wood-Based Composite Panel.**)

Hardener. A substance or mixture of substances that is part of an adhesive and is used to promote curing by taking part in the reaction.

Hardness. A property of wood that enables it to resist indentation.

Hardwoods. Generally one of the botanical groups of trees that have vessels or pores and broad leaves, in contrast to the conifers or softwoods. The term has no reference to the actual hardness of the wood.

Heart Rot. (See **Decay.**)

Heartwood. The wood extending from the pith to the sapwood, the cells of which no longer participate in the life processes of the tree. Heartwood may contain phenolic compounds, gums, resins, and other materials that usually make it darker and more decay resistant than sapwood.

Hemicellulose. A celluloselike material (in wood) that is easily decomposable as by dilute acid, yielding several different simple sugars.

Hertz. A unit of frequency equal to one cycle per second.

High Frequency Curing. (See **Radiofrequency Curing.**)

Hollow-Core Construction. A panel construction with faces of plywood, hardboard, or similar material bonded to a framed-core assembly of wood lattice, paperboard rings, or the like, which support the facing at spaced intervals.

Honeycomb Core. A sandwich core material constructed of thin sheet materials or ribbons formed to honeycomb-like configurations.

Honeycombing. Checks, often not visible at the surface, that occur in the interior of a piece of wood, usually along the wood rays.

Hot-Setting Adhesive. (See **Adhesive.**)

Hydrogen Bond. An intermolecular attraction force that results when the hydrogen of one molecule and a pair of unshared electrons on an electronegative atom of another molecule are attracted to one another.

Hydrophilic. Having a strong tendency to bind or absorb water.

Hydrophobic. Having a strong tendency to repel water.

Impreg. Wood in which the cell walls have been impregnated with synthetic resin so as to reduce materially its swelling and shrinking. Impreg is not compressed.

Incising. A pretreatment process in which incisions, slits, or perforations are made in the wood surface to increase penetration of preservative treatments. Incising is often required to enhance durability of some difficult-to-treat species, but incising reduces strength.

Increment Borer. An augerlike instrument with a hollow bit and an extractor, used to extract thin radial cylinders of

wood from trees to determine age and growth rate. Also used in wood preservation to determine the depth of penetration of a preservative.

Inorganic-Bonded Composites. Manufactured wood-based composites where an inorganic binder, typically gypsum, Portland-cement, or magnesia-cement, acts as a continuous matrix and fully encapsulates the wood elements.

Intergrown Knot. (See **Knot.**)

Interior Plywood. (See **Wood-Based Composite Panel.**)

Interlocked Grained. (See **Grain.**)

Interlocking Action. (See **Mechanical Adhesion.**)

Internal Stresses. Stresses that exist within an adhesive joint even in the absence of applied external forces.

Interphase. In wood bonding, a region of finite thickness as a gradient between the bulk adherend and bulk adhesive in which the adhesive penetrates and alters the adherend's properties and in which the presence of the adherend influences the chemical and/or physical properties of the adhesive.

Intumesce. To expand with heat to provide a low-density film; used in reference to certain fire-retardant coatings.

Isotropic. Exhibiting the same properties in all directions.

Joint. The junction of two pieces of wood or veneer.

Adhesive Joint—The location at which two adherends are held together with a layer of adhesive.

Assembly Joint—Joints between variously shaped parts or subassemblies such as in wood furniture (as opposed to joints in plywood and laminates that are all quite similar).

Butt Joint—An end joint formed by abutting the squared ends of two pieces.

Edge Joint—A joint made by bonding two pieces of wood together edge to edge, commonly by gluing. The joints may be made by gluing two squared edges as in a plain edge joint or by using machined joints of various kinds, such as tongued-and-grooved joints.

End Joint—A joint made by bonding two pieces of wood together end to end, commonly by finger or scarf joint.

Fingerjoint—An end joint made up of several meshing wedges or fingers of wood bonded together with an adhesive. Fingers are sloped and may be cut parallel to either the wide or narrow face of the piece.

Lap Joint—A joint made by placing one member partly over another and bonding the overlapped portions.

Scarf Joint—An end joint formed by joining with adhesive the ends of two pieces that have been tapered or beveled to form sloping plane surfaces, usually to a feather-edge, and with the same slope of the plane with respect

to the length in both pieces. In some cases, a step or hook may be machined into the scarf to facilitate alignment of the two ends, in which case the plane is discontinuous and the joint is known as a stepped or hooked scarf joint.

Starved Joint—A glue joint that is poorly bonded because an insufficient quantity of adhesive remained in the joint.

Sunken Joint—Depression in wood surface at a joint (usually an edge joint) caused by surfacing material too soon after bonding. (Inadequate time was allowed for moisture added with the adhesive to diffuse away from the joint.)

Joint Efficiency or Factor. The strength of a joint expressed as a percentage of the strength of clear straight-grained material.

Joist. One of a series of parallel beams used to support floor and ceiling loads and supported in turn by larger beams, girders, or bearing walls.

Kiln. A chamber having controlled air-flow, temperature, and relative humidity for drying lumber. The temperature is increased as drying progresses, and the relative humidity is decreased.

