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TESTING PAINTED WOOD: PAST PRACTICES AND RECOMMENDATIONS

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Summary

A brief history of paint research at the Forest Products Laboratory (Madison, Wisconsin) sets the stage for a discussion of testing paint on wood and wood products. Tests include laboratory and outdoor tests and I discuss them in terms of several degradation mechanisms (fading and loss of gloss, mildew growth, extractives bleed, and cracking, flaking, and peeling). The paper is not a review of standard tests, but rather my opinion and recommendations for developing testing programs to predict paint service life quickly and reliably.

1. Introduction

Materials testing, particularly testing paint performance on wood, is not "Rocket Science"—it's much more difficult! Think about the range of materials that you use:

- Varnish, tinted clears, semitransparent stain, solid color stain, paint, and two-part epoxies and urethanes
- Water-borne formulations, solvent-borne formulations
- Hardwoods
  - From balsa (*Ochroma pyramidale*), specific gravity (sg), 0.1 to
  - Ipe (*Tabebuia* genus), sg, 1.0
- Softwoods
  - From western redcedar (*Thuja plicata*), sg, 0.3 to
  - Loblolly pine (*Pinus taeda*), sg, 0.5
- Grain angle
  - Flat grain (flat sawn)
  - Vertical grain (quarter sawn)
- Wood Products
  - Lumber
  - Composites
  - Fiberboard

Note that the list of materials doesn't include application—complex variables that can effect finish performance more than materials interactions!

The number of combinations isn't infinite, but it's a really-really-big number. Testing all combinations is impossible. In fact, testing a specific finish is impossible even on a small fraction of wood species and composite wood products that consumers may paint. However, selecting substrate/finish combinations to yield paint performance information that is applicable to most anticipated uses is possible. The trick is to focus on a substrate or substrates that stress the coating in a way that represents stresses on coatings in service and develop laboratory tests to target specific types of degradation and the mechanism(s) causing the degradation. This is not easy! If one is not careful, a test that is supposed to test paint may actually test wood. For example, a few years ago, Bill Feist and I reported the results of several finishes on yellow poplar (*Liriodendron tulipifera*) and sweetgum (*Liquidambar styraciflua* L.) plywood (Williams and Feist 2004). As expected, paint lasted longer than semitransparent stain. In fact, the paint was in almost perfect condition after 12 years, whereas the semitransparent stain had completely weathered from the plywood surface, leaving a sound plywood panel (the wood was in almost perfect condition). The plywood under the "perfect" paint was badly decayed. Was the test designed to determine paint performance or wood durability? In that case, it was both. We reported interactions between wood durability and paint service life.

Following a brief review of wood properties that affect finish performance and an overview of finishing research at the Forest Products Laboratory (FPL), I introduce the concept of the "bathtub" plot. This concept is used to guide my discussion of methods for testing paint on wood. In some cases, the methods are already being used at FPL and other laboratories; in other cases, the methods are my opinions and suggestions for future work. This paper includes several topics:

- Overview of wood properties
- Background on the Forest Products Laboratory (FPL)
- Highlights from wood/paint research at FPL
- Effects of juvenile failure on the "20-year warranty"
- Analysis of various types of finish degradation (gloss, fade, mildew resistance, cracking, flaking, peeling, and film integrity)
- Recent studies at FPL
- Artificial weathering

2. Wood Properties

Wood Anatomy

Wood cell structure and thus anatomy of a wood species determine surface properties of wood, properties that affect adhesion and performance of finishes. As a tree grows, wood cells form under the bark of the stem or branch. Two types of cells form in softwoods (axial tracheids and ray cells) and three types of cells form in hardwoods (axial fibers, ray cells, and vessels). Cell structure determines whether a wood species is a hardwood or softwood, not the density (specific gravity) or its hardness. In the early part of the growing season in temperate climates, softwood axial tracheids have large open centers (lumina) and thin cell walls; this is earlywood (EW, formerly referred to as springwood). As the growing season progresses, cell walls become thicker and darker, forming latewood (LW, formerly called summerwood). In hardwoods, vessels form along with the axial fibers. Vessels formed throughout the growing season (i.e., in EW and LW) having about the same diameter give diffuse-porous hardwoods. Large-diameter vessels formed early in the growing season followed by small-diameter vessels later in the growing season give ring-porous hardwoods. Vessel size and placement may be between these two extremes to give semi-ring-porous hardwoods. As with softwood tracheids, hardwood LW fiber walls are thicker than EW fiber walls. Thus, LW has higher specific gravity than EW.

