Finishing of Wood

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Contents

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 then 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

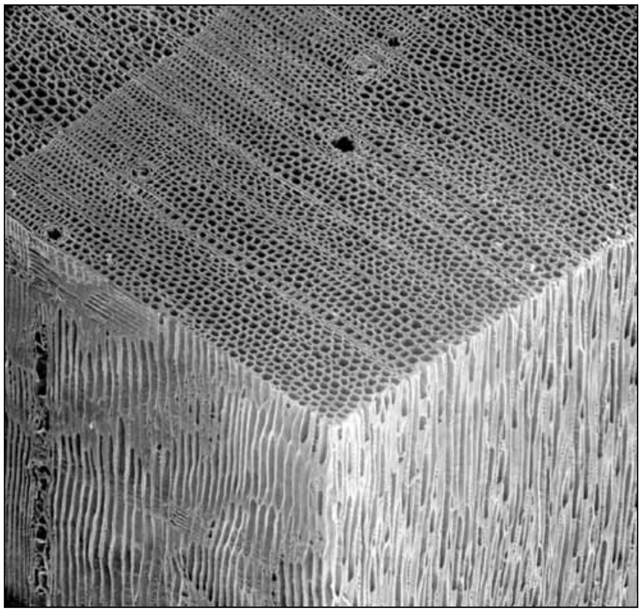

Figure 16–1. Micrograph of white spruce showing gradual transition of cell wall thickness and resin canal complexes. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

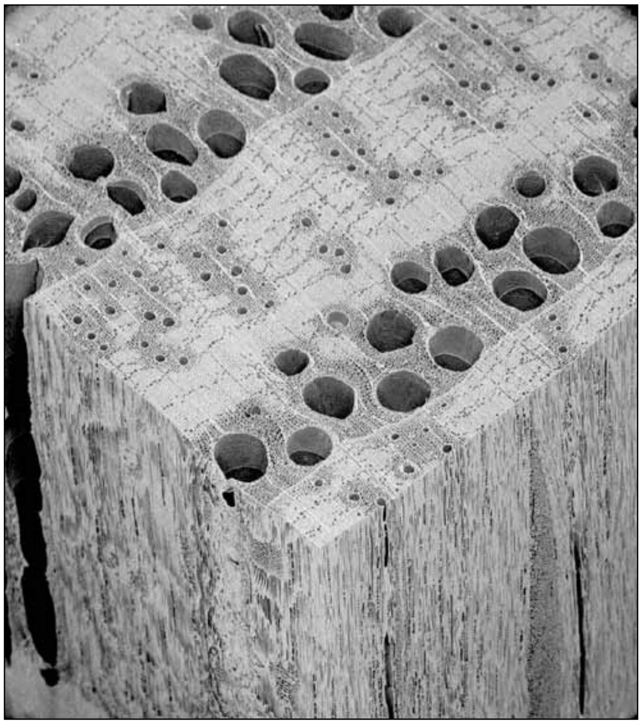

Figure16–2. Micrograph of red oak showing ring-porous vessels. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

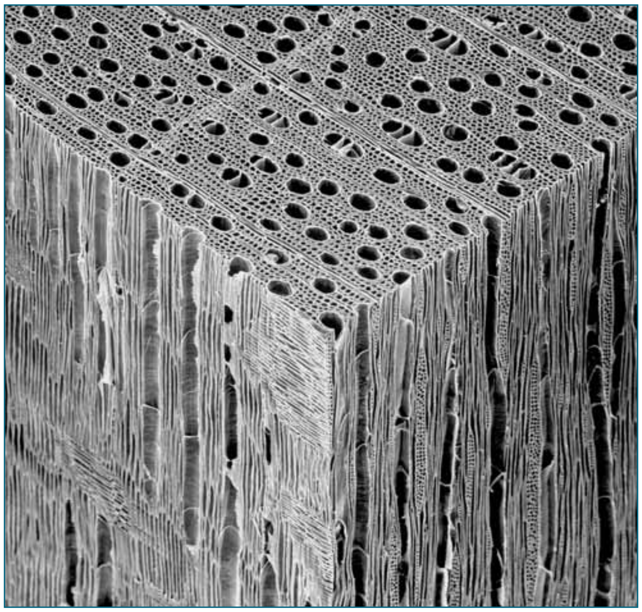

Figure 16–3. Micrograph of red maple showing diffuse-porous vessels. (Micrographs prepared by H.A. Core, W.A. Côté, and A.C. Day. Copyright by N.C. Brown Center for Ultrastructure Studies, College of Environmental Science and Forestry, State University of New York, Syracuse, New York. Used with permission.)