Kiln Dried. (See **Seasoning.**)

Knot. That portion of a branch or limb that has been surrounded by subsequent growth of the stem. The shape of the knot as it appears on a cut surface depends on the angle of the cut relative to the long axis of the knot.

Encased Knot—A knot whose rings of annual growth are not intergrown with those of the surrounding wood.

Intergrown Knot—A knot whose rings of annual growth are completely intergrown with those of the surrounding wood.

Loose Knot—A knot that is not held firmly in place by growth or position and that cannot be relied upon to remain in place.

Pin Knot—A knot that is not more than 12 mm (1/2 in.) in diameter.

Sound Knot—A knot that is solid across its face, at least as hard as the surrounding wood, and shows no indication of decay.

Spike Knot—A knot cut approximately parallel to its long axis so that the exposed section is definitely elongated.

Laminate. A product made by bonding together two or more layers (laminations) of material or materials.

Laminate, Paper-Based. A multilayered panel made by compressing sheets of resin-impregnated paper together into a coherent solid mass.

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Laminated Strand Lumber (LSL). (See **Structural Composite Lumber**.)

Laminated Veneer Lumber (LVL). (See **Structural Composite Lumber**.)

Lap Joint. (See **Joint**.)

Latewood. The portion of the growth ring that is formed after the earlywood formation has ceased. It is usually denser and stronger mechanically than earlywood.

Latex Paint. A paint containing pigments and a stable water suspension of synthetic resins (produced by emulsion polymerization) that forms an opaque film through coalescence of the resin during water evaporation and subsequent curing.

Lathe Checks. In rotary-cut and sliced veneer, the fractures or checks that develop along the grain of the veneer as the knife peels veneer from the log. The knife side of the veneer where checks occur is called the loose side. The opposite and log side of the veneer where checking usually does not occur is called the tight side.

Layup. The process of loosely assembling the adhesive-coated components of a unit, particularly a panel, to be pressed or clamped.

Lbs/MSGL. Abbreviation for rate of adhesive application in pounds of adhesive per 1,000 ft² of single glueline (bondline). (See **Spread**.) When both faces of an adherend are spread as in some plywood manufacturing processes, the total weight of adhesive applied may be expressed as Lbs/MDGL (pounds per 1,000 ft² double glueline).

Lignin. The second most abundant constituent of wood, located principally in the secondary wall and the middle lamella, which is the thin cementing layer between wood cells. Chemically, it is an irregular polymer of substituted propylphenol groups, and thus, no simple chemical formula can be written for it.

London Dispersion Forces. Intermolecular attraction forces between nonpolar molecules that result when instantaneous (nonpermanent) dipoles induce matching dipoles in neighboring molecules. London forces also exist between polar molecules.

Longitudinal. Generally, parallel to the direction of the wood fibers.

Loose Knot. (See **Knot**.)

Lumber. The product of the saw and planing mill for which manufacturing is limited to sawing, resawing, passing lengthwise through a standard planing machine, crosscutting to length, and matching. Lumber may be made from either softwood or hardwood (See also **Lumber for Dimension**.)

Board—Lumber that is less than 38 mm standard (2 in. nominal) thickness and greater than 38 mm standard (2 in. nominal) width. Boards less than 140 mm standard (6 in. nominal) width are sometimes called strips.

Dimension—Lumber with a thickness from 38 mm standard (2 in. nominal) up to but not including 114 mm standard (5 in. nominal) and a width of greater than 38 mm standard (2 in. nominal).

Dressed Size—The dimensions of lumber after being surfaced with a planing machine. The dressed size is usually 1/2 to 3/4 in. less than the nominal or rough size. A 2- by 4-in. stud, for example, actually measures about 1-1/2 by 3-1/2 in. (standard 38 by 89 mm).

Factory and Shop Lumber—Lumber intended to be cut up for use in further manufacture. It is graded on the percentage of the area that will produce a limited number of cuttings of a specified minimum size and quality.

Matched Lumber—Lumber that is edge dressed and shaped to make a close tongued-and-grooved joint at the edges or ends when laid edge to edge or end to end.

Nominal Size—As applied to timber or lumber, the size by which it is known and sold in the market (often differs from the actual size).

Patterned Lumber—Lumber that is shaped to a pattern or to a molded form in addition to being dressed, matched, or shiplapped, or any combination of these workings.

Rough Lumber—Lumber that has not been dressed (surfaced) but has been sawed, edged, and trimmed.

Shiplapped Lumber—Lumber that is edge dressed to make a lapped joint.

Shipping-Dry Lumber—Lumber that is partially dried to prevent stain and mold in transit.

Shop Lumber—(See **Factory and Shop Lumber**.)

Side Lumber—A board from the outer portion of the log—ordinarily one produced when squaring off a log for a tie or timber.

Structural Lumber—Lumber that is intended for use where allowable properties are required. The grading of structural lumber is based on the strength or stiffness of the piece as related to anticipated uses.

Surfaced Lumber—Lumber that is dressed by running it through a planer.

Timbers—Lumber that is standard 114 mm (nominal 5 in.) or more in least dimension. Timbers may be used as beams, stringers, posts, caps, sills, girders, or purlins.