The combination of EW/LW (and vessels in hardwoods) gives annual growth rings. In lumber cut from a log, these growth rings determine grain angle and slope of grain of the lumber. Properties of these growth rings and the grain angle that they determine affect the ease with which finishes can be applied (paintability) and how long finishes last (service life). Figures 1 and 2 illustrate the orientation of cells in a softwood and ring-porous hardwood. The large opening in the softwood (Figure 1) is a resin canal complex, not a vessel.

Cross-section micrographs of three hardwoods and three softwoods (Figure 3) show three types of growth characteristics. Softwoods may have "no transition" (no EW/LW boundary (A)), gradual transition between EW and LW (B), or abrupt transition between EW and LW (C). Note that the "no-transition" softwood is a tropical species (i.e., no seasons, therefore no EW/LW transition). Hardwoods may be diffuse porous (D), semi-ring porous (E), or ring porous (F). Finishing characteristics for wood fall into three categories:

I. Easy to finish ("no-transition" or gradual-transition softwoods and diffuse-porous hardwoods having narrow LW bands)
II. Moderately easy to finish (abrupt-transition softwoods or semi-ring-porous hardwoods having narrow LW bands)
III. Difficult to finish (abrupt-transition softwoods or ring-porous hardwoods having wide LW bands)

The important message from wood anatomy is to look at the wood. The six classifications (Figure 3) do not include all possible combinations of growth rate, grain, and surface texture. Micrographs of end grain clearly show the EW/LW transition. Extending the two-dimensional end-grain micrograph to an actual block of wood shows how these transitions affect paintability of the lateral surfaces (Figures 4 and 5). When determining paintability, look at grain angles (both flat grain versus vertical grain and slope of grain). Look at the width of the EW/LW bands and the transition between them. The blocks show radial and tangential surfaces (i.e., vertical and flat grain) for four softwoods. Note the gradual transitions and narrow LW bands on white pine (*Pinus strobus*) (Figure 4, left) and western redcedar (Figure 4, right) and the abrupt transition and wide LW bands on Douglas-fir (*Pseudotsuga menziesii*) (Figure 5, left) and loblolly pine (Figure 5, right). Surfaces having wide LW bands and abrupt transition between EW and LW are difficult to finish. In contrast, white pine and western redcedar do not have wide latewood bands, and these species give excellent paint performance. Moisture-induced dimensional change increases as wood density increases (see text box "Moisture"). Changes are greater for latewood than earlywood. Different dimensional change for "abrupt-transition" (or ring-porous) species at the earlywood/latewood boundary places stress on coatings.

MOISTURE
Water has three states—solid, liquid, and gas. Moisture is not one of the three states. However, it is a useful term for describing water in wood because the state may not be known. For example, wood having 50% water has some of the water as free water vapor, liquid water, or ice and some is hydrogen bound within the wood matrix. "Moisture movement" describes water moving through a wall of a structure because water vapor may condense to liquid or solid water. I use "moisture" when the state of water changes or is uncertain.