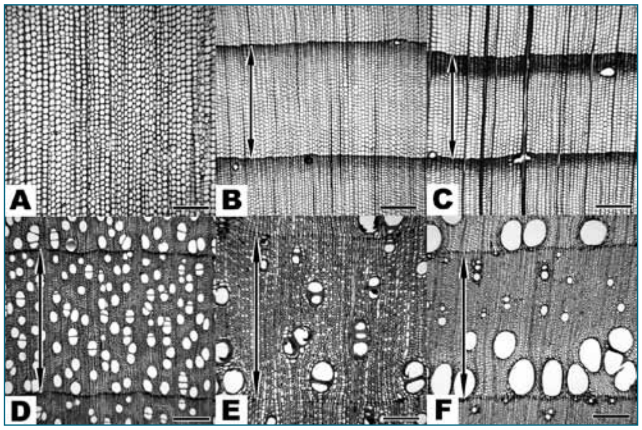

Figure 16–4. Cross-section micrographs of (A) a tropical softwood (*Podocarpus imbricate*), (B) white spruce (*Picea glauca*), (C) Douglas-fir, *Pseudotsuga menziesii* (D) sugar maple (*Acer saccharum*), (E) persimmon (*Diospyros virginiana*), and (F) white ash (*Fraxinus americana*). The arrows show 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.

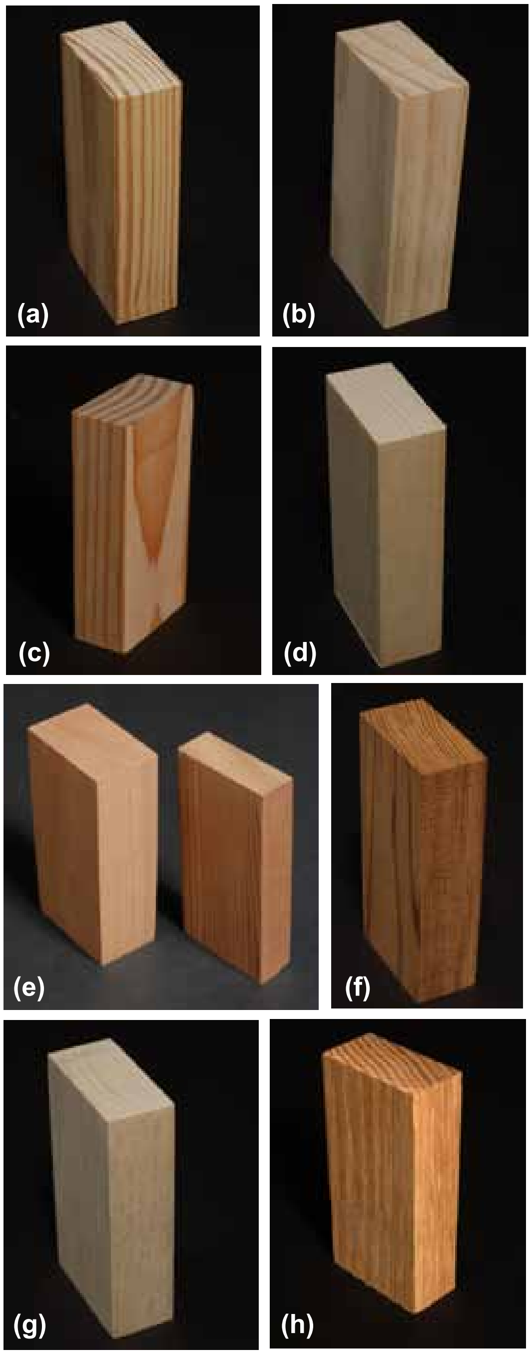

Figure 16–5. Wide LW bands characteristic of (a) the southern yellow pines, (b) radiata pine, and (c) Douglas-fir and narrow LW bands characteristic of (d) white pine, (e) redwood, and (f) western redcedar; (g) and (h) are examples of the difference in surface texture between diffuse-porous and ring 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 ovendry (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

[a] Specific gravity based on weight ovendry and volume at green or 12% moisture content.

[b] Dimensional change obtained by drying from green to ovendry. Values reported here are averages from a variety of sources and are provided for comparative purposes. For more specific values, see Chapter 4.

[c] I, easy to finish; III, difficult to finish.

[d] A, abrupt-transition softwood; G, gradual-transition softwood; R, ring-porous hardwood; D, diffuse-porous hardwood; SR, semi-ring-porous hardwood.

[e] GR, 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.

[f] Lumber and plywood.

[g] Coastal Douglas-fir.

[h] Loblolly, shortleaf; specific gravity of 0.54/0.59 for longleaf and slash.

[i] Redwood is listed as paintability "I" because its LW band is very narrow.

[j] Spruce. Values are for Engelmann spruce; other species are similar.