Yard Lumber—A little-used term for lumber of all sizes and patterns that is intended for general building purposes having no design property requirements.

Lumber for Dimension. The National Dimension Manufacturers Association defines both hardwood and softwood dimension components as being cut to a specific size from

kiln-dried rough lumber, bolts, cants, or logs. Dimension components include Flat Stock (solid and laminated) for furniture, cabinet, and specialty manufactures. This term has largely superseded the terms “hardwood dimension” and “dimension parts.” (See also **Lumber**).

Lumen. In wood anatomy, the cell cavity.

Manufacturing Defects. Includes all defects or blemishes that are produced in manufacturing, such as chipped grain, loosened grain, raised grain, torn grain, skips in dressing, hit and miss (series of surfaced areas with skips between them), variation in sawing, miscut lumber, machine burn, machine gouge, mismatching, and insufficient tongue or groove.

Mastic. A material with adhesive properties, usually used in relatively thick sections, that can be readily applied by extrusion, trowel, or spatula. (See **Adhesive**.)

Matched Lumber. (See **Lumber**.)

Mechanical Adhesion. Adhesion between surfaces in which the adhesive holds the parts together by interlocking action.

Medium-Density Fiberboard. (See **Wood-Based Composite Panel**.)

Millwork. Planed and patterned lumber for finish work in buildings, including items such as sash, doors, cornices, panelwork, and other items of interior or exterior trim. Does not include flooring, ceiling, or siding.

Mineral Streak. An olive to greenish-black or brown discoloration of undetermined cause in hardwoods.

Modified Wood. Wood processed by chemical treatment, compression, or other means (with or without heat) to impart properties quite different from those of the original wood.

Moisture Content. The amount of water contained in the wood, usually expressed as a percentage of the weight of the oven-dry wood.

Molecular Weight. The sum of the atomic weights of the atoms in a molecule.

Moulding. A wood strip having a curved or projecting surface, used for decorative purposes.

Monomer. A relatively simple molecular compound that can react at more than one site to form a polymer.

Mortise. A slot cut into a board, plank, or timber, usually edgewise, to receive the tenon of another board, plank, or timber to form a joint.

Nanoindentation Hardness. A hardness measurement conducted at the nanometer scale. Nanoindentation hardness uses an extremely small indenter of a hard material and specified shape to press into the surface of a specimen with sufficient force to cause deformation.

Naval Stores. A term applied to the oils, resins, tars, and pitches derived from oleoresin contained in, exuded by, or

extracted from trees, chiefly species of pines (genus *Pinus*). Historically, these were important items in the stores of wood sailing vessels.

Nominal-Size Lumber. (See **Lumber for Dimension**.)

Nonpolar. (See **Polar**.)

Nonpressure Process. Any process of treating wood with a preservative or fire retardant where pressure is not applied. Some examples are surface applications by brushing or brief dipping, soaking in preservative oils, or steeping in solutions of waterborne preservatives; diffusion processes with waterborne preservatives; and vacuum treatments.

Oil Paint. A paint containing a suspension of pigments in an organic solvent and a drying oil, modified drying oil, or synthetic polymer that forms an opaque film through a combination of solvent evaporation and curing of the oil or polymer.

Old Growth. Timber in or from a mature, naturally established forest. When the trees have grown during most if not all of their individual lives in active competition with their companions for sunlight and moisture, this timber is usually straight and relatively free of knots.

Oleoresin. A solution of resin in an essential oil that occurs in or exudes from many plants, especially softwoods. The oleoresin from pine is a solution of pine resin (rosin) in turpentine.

Open Assembly Time. (See **Time, Assembly**.)

Open Grain. (See **Grain**.)

Oriented Strandboard. (See **Wood-Based Composite Panel**.)

Oriented Strand Lumber (OSL). (See **Structural Composite Lumber**.)

Orthotropic. Having unique and independent properties in three mutually orthogonal (perpendicular) planes of symmetry. A special case of anisotropy.

Ovendry Wood. Wood dried to a relatively constant weight in a ventilated oven at 102 to 105 °C (215 to 220 °F).

Overlay. A thin layer of paper, plastic, film, metal foil, or other material bonded to one or both faces of panel products or to lumber to provide a protective or decorative face or a base for painting.

Paint. Any pigmented liquid, liquifiable, or mastic composition designed for application to a substrate in a thin layer that converts to an opaque solid film after application.

Pallet. A low wood or metal platform on which material can be stacked to facilitate mechanical handling, moving, and storage.

Paperboard. The distinction between paper and paperboard is not sharp, but broadly speaking, the thicker (greater than

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0.3 mm (0.012 in.)), heavier, and more rigid grades of paper are called paperboard.

Papreg. Any of various paper products made by impregnating sheets of specially manufactured high-strength paper with synthetic resin and laminating the sheets to form a dense, moisture-resistant product.

Parallel Strand Lumber (PSL). (See **Structural Composite Lumber.**)

Parenchyma. Short cells having simple pits and functioning primarily in the metabolism and storage of plant food materials. They remain alive longer than the tracheids, fibers, and vessel elements, sometimes for many years. Two kinds of parenchyma cells are recognized—those in vertical strands, known more specifically as axial parenchyma, and those in horizontal series in the rays, known as ray parenchyma.