Wood specific gravity, radial and tangential dimensional change, EW/LW transition, EW/LW ratio, and paintability for common North American wood species are listed in Table 1. Shrinkage values given in Table 1 were obtained from drying wood from its green state (fiber saturation) to ovendry (0% MC); swelling values would be about the same. Some species have wide LW bands (Figure 5). For softwoods, the transition is gradual (G) or abrupt (A). G/A for western hemlock (*Tsuga heterophylla*) indicates that some samples are A and some are G. For hardwoods, the transition is diffuse porous (D), ring porous (R), or semi-ring porous (SR). Estimates of paintability are based on EW/LW transition and EW/LW ratio. For example, softwoods having gradual transition and less than about 1/3 LW are listed as I; those having abrupt transition and greater than about 1/3 LW are listed as III. For hardwoods, diffuse-porous species are listed as I; ring-porous species having greater than about 1/3 LW are listed as III. These paintability estimates don't take into consideration the dimensional change or grain angle. For example, flat grain white pine would not be as paintable as vertical grain. Redwood (*Sequoia sempervirens*) is listed in category I even though it is an abrupt-transition species because the LW bands are narrow. Table 1 merely gives a starting point for evaluating paintability of a species. One needs to look at the lumber and evaluate its paintability. Some wood species have many appearance grades of lumber; grade affects paintability. For example, high-grade lumber of a species in category II may have better paintability than low-grade lumber in category I.

Within a single wood species, different pieces show variation in growth rate, density, EW/LW ratio, heartwood/sapwood content, and grain angle. Ensuring matched pieces of wood is impossible, so one shouldn't expect to evaluate finish performance by assuming the substrate is the same for various finishes. One should not assume wood properties are the same from one end of a 2-m-long board to the other end. In these types of "matched wood substrate experiments," the substrate probably affects the finish performance, but researchers assume they remove this variability. This is a big mistake—really big! The literature includes many cases of this type of experiment. The report often gives a ranking to the various finishes. If researchers would repeat the work, even using the same wood species, I believe the ranking would be different!

Several factors affect finish performance:

- Density (overall density, EW/LW density difference, and how abruptly density changes at the EW/LW boundary)
- Thickness of latewood bands
- Ray cells (number and placement)
- Vessels (size and distribution)
- Extractives content (water-soluble and solvent-soluble)
- Growth rate (Some species grow faster than others, and site conditions affect growth rate.)

Weathered Wood

Weathering is the general term describing outdoor degradation of materials and manifests itself physically and chemically (e.g., cracking and exfoliation of rock, corrosion of metals, and photodegradation of organic materials). Ultraviolet (UV) radiation in sunlight catalyzes photodegradation of organic materials augmented by moisture, temperature change, freeze/thaw cycles, abrasion by windblown particles, and growth of microorganisms. Photochemical degradation occurs at and near the surface of wood, wood products, and finishes.

Photochemical degradation cleaves chemical bonds of lignin, which weakens fiber-to-fiber adhesion. As fiber-to-fiber adhesion weakens, fibers slowly erode from the surface. Badly weathered wood having loosely attached fibers on the surface obviously cannot hold paint. A weathered surface is not obvious on wood that has been outdoors for less than 2 to 3 weeks. The wood appears unchanged. Recent research has shown that chemical changes of wood exposed to sunlight for 1, 2, 4, 8, or 16 weeks prior to painting (preweathering) affect 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 primers with one acrylic-latex top-coat over planed all-heartwood vertical-grain western redcedar. For species with low specific gravity, the wood must be finished as soon as possible after installation, or better yet, primed before installation. In other tests using dense wood species such as Douglas-fir and southern yellow pine, little loss of paint adhesion was noted until boards had been preweathered for 3 to 4 weeks. Species and amount of weathering are important if one is using weathered wood to test paint adhesion.

3. Finish Research at the Forest Products Laboratory

Finish research at the Forest Products Laboratory (FPL) is different from that of the paint industry in several ways. Our tests last a long time—usually more than 10 years and sometime up to 20 years (Figure 6). The tests focus on the interactions of substrate and finish, usually as they relate to paint adhesion, cracking, flaking, and peeling. Our primary focus is on the way wood affects paint performance. We obtain general information on generic finishes versus substrate (e.g., the service life of semitransparent stains versus solid-color stains on smooth Douglas-fir lumber and plywood). Paint tests by industry are often short term and focus on paint surfaces (gloss, fade, mildew growth). These degradations may be apparent with short test periods and need to be determined because if they occur, they indicate potential problems with short-term customer satisfaction.