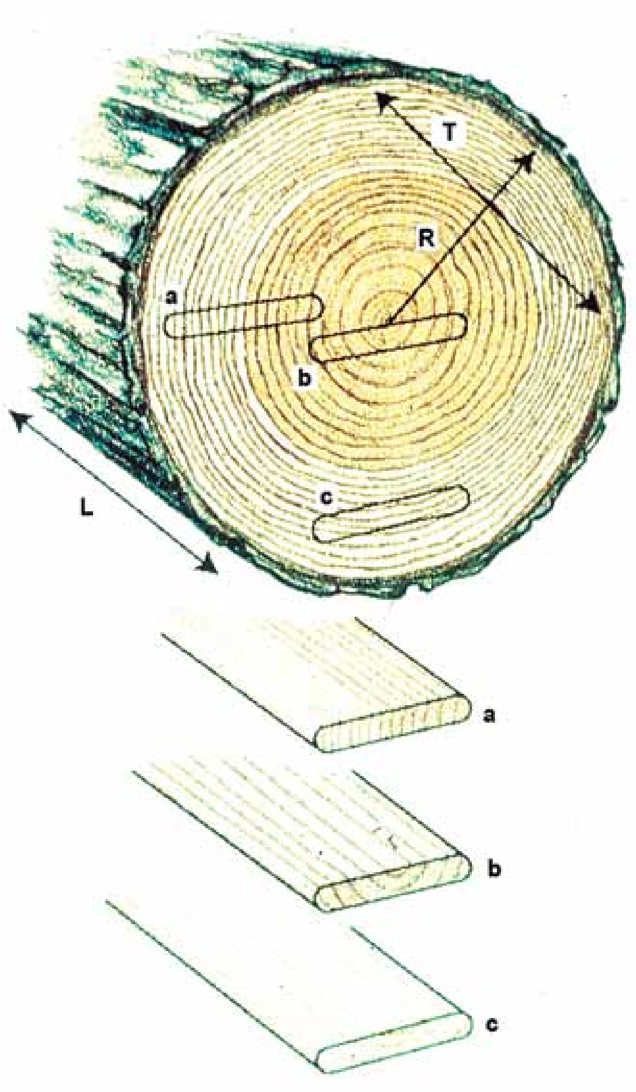

Figure 16–6. Lumber grain affects finish performance: (a) edge-grain (vertical-grain or quartersawn) board; (b) edge-grain board containing pith; (c) flat-grain (slash-grain or plain-sawn) board. Arrows show radial (R), tangential (T), and longitudinal (L) orientation of wood grain.

Moisture

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.

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 ovendry 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 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 ovendry 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).

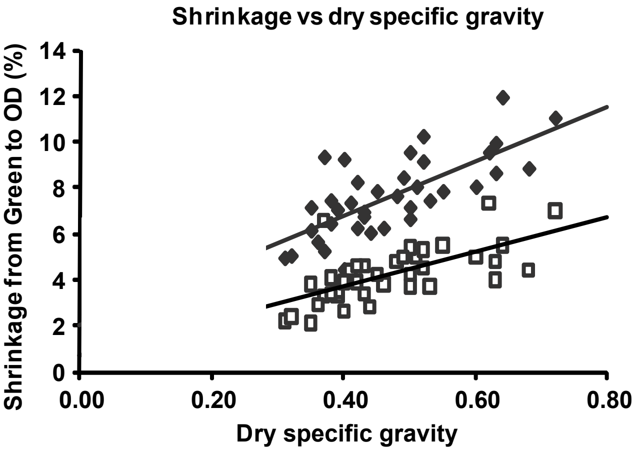

Figure 16–7. Plots of radial (□) and tangential (♦) shrinkage from green to oven dry (OD) as a function of specific gravity for various hardwoods and softwoods from Table 16–1. Lines show least-squares fit.

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.

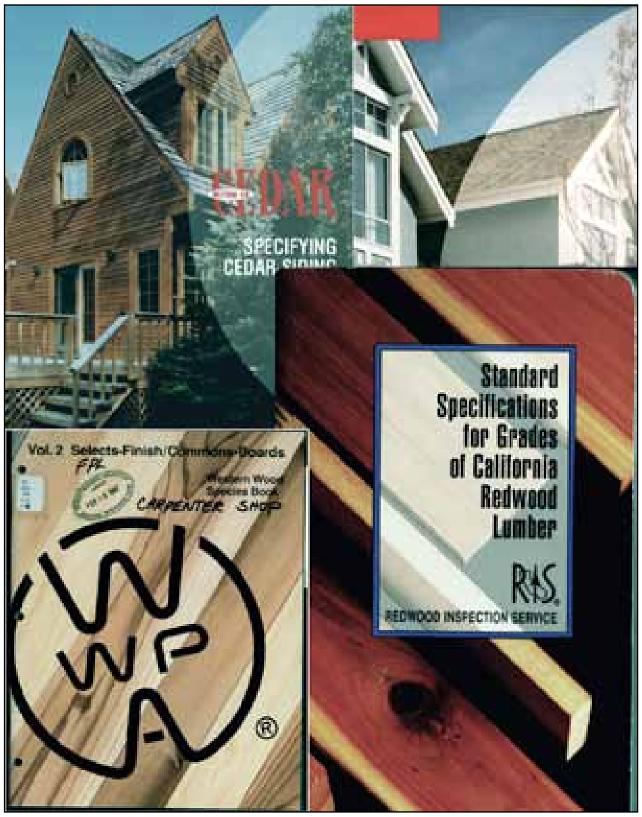

Figure 16–8. Examples of trade association brochures describing wood products.

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 semitransparent 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

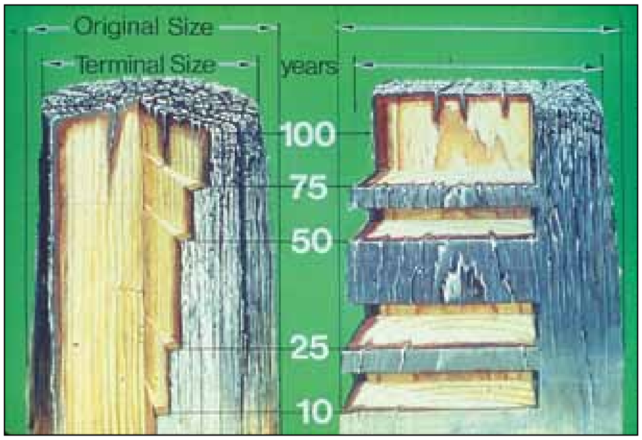

Figure 16–12. Artist's rendition of weathering process of round and square timbers. As cutaway shows, interior wood below surface is relatively unchanged.