Particleboard. (See **Wood-Based Composite Panel.**)

Particles. The aggregate component of particleboard manufactured by mechanical means from wood. These include all small subdivisions of wood such as chips, curls, flakes, sawdust, shavings, slivers, strands, wafers, wood flour, and wood wool.

Peck. Pockets or areas of disintegrated wood caused by advanced stages of localized decay in the living tree. It is usually associated with cypress and incense-cedar. There is no further development of peck once the lumber is seasoned.

Peel. To convert a log into veneer by rotary cutting. In an adhesively bonded joint, the progressive separation of a flexible member from either a rigid member or another flexible member.

Phloem. The tissues of the inner bark, characterized by the presence of sieve tubes and serving for the transport of elaborate foodstuffs.

Pile. A long, heavy timber, round or square, that is driven deep into the ground to provide a secure foundation for structures built on soft, wet, or submerged sites (for example, landing stages, bridge abutments).

Pin Knot. (See **Knot.**)

Pitch Pocket. An opening extending parallel to the annual growth rings and containing, or that has contained, pitch, either solid or liquid.

Pitch Streaks. A well-defined accumulation of pitch in a more or less regular streak in the wood of certain conifers.

Pith. The small, soft core occurring near the center of a tree trunk, branch, twig, or log.

Pith Fleck. A narrow streak, resembling pith on the surface of a piece; usually brownish, up to several centimeters long; results from burrowing of larvae in the growing tissues of the tree.

Plainsawn. (See **Grain.**)

Planing Mill Products. Products worked to pattern, such as flooring, ceiling, and siding.

Plank. A broad, thick board laid with its wide dimension horizontal and used as a bearing surface.

Plasticizing Wood. Softening wood by hot water, steam, or chemical treatment to increase its moldability.

Plywood. (See **Wood-Based Composite Panel.**)

Pocket Rot. (See **Decay.**)

Polar. Characteristic of a molecule in which the positive and negative electrical charges are permanently separated, as opposed to nonpolar molecules in which the charges coincide. Water, alcohol, and wood are polar in nature; most hydrocarbon liquids are not.

Polymer. A compound formed by the reaction of simple molecules having functional groups that permit their combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by polymerization (addition polymer) or polycondensation (condensation polymer). When two or more different monomers are involved, the product is called a copolymer.

Polymerization. A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more different monomers are involved, the process is called copolymerization.

Pore. (See **Vessel Elements.**)

Postformed Plywood. (See **Wood-Based Composite Panel.**)

Post Cure. (1) A treatment (normally involving heat) applied to an adhesive assembly following the initial cure, to complete cure, or to modify specific properties. (2) To expose an adhesive assembly to an additional cure, following the initial cure; to complete cure; or to modify specific properties.

Pot Life. (See **Working Life.**)

Precure. Condition of too much cure, set, or solvent loss of the adhesive before pressure is applied, resulting in inadequate flow, transfer, and bonding.

Preservative. Any substance that, for a reasonable length of time, is effective in preventing the development and action of wood-rotting fungi, borers of various kinds, and harmful insects that deteriorate wood.

Pressure Process. Any process of treating wood in a closed container whereby the preservative or fire retardant is forced into the wood under pressures greater than one atmosphere. Pressure is generally preceded or followed by vacuum, as in the vacuum-pressure and empty-cell processes respectively;

or they may alternate, as in the full-cell and alternating-pressure processes.

Progressive Kiln. (See **Kiln.**)

Psychrometer. An instrument for measuring the amount of water vapor in the atmosphere. It has both a dry-bulb and wet-bulb thermometer. The bulb of the wet-bulb thermometer is kept moistened and is, therefore, cooled by evaporation to a temperature lower than that shown by the dry-bulb thermometer. Because evaporation is greater in dry air, the difference between the two thermometer readings will be greater when the air is dry than when it is moist.

Quartersawn. (See **Grain.**)

Radial. Coincident with a radius from the axis of the tree or log to the circumference. A radial section is a lengthwise section in a plane that passes through the centerline of the tree trunk.

Radiofrequency (RF) Curing. Curing of bondlines by the application of radiofrequency energy. (Sometimes called high-frequency curing.)

Rafter. One of a series of structural members of a roof designed to support roof loads. The rafters of a flat roof are sometimes called roof joists.

Raised Grain. A roughened condition of the surface of dressed lumber in which the hard latewood is raised above the softer earlywood but not torn loose from it.

Rays, Wood. Strips of cells extending radially within a tree and varying in height from a few cells in some species to 4 or more inches in oak. The rays serve primarily to store food and transport it horizontally in the tree. On quartersawn oak, the rays form a conspicuous figure, sometimes referred to as flecks.

Reaction Wood. Wood with more or less distinctive anatomical characters, formed typically in parts of leaning or crooked stems and in branches. In hardwoods, this consists of tension wood, and in softwoods, compression wood.

Relative Humidity. Ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor but, for accuracy, should be considered on the basis of vapor pressures.