Following is a historical perspective of finishing research at the Forest Products Laboratory.

Prior to 1950

The wood finishing program at the FPL started about 1922. Frederick L. Browne wrote the early history (1922-1963) of wood finishing ("The Origin and Early History of the Paint Section"), which is contained in "Chronicle of 65 Years of Wood Finishing at the Forest Products Laboratory" (Gorman and Feist 1989). In the section on Test-Fence Studies, Browne stated,

> The favorite excuse for failure of house paints in 1922 was the unsuitable nature of the wood painted. The opinions of the paint industry and of painting contractors were highly conflicting, but they might be summarized, with little exaggeration, to the effect that eastern white pine was the only wood fit to paint; but even the white pine then available was not what it used to be. Clearly our first problem in house paints was to discover the facts about the painting characteristics of the various woods and cuts of wood.

Dr. Brown wrote this approximately 50 years ago and referred to the state of the wood/paint industry in 1922—almost 100 years ago! I find it interesting that the white pine then available "was not what it used to be"! I guess wood is never "what it used to be"—whatever that is!

In my opinion, the most serious problem with paint during those years was the flow of moisture from inside structures to siding (see text box "Moisture"). Structures had no vapor retarder/air barrier. Research using the blister box helped explain how moisture affected paint. This work led to the development of the "Madison Formula," an oil-based semitransparent stain. Based on the Madison Formula, paint companies developed other semitransparent stains—a new product line for the paint industry. Laboratory tests, such as the blister box, augmented information from field tests and paint evaluations on existing structures.

From 1922 to 1960, researchers at FPL worked with those in industry to improve paint performance on wood. Following are a few noteworthy accomplishments:

- Worked with the paint industry to develop wood primer paint
- Identified compatibility problems between different paint formulations
- Established procedures for determining moisture-excluding effectiveness of paint
- Developed the "blister box" to show the effect of moisture diffusion through structure walls
- Developed water-repellent preservatives and semitransparent stains
- Convinced the paint industry of the need for sufficient film-build with paint coatings

Since 1950

Modern structures usually have a vapor retarder/air barrier to limit the flow of humid air through the structure envelope. When these barriers are installed properly (e.g., without holes for plumbing and electrical service), inside water vapor seldom causes catastrophic paint failure; therefore, blister box experiments ceased. Laboratory experiments focused on accelerated weathering using carbon arc and xenon arc weatherometers and adhesion testing. However, outdoor field tests remained an important part of the paint program. Field tests evaluated the performance of generic finishes on different substrates. Our research still involves evaluating wood paintability (not comparing different brands of paint).

Over the past 50 years, experimental design of outdoor tests has evolved. From 1950 to 1985, almost all studies used a panel made up of three pieces of siding on a plywood backing (Figure 7). Figure 7 shows a two- or three-coat paint system (oil-alkyd primer/acrylic latex top-coat) on western redcedar after 29 years on the test fence near Madison Wisconsin. End grain was not sealed and the three pieces of siding were the "replicates". In the mid-1980s, researchers at FPL started using 4-ft (1.2-m) boards instead of panels (Figure 8). Half the board was usually pretreated with a WRP. Various sections of the board had one top-coat, primer plus one top-coat, or primer plus two top-coats, with or without the WRP pretreatment. We designed experiments to evaluate various types of finish on different wood species and the interaction of WRPs. We used three or six boards ("replicates") for each experimental parameter. Recent experiments evaluate interactions of wood/finishes on wall systems (rain screen (Figure 9) or flashing (Figure 10)). In our latest field studies, we use statistical designs to focus our studies on specific degradation mechanisms (e.g., evaluating effects of wood density, grain angle, and growth rate on paint cracking and flaking).