(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 hydroscopic 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]

		Erosion (µm) after various exposure times[c]											
		4 years		8 years		10 years		12 years		14 years		16 years	
Wood species	Avg. SG[b]	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	—	—

[a] Data from three studies are shown. Specimens were exposed vertically facing south. Radial surfaces were exposed with the grain vertical. EW denotes earlywood; LW, latewood.
[b] SG is specific gravity.
[c] All 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

[a]Sapwood was initially finished and conditioned to 26 °C (80 °F) and 30% RH, then exposed to the same temperature and 90% RH.
[b]WRP would be about the same.

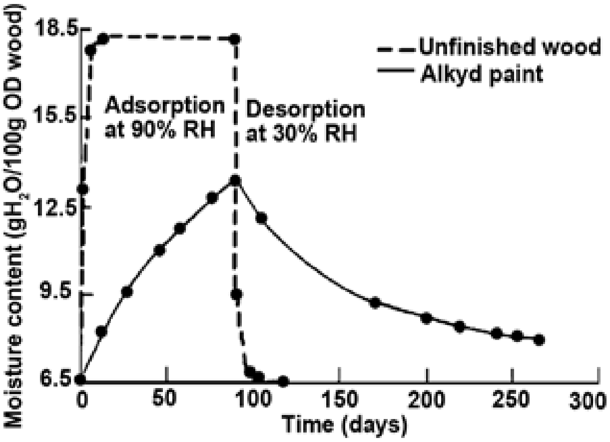

Figure 16–13. Change in moisture content of ponderosa pine sapwood finished with three coats of aliuminum-pigmented alkyd paint and exposed to 90% and 30% RH at 26 °C (80 °F), compared with moisture content of unfinished wood.

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 rainscreen 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 semitransparent 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]

	Tinted finishes such as deck finishes		Semitransparent stain		Paint and solid-color stain		
						Expected service life[d] (years)	
Type of exterior wood surface	Suitability	Expected service life[b] (years)	Suitability	Expected service life[c] (years)	Suitability	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

[a] Estimates 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).

[b] The higher the pigment concentration, the longer the service life. Mildew growth on surface usually indicates the need for refinishing.

[c] Smooth 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.

[d] Expected 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.

[e] Medium-density overlay (MDO) is painted.

[f] Edges are vulnerable to water absorption and need to be sealed.

[g] Water-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

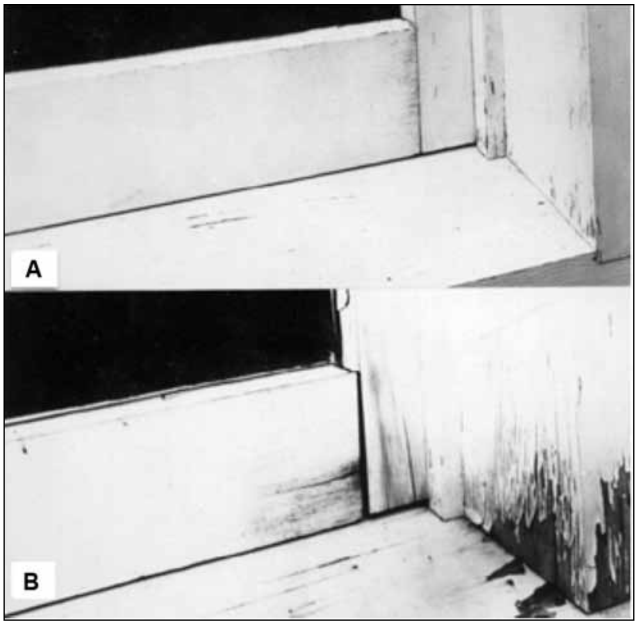

Figure 16–19. Effect of water-repellent preservative treatment after 5 years of outdoor exposure. A, window sash and frame treated with a water-repellent preservative and then painted; B, window sash and frame not treated before painting.

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 manufactures 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 of lumber, edges of plywood, and back-priming and are discussed in several sections of this chapter.

> 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.

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 $m^2\ L^{-1}$ (250 $ft^2\ gal^{-1}$) on a smooth surface or 3.7 $m^2\ L^{-1}$ (150 $ft^2\ gal^{-1}$) 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]

			Maintenance	
Finish	Application process	Appearance of wood	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[c]; 6–15 years for solid-color stain[e]

[a] Compilation of data from observations of many researchers.

[b] Vertical exposure; service life depends on surface preparation, climate and exposure, amount and quality of finish, and the wood species and its surface texture.

[c] Service 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.

[d] If 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).