Resilience. The property whereby a strained body gives up its stored energy on the removal of the deforming force.

Resin. (1) Solid, semisolid, or pseudosolid resin—An organic material that has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally. (2) Liquid resin—an organic polymeric liquid that, when converted to its final state for use, becomes a resin.

Resin Ducts. Intercellular passages that contain and transmit resinous materials. On a cut surface, they are usually inconspicuous. They may extend vertically parallel to the axis of the tree or at right angles to the axis and parallel to the rays.

Retention by Assay. The determination of preservative retention in a specific zone of treated wood by extraction or analysis of specified samples.

Rheology. The study of the deformation and flow of matter.

Ring Failure. A separation of the wood during seasoning, occurring along the grain and parallel to the growth rings. (See **Shake.**)

Ring-Porous Woods. A group of hardwoods in which the pores are comparatively large at the beginning of each annual ring and decrease in size more or less abruptly toward the outer portion of the ring, thus forming a distinct inner zone of pores, known as the earlywood, and an outer zone with smaller pores, known as the latewood.

Ring Shake. (See **Shake.**)

Rip. To cut lengthwise, parallel to the grain.

Roll Spreading. Application of a film of a liquid material to a surface by means of rollers.

Room-Temperature-Setting Adhesive. (See **Adhesive.**)

Rot. (See **Decay.**)

Rotary-Cut Veneer. (See **Veneer.**)

Rough Lumber. (See **Lumber.**)

Sap Stain. (See **Stain.**)

Sapwood. The wood of pale color near the outside of the log. Under most conditions, the sapwood is more susceptible to decay than heartwood.

Sash. A frame structure, normally glazed (such as a window), that is hung or fixed in a frame set in an opening.

Sawn Veneer. (See **Veneer.**)

Saw Kerf. (1) Grooves or notches made in cutting with a saw. (2) That portion of a log, timber, or other piece of wood removed by the saw in parting the material into two pieces.

Scarf Joint. (See **Joint.**)

Schedule, Kiln Drying. A prescribed series of dry- and wet-bulb temperatures and air velocities used in drying a kiln charge of lumber or other wood products.

Seasoning. Removing moisture from green wood to improve its serviceability.

Air Dried—Dried by exposure to air in a yard or shed, without artificial heat.

Kiln Dried—Dried in a kiln with the use of artificial heat.

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Second Growth. Timber that has grown after the removal, whether by cutting, fire, wind, or other agency, of all or a large part of the previous stand.

Semitransparent Stain. A suspension of pigments in either a drying oil–organic solvent mixture or a water–polymer emulsion, designed to color and protect wood surfaces by penetration without forming a surface film and without hiding wood grain.

Set. A permanent or semipermanent deformation. In reference to adhesives, to convert an adhesive into a fixed or hardened state by chemical or physical action, such as condensation, polymerization, oxidation, vulcanization, gelation, hydration, or evaporation of volatile constituents.

Shake. A separation along the grain, the greater part of which occurs between the rings of annual growth. Usually considered to have occurred in the standing tree or during felling.

Shakes. In construction, shakes are a type of shingle usually hand cleft from a bolt and used for roofing or weatherboarding.

Shaving. A small wood particle of indefinite dimensions developed incidental to certain woodworking operations involving rotary cutterheads usually turning in the direction of the grain. This cutting action produces a thin chip of varying thickness, usually feathered along at least one edge and thick at another and generally curled.

Shear. In an adhesively bonded joint, stress, strain, or failure resulting from applied forces that tends to cause adjacent planes of a body to slide parallel in opposite directions.

Sheathing. The structural covering, usually of boards, building fiberboards, plywood, or oriented strandboard, placed over exterior studding or rafters of a structure.

Shelf Life. (See **Storage Life.**)

Shiplapped Lumber. (See **Lumber.**)

Shipping-Dry Lumber. (See **Lumber.**)

Shop Lumber. (See **Lumber.**)

Side Grained. (See **Grain.**)

Side Lumber. (See **Lumber.**)

Siding. The finish covering of the outside wall of a frame building, whether made of horizontal weatherboards, vertical boards with battens, shingles, or other material.

Slash Grained. (See **Grain.**)

Sliced Veneer. (See **Veneer.**)

Soft Rot. (See **Decay.**)

Softwoods. Generally, one of the botanical groups of trees that have no vessels and in most cases have needlelike or scalelike leaves, the conifers, also the wood produced by

such trees. The term has no reference to the actual hardness of the wood.

Solid Color Stains (Opaque Stains). A suspension of pigments in either a drying oil–organic solvent mixture or a water–polymer emulsion designed to color and protect a wood surface by forming a film. Solid color stains are similar to paints in application techniques and in performance.

Solids Content. The percentage of weight of the nonvolatile matter in an adhesive.

Solvent Adhesive. (See **Adhesive.**)

Sound Knot. (See **Knot.**)

Specific Adhesion. Adhesion between surfaces that are held together by valence forces of the same type as those that give rise to cohesion.

Specific Gravity. As applied to wood, the ratio of the oven-dry weight of a sample to the weight of a volume of water equal to the volume of the sample at a specified moisture content (green, air dry, or oven-dry).