20-Year Warranty

If paint on wood lasts 1 year, it should last 20 years. Tests should be designed to detect failures that often occur within 1 year (juvenile failures). Juvenile failures are those failures that occur at a decreasing rate at the beginning of the life of a product (or living things, for that matter). They are most easily explained using a "bathtub plot" (Figure 11) (Wilkins 2002a,b). The plot is a Wiebull distribution of three types of failures superimposed: a juvenile failure curve on the left side (caused primarily by flaws), constant failure rate shown by the flat portion in the middle (based on random failures that may have nothing to do with product durability), and end-of-life failure curve on the right side (wearing out). The slope of Wiebull distributions for juvenile failures (decreasing rate) and end-of-life (increasing rate) become small at the center of the bathtub plot and can be ignored. The random failure rate is the dominant effect through the central portion of the bathtub plot.

In materials testing, we need to understand which part of the plot we are using to predict "service life." The rate of failure for the juvenile failure portion is not constant (i.e., it is defined as the portion having decreasing rate). We can predict any service life, depending on the portion of the curve selected. If one picks a rate early in the juvenile failure portion, one gets a rather short service life. Estimating service life from the flat portion of the curve gives an extremely long service life prediction. The rate of failure in the flat portion gives a mean time between failures (MTBF). This abbreviation is often corrupted to "mean time ***before*** failure." Some people even assume it means "***minimum*** time ***before*** failure." This is not wise! That is, rate of failure of the flat portion of the curve does not equate to service life. It ignores juvenile and end-of-life failure portions of the curve. For example, if the low rate of failure at the flat portion of the bathtub plot is used to predict service life, one often gets a prediction of "hundreds of years." The end-of-life portion of the bathtub plot comes into play long before "hundreds of years." A better way of predicting performance is to consider mean time to failure (MTTF). This includes the end-of-life failure mode but may not include juvenile failures (Figure 12).

These are easy concepts to understand and to visualize for human life. Juvenile death may be caused by birth defects (left side), random death by accidents (middle), and then we wear out and die (right side). Insurance companies have this all figured out—term insurance for a 30-year old is cheap because they probably base the rate on MTBF in the flat portion of the curve.

How can we apply these concepts to testing paint on wood? First, we need a large population (a large *n*). Second, we target testing to isolate various types of failure. That is, we conduct more than one type of test. We design tests to evaluate specific types of failure and their interactions. Third, we use measurement techniques other than "how it looks." That means developing instrumental measurement techniques, data collection systems, databases, and software to manipulate the data. (Though I must admit—consumers use the "how it looks" evaluation system, so we shouldn't ignore it.)

Large *n* is the secret! We need to evaluate performance in two areas of the bathtub plot: juvenile failure and end-of-life. The most important area may be the juvenile failure portion. (These are the failures that often land a company in court!) A large number of replicates enable one to evaluate failure in terms of rate and determine juvenile failure from decreasing rate and end-of-life failure from increasing rate. Field studies having only three replicates enable one to observe general trends, but the studies lack sufficient replicates to evaluate juvenile and end-of-life failures. If we continue to "hang three specimens on the fence to see what we get," we'll continue to get little value for what it costs to do field experiments. In the following sections, I point out where one can use field, laboratory, and accelerated tests having large *n* to determine juvenile and end-of-life failures.

What Are You Testing?

Target tests—we need to decide ahead of time what type of degradation we are evaluating and design tests to assess that degradation. In paint testing experiments, substrate has a strong influence on finish performance for some types of degradation but not for others. If substrate has an effect, use it to focus the experiments to get answers quickly, precisely, and accurately. Some tests may be done on non-wood substrates. I classify finish degradation in two ways: changes in appearance and film degradation/debonding. Appearance changes (such as gloss, fade, extractives bleed, and mildew) affect paint surfaces. Degradation/debonding (such as cracking, flaking ,and peeling) affect the finish film and interphase between paint and substrate. Consider methods and measurements that can distinguish between juvenile failures and end-of-life failures.