[e] Service 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 $m^2\ L^{-1}$ (200 to 400 $ft^2\ gal^{-1}$) on smooth wood and from 2.4 to 4.9 $m^2\ L^{-1}$ (100 to 200 $ft^2\ gal^{-1}$) 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 l 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 inorganic 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 recommended 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 $m^2 L^{-1}$ (250 to 300 $ft^2 gal^{-1}$) 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 $m^2 L^{-1}$ (400 $ft^2 gal^{-1}$).

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 topcoats 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.

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, manufactures 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

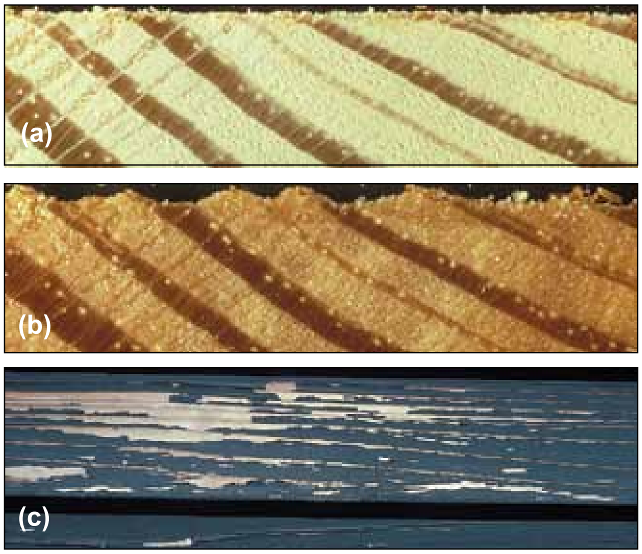

Figure 16–22. (a) Cross-section view of flat-grain southern yellow pine showing dense LW bands crushed into less dense EW directly beneath them; (b) raised grain caused by rebound of LW bands following wetting; (c) a thin coat of film-forming finish applied over a stressed flat-grain surface will crack 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.

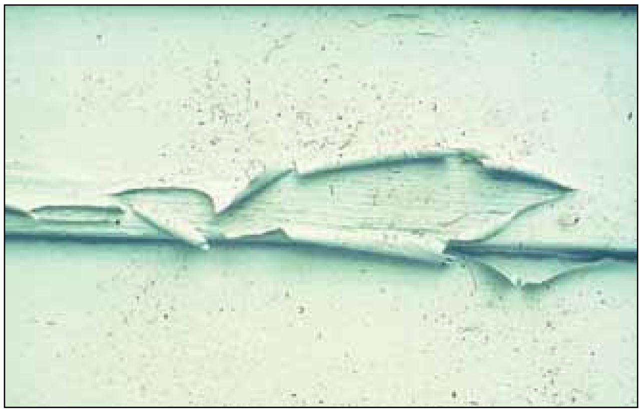

Figure 16–23. Intercoat peeling of paint, usually caused by poor preparation of old paint surface or excessive weathering of primer prior to application of top coat.

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) 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).

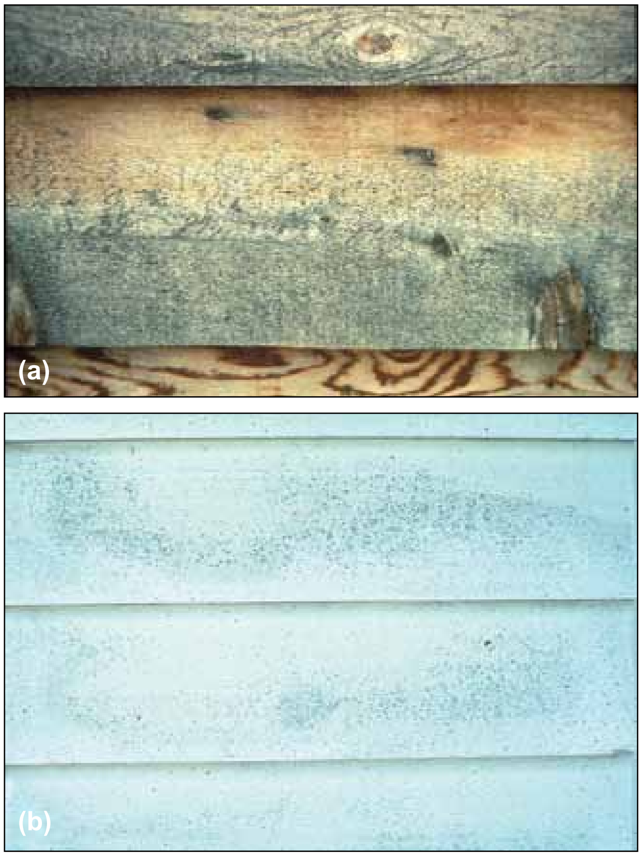

Figure 16–24. Mildew is most common in shaded, moist, or protected areas (a) on wood and (b) on painted wood.

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.