Spike Knot. (See **Knot.**)

Spiral Grained. (See **Grain.**)

Spread. The quantity of adhesive per unit joint area applied to an adherend. (See **Lbs/MSGL.**)

Single spread—Refers to application of adhesive to only one adherend of a joint.

Double spread—Refers to application of adhesive to both adherends of a joint.

Squeezeout. Bead of adhesive squeezed out of a joint when pressure is applied.

Stain. A discoloration in wood that may be caused by such diverse agencies as micro-organisms, metal, or chemicals. The term also applies to materials used to impart color to wood.

Blue Stain—A bluish or grayish discoloration of the sapwood caused by the growth of certain dark-colored fungi on the surface and in the interior of the wood; made possible by the same conditions that favor the growth of other fungi.

Brown Stain—A rich brown to deep chocolate-brown discoloration of the sapwood of some pines caused by a fungus that acts much like the blue-stain fungi.

Chemical Brown Stain—A chemical discoloration of wood, which sometimes occurs during the air drying or kiln drying of several species, apparently caused by the concentration and modification of extractives.

Sap Stain—A discoloration of the sapwood caused by the growth of certain fungi on the surface and in the interior of the wood; made possible by the same conditions that favor the growth of other fungi.

Sticker Stain—A brown or blue stain that develops in seasoning lumber where it has been in contact with the stickers.

Starved Joint. (See **Joint.**)

Static Bending. Bending under a constant or slowly applied load; flexure.

Staypak. Wood that is compressed in its natural state (that is, without resin or other chemical treatment) under controlled conditions of moisture, temperature, and pressure that practically eliminate springback or recovery from compression. The product has increased density and strength characteristics.

Stickers. Strips or boards used to separate the layers of lumber in a pile and thus improve air circulation.

Sticker Stain. (See **Stain.**)

Storage Life. The period of time during which a packaged adhesive can be stored under specific temperature conditions and remain suitable for use. Sometimes called shelf life.

Straight Grained. (See **Grain.**)

Strand. (1) A type of wood flake with a high aspect ratio which allows for orientation. It is used in oriented strand board, oriented strand lumber, and laminated strand lumber. (2) A wood element with a high aspect ratio manufactured from veneer. It is used in parallel strand lumber.

Strength. (1) The ability of a member to sustain stress without failure. (2) In a specific mode of test, the maximum stress sustained by a member loaded to failure.

Strength Ratio. The hypothetical ratio of the strength of a structural member to that which it would have if it contained no strength-reducing characteristics (such as knots, slope-of-grain, shake).

Stress-Wave Timing. A method of measuring the apparent stiffness of a material by measuring the speed of an induced compression stress as it propagates through the material.

Stressed-Skin Construction. A construction in which panels are separated from one another by a central partition of spaced strips with the whole assembly bonded so that it acts as a unit when loaded.

Stringer. A timber or other support for cross members in floors or ceilings. In stairs, the support on which the stair treads rest.

Structural Composite Lumber (SCL). (Wood elements glued together to form products that are similar in size to solid-sawn lumber)

Laminated Strand Lumber (LSL)—Similar to oriented strand lumber with somewhat longer strands.

Laminated Veneer Lumber (LVL)—Structural composite lumber manufactured from veneers laminated

into a panel with the grain of all veneer running parallel to each other. The resulting panel is ripped to common lumber dimensions.

Oriented Strand Lumber (OSL)—Structural composite lumber made from wood strand elements similar to those used in oriented strand board. The strands are oriented primarily along the length of the member.

Parallel Strand Lumber (PSL)—Structural composite lumber made from high aspect ratio wood strand elements manufactured from veneer oriented primarily along the length of the member. It is manufactured in billets and cut to lumber dimensions.

Structural Lumber. (See **Lumber.**)

Structural Timbers. Pieces of wood of relatively large size, the strength or stiffness of which is the controlling element in their selection and use. Examples of structural timbers are trestle timbers (stringers, caps, posts, sills, bracing, bridge ties, guardrails); car timbers (car framing, including upper framing, car sills); framing for building (posts, sills, girders); ship timber (ship timbers, ship decking); and crossarms for poles.

Stud. One of a series of slender wood structural members used as supporting elements in walls and partitions.

Substrate. A material upon the surface of which an adhesive-containing substance is spread for any purpose, such as bonding or coating. A broader term than adherend. (See **Adherend.**)

Surface Inactivation. In adhesive bonding to wood, physical and chemical modifications of the wood surface that result in reduced ability of an adhesive to properly wet, flow, penetrate, and cure.

Surface Tension. The force per unit length acting in the surface of a liquid that opposes the increase in area of the liquid (spreading).

Surfaced Lumber. (See **Lumber.**)

Symmetrical Construction. Panels in which the plies on one side of a center ply or core are essentially equal in thickness, grain direction, properties, and arrangement to those on the other side of the core.

Tack. The property of an adhesive that enables it to form a bond of measurable strength immediately after adhesive and adherend are brought into contact under low pressure.