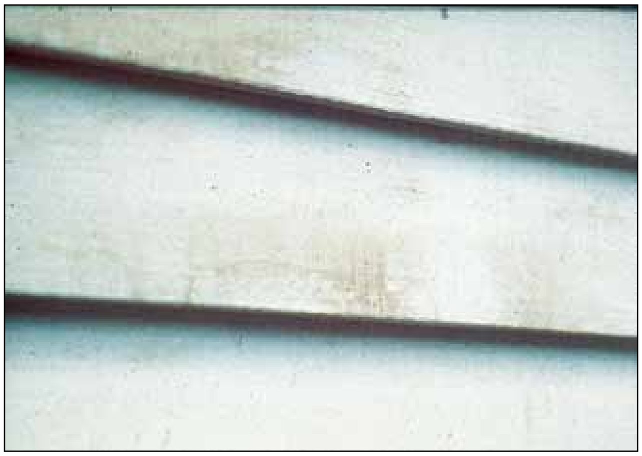

Figure 16–25. High moisture content of wood can cause diffuse extractives bleed, particularly if a stain-blocking primer is not used.

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.

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, 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 topcoat.

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.

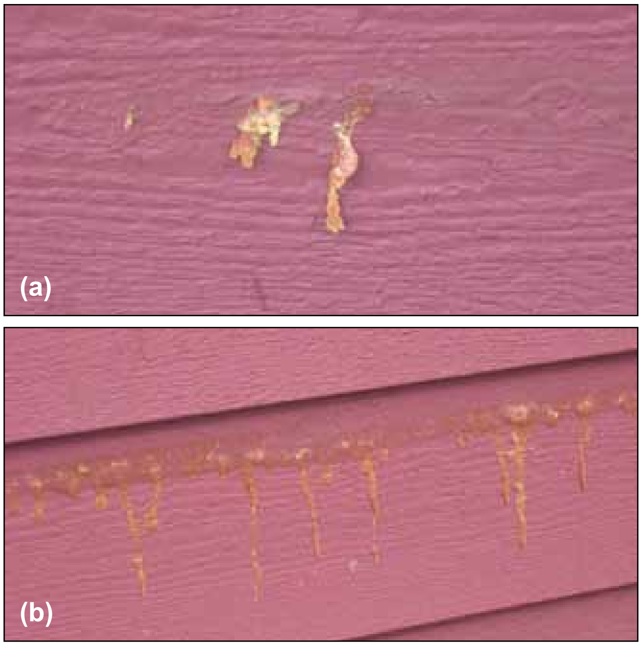

Figure 16–30. (a) Pitch exudation from an isolated spot; (b) pitch exudation from a large pocket or seam.

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 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 substrate. Apply varnish directly to wood or stain prior to varnishing.

Figure 16–31. Number 2 grade of hickory finished to accentuate the beauty of the various colors, knots, and grain pattern of this species.

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 ($2Na_2CO_3{\cdot}3H_2O_2$). 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 manufactures 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 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.

Literature Cited

AWPA. 2008. Book of standards. Birmingham, AL: American Wood Protection Association.

Sabin, A.H. 1927. Technology of paint and varnish. 3rd ed. London: John Wiley & Sons.

Schofield, M. 2008. Fine wood working. Newtown, CT: The Taunton Press. September/October (Issue 200): 52–58.

Wicks, Z.W., Jr.; Jones, F.N.; Pappas, S.P.; Wicks, D.A. 2007. Organic Coatings: Science and Technology. 3rd ed. Hoboken, NJ: John Wiley & Sons.

Additional References

APA. 1979. Stains and paints on plywood. Pamphlet B407B. Tacoma, WA: American Plywood Association.

Arnold, M.; Feist, W.C.; Williams, R.S. 1992. Effect of weathering of new wood on the subsequent performance of semitransparent stains. Forest Products Journal. 42(3): 10–14.

ASTM. 2003. Standard specification for zinc coating (hot-dip) on iron and steel hardware. A 153/A 153M–01a. West Conshohocken, PA: ASTM International. 1(6).

Black, J.M.; Mraz, E.A. 1974. Inorganic surface treatments for weather-resistant natural finishes. Res. Pap. FPL–232. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 44 p.

Bussjaeger, S.; Daisey, G.; Simmons, R.; Spindel, S.; Williams, S. 1999. Mildew and mildew control for wood surfaces. JCT Coatings Tech. 71(890): 67–69.

Cassens, D.L.; Feist, W.C. 1980a. Wood finishing: finishing exterior plywood, hardboard and particle board. North Central Region Extension Pub. 132. West Lafayette, IN: Purdue University, Cooperative Extension Service.

Cassens, D.L.; Feist, W.C. 1980b. Wood finishing: paint failure problems and their cure. North Central Region Extension Pub. 133. West Lafayette, IN: Purdue University, Cooperative Extension Service.

Cassens, D.L.; Feist, W.C. 1980c. Wood finishing: discoloration of house paint—causes and cures. North Central Region Extension Pub. 134. West Lafayette, IN: Purdue University, Cooperative Extension Service.

Cassens, D.L.; Feist, W.C. 1980d. Wood finishing: selection and application of exterior finishes for wood. North Central Region Extension Pub. 135. West Lafayette, IN: Purdue University, Cooperative Extension Service.

Cassens, D.L.; Feist, W.C. 1980e. Wood finishing: finishing and maintaining wood floors. North Central Region Extension Pub. 136. West Lafayette, IN: Purdue University, Cooperative Extension Service.