Tangential. Strictly, coincident with a tangent at the circumference of a tree or log, or parallel to such a tangent. In practice, however, it often means roughly coincident with a growth ring. A tangential section is a longitudinal section through a tree or limb perpendicular to a radius. Flat-grained lumber is sawed tangentially.

Temperature, Curing. The temperature to which an adhesive or an assembly is subjected to cure the adhesive. The

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temperature attained by the adhesive in the process of curing (adhesive curing temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature).

Temperature, Setting. (See **Temperature, Curing.**)

Tenon. A projecting member left by cutting away the wood around it for insertion into a mortise to make a joint.

Tension. In an adhesively bonded joint, a uniaxial force tending to cause extension of the assembly, or the counteracting force within the assembly that resists extension.

Tension Wood. Abnormal wood found in leaning trees of some hardwood species and characterized by the presence of gelatinous fibers and excessive longitudinal shrinkage. Tension wood fibers hold together tenaciously, so that sawed surfaces usually have projecting fibers and planed surfaces often are torn or have raised grain. Tension wood may cause warping.

Texture. A term often used interchangeably with grain. Sometimes used to combine the concepts of density and degree of contrast between earlywood and latewood. In this handbook, texture refers to the finer structure of the wood rather than the annual rings. (See also **Grain.**)

Thermoplastic. (1) Capable of being repeatedly softened by heat and hardened by cooling. (2) A material that will repeatedly soften when heated and harden when cooled.

Thermoset. A cross-linked polymeric material.

Thermosetting. Having the property of undergoing a chemical reaction by the action of heat, catalyst, ultraviolet light, and hardener, leading to a relatively infusible state.

Timbers, Round. Timbers used in the original round form, such as poles, piling, posts, and mine timbers.

Timber, Standing. Timber still on the stump.

Timbers. (See **Lumber.**)

Time, Assembly. The time interval between the spreading of the adhesive on the adherend and the application of pressure or heat, or both, to the assembly. (For assemblies involving multiple layers or parts, the assembly time begins with the spreading of the adhesive on the first adherend.)

Open Assembly Time—The time interval between the spreading of the adhesive on the adherend and the completion of assembly of the parts for bonding.

Closed Assembly Time—The time interval between completion of assembly of the parts for bonding and the application of pressure or heat, or both, to the assembly.

Time, Curing. The period during which an assembly is subjected to heat or pressure, or both, to cure the adhesive.

Time, Setting. (See **Time, Curing.**)

Toughness. A quality of wood that permits the material to absorb a relatively large amount of energy, to withstand repeated shocks, and to undergo considerable deformation before breaking.

Tracheid. The elongated cells that constitute the greater part of the structure of the softwoods (frequently referred to as fibers). Also present in some hardwoods.

Transfer. In wood bonding, the sharing of adhesive between a spread and an unspread surface when the two adherends are brought into contact.

Transverse. Directions in wood at right angles to the wood fibers. Includes radial and tangential directions. A transverse section is a section through a tree or timber at right angles to the pith.

Treenail. A wooden pin, peg, or spike used chiefly for fastening planking and ceiling to a framework.

Trim. The finish materials in a building, such as moldings, applied around openings (window trim, door trim) or at the floor and ceiling of rooms (baseboard, cornice, and other moldings).

Truss. An assembly of members, such as beams, bars, rods, and the like, so combined as to form a rigid framework. All members are interconnected to form triangles.

Twist. A distortion caused by the turning or winding of the edges of a board so that the four corners of any face are no longer in the same plane.

Tyloses. Masses of parenchyma cells appearing somewhat like froth in the pores of some hardwoods, notably the white oaks and black locust. Tyloses are formed by the extension of the cell wall of the living cells surrounding vessels of hardwood.

Ultrasonics. (See **Stress-Wave Timing.**)

van der Waal Forces. Physical forces of attraction between molecules, which include permanent dipole, induced dipole, hydrogen bond, and London dispersion forces.

Vapor Retarder. A material with a high resistance to vapor movement, such as foil, plastic film, or specially coated paper, that is used in combination with insulation to control condensation.

Veneer. A thin layer or sheet of wood.

Rotary-Cut Veneer—Veneer cut in a lathe that rotates a log or bolt, chucked in the center, against a knife.

Sawn Veneer—Veneer produced by sawing.

Sliced Veneer—Veneer that is sliced off a log, bolt, or flitch with a knife.

Vertical Grained. (See **Grain.**)

Vessel Elements. Wood cells in hardwoods of comparatively large diameter that have open ends and are set one above the other to form continuous tubes called vessels. The openings of the vessels on the surface of a piece of wood are usually referred to as pores.

Virgin Growth. The growth of mature trees in the original forests.

Viscoelasticity. The ability of a material to simultaneously exhibit viscous and elastic responses to deformation.

Viscosity. The ratio of the shear stress existing between laminae of moving fluid and the rate of shear between these laminae.

Wane. Bark or lack of wood from any cause on edge or corner of a piece except for eased edges.

Warp. Any variation from a true or plane surface. Warp includes bow, crook, cup, and twist, or any combination thereof.

Water Repellent. A liquid that penetrates wood that materially retards changes in moisture content and dimensions of the dried wood without adversely altering its desirable properties.

Water-Repellent Preservative. A water repellent that contains a preservative that, after application to wood and drying, accomplishes the dual purpose of imparting resistance to attack by fungi or insects and also retards changes in moisture content.

Weathering. The mechanical or chemical disintegration and discoloration of the surface of wood caused by exposure to light, the action of dust and sand carried by winds, and the alternate shrinking and swelling of the surface fibers with the continual variation in moisture content brought by changes in the weather. Weathering does not include decay.

Wet Strength. The strength of an adhesive joint determined immediately after removal from water in which it has been immersed under specified conditions of time, temperature, and pressure.

Wet-Bulb Temperature. The temperature indicated by the wet-bulb thermometer of a psychrometer.

Wettability. A condition of a surface that determines how fast a liquid will wet and spread on the surface or if it will be repelled and not spread on the surface.

Wetting. The process in which a liquid spontaneously adheres to and spreads on a solid surface.

White-Rot. (See **Decay.**)

Wood-Based Composite Panel. A generic term for a material manufactured from wood veneer, strands, flakes, particles, or fibers or other lignocellulosic material and a synthetic resin or other binder.

Cellulosic Fiberboard—A generic term for a low-density panel made from lignocellulosic fibers characterized by an integral bond produced by interfelting of the fibers, to which other materials may have been added during manufacture to improve certain properties, but which has not been consolidated under heat and pressure as a separate stage in manufacture; has a density of less than 496 kg m⁻³ (31 lb ft⁻³) (specific gravity 0.50) but more than 160 kg m⁻³ (10 lb ft⁻³) (specific gravity 0.16).

Exterior Plywood—A general term for plywood bonded with a type of adhesive that by systematic tests and service records has proved highly resistant to weather; microorganisms; cold, hot, and boiling water; steam; and dry heat.

Fiberboard—A generic term inclusive of panel products of various densities manufactured of refined or partially refined wood (or other lignocellulosic) fibers. Bonding agents may be added.

Flakeboard—A generic term indicating a manufactured panel product composed of flakes bonded with a synthetic resin.

Hardboard—A generic term for a panel manufactured primarily from interfelted lignocellulosic fibers (usually wood), consolidated under heat and pressure in a hot press to a density of 496 kg m⁻³ (31 lb ft⁻³) or greater. May be manufactured using either a dry-process or wet-process.

Interior Plywood—A general term for plywood manufactured for indoor use or in construction subjected to only temporary moisture. The adhesive used may be interior, intermediate, or exterior.

Medium-Density Fiberboard—A dry-process fiberboard manufactured from lignocellulosic fibers combined with a synthetic resin or other suitable binder. The panels are manufactured to a density of 496 kg m⁻³ (31 lb ft⁻³) (0.50 specific gravity) to 880 kg m⁻³ (55 lb ft⁻³) (0.88 specific gravity) by the application of heat and pressure by a process in which the interfiber bond is substantially created by the added binder.

Oriented Strandboard—A type of flakeboard product composed of strand-type flakes that are purposefully aligned in directions that make a panel stronger, stiffer, and with improved dimensional properties in the alignment directions than a panel with random flake orientation.

Particleboard—A panel product manufactured from wood particles usually in three layers. For good surface characteristics, the outer layers have smaller particles and the interior uses coarser particles. The particles in the core may or may not be aligned.

Plywood—A glued wood panel made up of relatively thin layers of veneer with the grain of adjacent layers at right

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angles or of veneer in combination with a core of lumber or of reconstituted wood. The usual constructions have an odd number of layers.

Wood Failure. The rupturing of wood fibers in strength tests of bonded joints usually expressed as the percentage of the total area involved that shows such failure. (See **Failure, Adherend.**)

Wood Flour. Wood reduced to finely divided particles, approximately the same as those of cereal flours in size, appearance, and texture, and passing a 40 to 100 mesh screen.

Wood Substance. The solid material of which wood is composed. It usually refers to the extractive-free solid substance of which the cell walls are composed, but this is not always true. There is not a wide variation in chemical composition or specific gravity between the wood substance of various species. (The characteristic differences of species are largely due to differences in extractives and variations in relative amounts of cell walls and cell cavities.)

Wood-Thermoplastic Composite. Manufactured composite materials consisting primarily of wood elements and thermoplastic. The wood element may either serve as a reinforcement or filler in a continuous thermoplastic matrix, or the thermoplastic may act as a binder to the wood element.

Wood Wool. Long, curly, slender strands of wood used as an aggregate component for some particleboards and cement-bonded composites. Sometimes referred to as excelsior.

Workability. The degree of ease and smoothness of cut obtainable with hand or machine tools.

Working Life. The period of time during which an adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains suitable for use. Also called pot life.

Working Properties. The properties of an adhesive that affect or dictate the manner of application to the adherends to be bonded and the assembly of the joint before pressure application (such as viscosity, pot life, assembly time, setting time).

Xylem. The portion of the tree trunk, branches, and roots that lies between the pith and the cambium (that is the wood).

Yard Lumber. (See **Lumber.**)

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