Daniels, T.; Hirsch, M.; McClelland, K.; Ross, A.; Williams, R.S. 2004. Clear exterior finishes: finding the balance between aesthetics and durability. JCT Coatings Tech. 1(9): 42–48.

Feist, W.C. 1979. Protection of wood surfaces with chromium trioxide. Res. Pap. FPL–339. Madison, WI: U.S.

Department of Agriculture, Forest Service, Forest Products Laboratory. 11 p.

Feist, W.C. 1982a. Weathering characteristics of finished wood-based panel products. JCT Coatings Tech. 54(686): 43–50.

Feist, W.C. 1982b. Weathering of wood in structural uses. In: Meyer, R.W.; Kellogg, R.M., eds. Structural use of wood in adverse environments. New York: Van Nostrand Reinhold Company. 156–178.

Feist, W.C. 1990. Outdoor wood weathering and protection. In: Rowell, R., ed. Archaeological wood, properties, chemistry, and preservation. Advanced in Chemistry Series No. 225. Washington, DC: American Chemical Society: 263–298. Chapter 11.

Feist, W.C. 1996. Finishing exterior wood. Federation Series on Coatings Technology. Blue Bell, PA: Federation of Societies for Coatings Technology.

Feist, W.C.; Hon, D.N.–S. 1984. Chemistry of weathering and protection. In: Rowell, R.M., ed. The chemistry of solid wood. Advances in Chemistry Series No. 207. Washington, DC: American Chemical Society: 401–451. Chapter 11.

Feist, W.C.; Mraz, E.A. 1980. Performance of mildewcides in a semitransparent stain wood finish. Forest Products Journal. 30(5): 43–46.

Feist, W.C.; Ross, A.S. 1995. Performance and durability of finishes on previously coated CCA-treated wood. Forest Products Journal. 45(9): 29–36.

Feist, W.C.; Williams, R.S. 1991. Weathering durability of chromium treated Southern Pine. Forest Products Journal. 41(1): 8 14.

Gorman, T.M.; Feist, W.C. 1989. Chronicle of 65 years of wood finishing research of the Forest Products Laboratory. Gen. Tech. Rep. FPL–GTR–60. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Jourdain, C.; Dwyer, J.; Kersall, K.; Mall, D.; Springate, R.; Williams, S. 1999. Changing nature of wood products—what does it mean for coatings and finish performance? JCT Coatings Tech. 71(890): 61–66.

Kalnins, M.A.; Feist, W.C. 1993. Increase in wettability of wood with weathering. Forest Products Journal. 43(2): 55–57.

Kiguchi, M.; Evans, P.D.; Ekstedt, J.; Williams, R.S.; Kataoka, Y. 2001. Improvement of the durability of clear coatings by grafting of UV-absorbers on to wood. Surface Coatings International Part B: Coatings Transactions. 84(B4): 263–270.

Mall, D.D.; Bonura, T.; Bussjaeger, S.; Carll, C.; Panila, D.; Williams, R.S. 2004. Frequently asked questions: wood and coatings applications. JCT Coatings Tech. 1(3): 36–49.

McDonald, K.A.; Falk, R.H.; Williams, R.S.; Winandy, J.E. 1996. Wood decks: materials, construction, and finishing. Madison, WI: Forest Products Society. 94 p.

Miller, R.B.; Wiedenhoeft, A.C.; Williams, R.S.; Stockman, W.; Green, F. 2003. Characteristics of ten tropical hardwoods from certified forests in Bolivia: part II, natural durability to decay fungi. Wood and Fiber Science. 35(3): 429–433.

Niemiec, S.S.; Brown, T.D. 1988. Care and maintenance of wood shingle and shake roofs. Corvallis, OR: Oregon State University Extension Service. EC 1271. (September).

Richter, K.; Feist, W.C.; Knaebe, M.T. 1995. The effect of surface roughness on the performance of finishes. Part 1. Roughness characterization and stain performance. Forest Products Journal. 45(7/8): 91–97.

Ross, A.; Daisey, G.; Jourdain, C.; Williams, R.S. 1998. Cleaners and restorers for wood decks. The Paint Dealer. (April): 30–33.

Ross, A.S.; Feist, W.C. 1993. The effects of CCA-treated wood on the performance of surface finishes. American Paint and Coatings Journal. 78(9): 41–54.

Ross, A.S.; Bussjaeger, R.C.; Feist, W.C. 1992. Professional finishing of CCA-pressure-treated wood. American Painting Contractor. 69(7): 107–114.

Sell, J.; Feist, W.C. 1986. Role of density in the erosion of wood during weathering. Forest Products Journal. 36(3): 57–60.

Simpson, W.T., ed. 1991. Dry kiln operator’s manual. Agric. Handb. 188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 274 p.

Tichy, R.J. 1997. Interior wood finishing: industrial use guide. Madison, WI: Forest Products Society. 113 p.

USDA. 1998. Rehabilitation of wood-frame houses. Agric. Handb. 804. Washington, DC: U.S. Department of Agriculture, Forest Service. 240 p.

WDMA. 1999. Industry standard for water-repellent preservative treatment for millwork. IS4–99. Des Plaines, IL: Window and Door Manufacturer’s Association.

Williams, R.S. 1986. Effects of acid rain on painted wood surfaces: importance of the substrate. In: Baboian, R., ed. Materials degradation caused by acid rain. ACS Symposium Series 318. Washington, DC: American Chemical Society: 310–331.

Williams, R.S. 1990a. Acidic deposition: state of science and technology. In: Effects of acidic deposition on materials.

Report 19. National Acid Precipitation Assessment Program. 19/165 19/202. Vol. 3.

Williams, R.S. 1990b. Effects of acidic deposition on painted wood. In: Effects of acidic deposition on materials. State of Science and State of Technology, Report 19. National Acid Precipitation Assessment Program: 19/165–19/202. Vol. 3.

Williams, R.S. 1991. Effects of acidic deposition on painted wood: a review. JCT Coatings Tech. 63(800): 53 73.

Williams, R.S. 2005. Weathering of wood. In: Rowell, R.M., ed. Handbook of Wood Chemistry and Wood Composites. Boca Raton: CRC Press. Chapter 7.

Williams, R.S.; Feist, W.C. 1993a. Durability of paint or solid-color stain applied to preweathered wood. Forest Products Journal. 43(1): 8–14.

Williams, R.S.; Feist, W.C. 1993b. Effect of weathering of wood prior to finishing on paint bond strength and durability. In: Proceedings of the Polymeric Materials Science and Engineering Division. Denver, CO: American Chemical Society Spring Meeting. 1993; March 29 April 2.

Williams, R.S.; Feist, W.C. 1994. Effect of preweathering, surface roughness, and wood species on the performance of paint and stains. JCT Coatings Tech. 66(828): 109–121.

Williams, R.S.; Feist, W.C. 1999. Selection and application of exterior stains for wood. Gen. Tech. Rep. FPL–GTR–106. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 1–9.

Williams, R.S.; Feist, W.C. 1999. Water repellent and water repellent preservative finishes for wood. Gen. Tech. Rep. FPL–GTR–109. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 1–12.

Williams, R.S.; Feist, W.C. 2001. Duration of wood preweathering: effect on the service life of subsequently applied paint. JCT Coatings Tech. 73(930): 65–72.

Williams, R.S.; Feist, W.C. 2004. The service life of semitransparent stain, solid color stain, and latex paint on yellow-poplar and sweetgum plywood and the effect of these finishes on wood durability. Forest Products Journal. 54(7/8): 96–101.

Williams, R.S.; Knaebe, M. 2000. Restoration of severely weathered wood. JCT Coatings Tech. 72(902): 43–51.

Williams, R.S.; Knaebe, M.T.; Feist, W.C. 1996. Finishes for exterior wood. Madison, WI: Forest Products Society.

Williams, R.S.; Miller, R.B.; Gangstad, J. 2001. Characteristics of ten tropical hardwoods from certified forests in Bolivia: part I, weathering characteristics and dimensional stability. Wood and Fiber Science. 33(4): 618–626.

Williams, R.S.; Plantinga, P.L.; Feist, W.C. 1990. Photodegradation of wood affects paint adhesion. Forest Products Journal. 40(1): 45–49.

Williams, R.S.; Sotos, P.; Feist, W.C. 1999. Evaluation of several paint systems on severely weathered wood. JCT Coatings Tech. 71(895): 97–102.

Williams, R.S.; Winandy, J.E.; Feist, W.C. 1987a. Adhesion of paint to weathered wood. Forest Products Journal. 37(11/12): 29–31.

Williams, R.S.; Winandy, J.E.; Feist, W.C. 1987b. Paint adhesion to weathered wood. JCT Coatings Tech. 59(749): 43–49.

Williams, R.S.; Winandy, J.E.; Feist, W.C. 2002. Correlation of adhesive strength with service life of paint applied to weathered wood. Paper 161. In: Proceedings, 9th durability of building materials and components conference. Brisbane, Australia: 17–20 March.

Williams, R.S.; Jourdain, C.; Daisey, G.; Springate, R.W. 2000. Wood properties affecting finish service life. JCT Coatings Tech. 72(902): 35–42.

Williams, R.S.; Knaebe, M.T.; Evans, J.W.; Feist, W.C. 2001. Erosion rates of wood during natural weathering: part III, effect of exposure angle on erosion rates. Wood and Fiber Science. 33(1): 50–57.

Williams, R.S.; Knaebe, M.T.; Sotos, P.G.; Feist, W.C. 2001. Erosion rates of wood during natural weathering: part I, effect of grain angle and surface texture. Wood and Fiber Science. 33(1): 33–42.

Williams, R.S.; Lacher, S.; Halpin, C.; White, C. 2005. Evaluating weather factors and material response during outdoor exposure to determine accelerated test protocols for predicting service life. In: Martin, J.W.; Ryntz, R.A.; Dickie, R.A., eds. Service Life Prediction, Challenging the Status Quo, Federation of Societies for Coatings Technology. Proceedings, 3rd international symposium on service life prediction. Sedona, AZ. 2004 February 1–6.

Williams, R.S.; Ross, A.S.; Sotos, P.; Cheeks, C.N. 2001. Water-repellent preservative treatment of brick molding prior to factory priming improves paint service life. In: Proceedings of the annual meeting of the American Wood Preserver's Association. (Vol. 97): 65–67.