Gloss, Fade (Appearance)

Appearance of finished wood is unacceptable if the finish fades or loses gloss. Fading and loss of gloss are surface degradations of finishes (i.e., they don't usually involve the finish/wood interface) induced by ultraviolet (UV) radiation and visible light (particularly short-wavelength blue light). Loss of gloss is a degradation of the polymer in the finish and occurs with film-forming finishes such as paint. All finishes degrade in this way over time, and we consider it normal aging. Film integrity is not compromised unless the polymer rapidly degrades to give excessive chalking. Fading is a degradation of pigments in the film. Mineral pigments, such as iron oxide, are light stable; organic pigments tend to degrade. Loss of gloss causes the surface to become less smooth and the change in surface texture may influence the evaluation of fading. Evaluate gloss and fading often to determine rate of change; decreasing rate could indicate a juvenile failure.

Accelerated test methods may work well for UV-radiation-induced fading and loss of gloss, and these degradations may follow the "law of reciprocity." That is, one can shorten the test time by increasing the intensity of the radiation. For example, 100 h at one-sun intensity is equivalent to 50 h at two-suns or 25 h at four-suns.

The law of reciprocity may not hold for all polymer systems, but if it can be used, it can shorten test time. Water spray may wash away degradation products, thus adding mechanical abrasion as a contributing factor. Temperature may also affect degradation rate, but freeze/thaw is probably not a factor. The most important factors are radiation wavelength and its intensity, temperature, and abrasion by water spray. If accelerated tests are used, the 102 min of radiation/18 min of water spray (102/18 cycle) may be acceptable, but nothing is special about this cycle. In fact, to test finish/wood interactions, it is probably not appropriate. A schedule of 24 h UV radiation and 4 h water spray (spray during the light) each day causes greater dimensional change of wood than the 102/18 cycle and is more representative of the strains imposed on paint outdoors. Turning off the radiation during the spray is not necessary, even if they are doing different things (UV degradation of the polymer—water abrasion of the surface). If the mechanism of degradation is UV-radiation-induced degradation, maximize the radiation to decrease the test time. Measure the UV radiation intensity and wavelength distribution (the intensity at several wavelengths) and integrate over time to obtain dose. Obtain loss in performance (degradation) of gloss or fade versus dose, particularly the degradation at several wavelengths if possible. This requires filters—difficult, but possible! Quantify degradation in terms of radiation "dose" causing the degradation. By determining degradation in terms of dose, not time, you can compare different experiments and build a database. Don't be satisfied with a single experiment that merely gives a ranking of finishes for "that experiment."

Because gloss loss and fading are a coating surface degradation, substrate is not a factor in the degradation. However, substrate can affect the results. For example, surface changes of the substrate, such as raised grain, may show through the coating and affect the appearance (gloss). Highly colored wood substrates or those having knots can cause surface discoloration and interfere with evaluation of fading. So instead of using wood as a substrate, consider using metal, fiberboard, or products having a paper overlay for smooth stable surfaces for evaluating gloss or fading. If using wood, sapwood of a fine-grained species may be acceptable. Photograph panels before painting them and when evaluating them. Evaluate fade and gloss using automated systems; store photographs and evaluations along with all experimental condition (such as time of wetness, relative humidity, temperature during exposure, radiation intensity and dose). These other factors become important when comparing different experiments.

Mildew Resistance (Appearance)

As with gloss and fade, mildew growth affects finish appearance. In most cases, the finish is not degraded; the mildew merely lives on the finish surface. However, in some cases, mildew on an infested wood substrate can grow through the finish. In fact, it may grow at the wood/finish interface, through the finish, and on the finish surface. This can be noticeable on clear or lightly pigmented finishes. Finish formulation and wood species affect mildew growth and may interact. Extractives in highly colored wood such as western redcedar and redwood may interact with linseed oil in a finish to give severe mildew growth within several weeks of outdoor exposure, particularly during rainy humid weather. Mildew usually refers to *Aureobasidium* sp., which includes 14 species. The most common species on wood is *Aureobasidium pullulans*. *A. pullulans* lacks the enzymes to degrade wood or polymers in finishes. The important word here is polymer! Oil-alkyds for wood products are generally long-oil alkyds (i.e., they have excess oil—free oil—not polymerized). Linseed oil is a food for mildew. Extractives in wood are not polymerized—more food. Mildew is always looking for a free lunch—and we often do our best to provide it:

- Linseed and tung oils—free lunch
- Oil-alkyds—free lunch
- Semitransparent stains—free lunch
- Oil-based solid-color stains—free lunch
- Latex-based solid-color stains—no free lunch, but porous; mycelium can grow through the film to get to the wood—free lunch
- Additives in finishes—?????—maybe more free lunch

Substrate may influence mildew growth; however, weather has a much greater effect on its growth. A finish may perform well for several years during dry weather, develop mildew during a wet year, and show less mildew growth when the weather becomes dry again. Mildew can occur quickly, but it shouldn't be considered a juvenile failure—the rate may not decrease over time.

Test protocols for evaluating mildew resistance of coatings are difficult. Outdoor tests don't work well because they are dependent on the weather. Both "good years" (a lot of mildew growth) and "bad years" (little mildew growth) occur, so comparing one year with another or one site with another is impossible. Outdoor exposure tests for more than 50 years at sites near Madison, Wisconsin, and Gulfport, Mississippi, usually showed worse mildew near Gulfport. However, some years it was worse near Madison. *You just can't depend on the weather* or quantify the dose. How do you measure the dose (i.e., quantify the factors causing mildew growth)? Is it the amount of rain, time of wetness, number of rainy days, or amount of time with RH above 70%, 80%, or 90%? Measuring the response (the amount of mildew) is not easy, either. Comparing one experiment with another and separating the affect of UV degradation on mildew growth are difficult. Conventional "wisdom" suggests that mildew grows more on the north side of structures than on the south side, but this is not true for all situations. Mildew grows where it can stay attached to the surface. For example, it is more prevalent on the grout between tiles than on the tiles in a shower. Mildew often grows on surfaces roughened by photochemical degradation. Thus, it may be more prevalent on the south side of a structure than the north side.

In contrast to the difficulties associated with field tests, laboratory methods may make it easier to use known organisms under controlled conditions, monitor growth photographically, and quantify results with image analysis. One can then compare results from one experiment with those from another. If tests are conducted on wood, mildew growth is a combination of factors from the finish and the wood. Researchers need to include several wood species and ensure that the test boards have heartwood. Western redcedar and redwood have traditionally been used, but one should include other species. Sapwood of spruce (*Picea* sp.) and pine contain free sugars and other foods that are readily available for mildew and other microorganisms such as blue stain (*Ceratocystic*- and *Leptographium*- type species). Blue stain may infect pine sapwood through pine beetle attack of living trees, log storage prior to sawing, or wood getting wet in service. As with *A. pullulans*, blue stain can be an appearance problem for clear and semitransparent finishes. Rather than using boards, one should consider tests using a sawdust/finish-resin medium prepared from several wood species, resin systems, and mildewcides; results may be seen within several weeks. This type of test is easy to do, can include many replicates, and is repeatable. It doesn't depend of the weather.

Extractives Bleed (Appearance)

In many hardwoods and softwoods, the heartwood contains water-soluble extractives. (Sapwood does not contain extractives.) Western redcedar and redwood are two common softwoods that contain water-soluble extractives. Extractives give these species their attractive color and natural decay resistance, but they can also discolor paint. Discoloration shows in two ways: diffused and run-down extractives bleed. Diffused extractives bleed is caused by (1) water from rain and dew that penetrates a porous or thin paint coating, (2) water that penetrates unsealed end grain of siding, railings, trim, or other components, and (3) absorption of water vapor in high humidity areas such as bathrooms, swimming pools, and green houses (Figure 13). Run-down extractives bleed is caused by (1) wind-blown water that wets the back side of siding, (2) condensation of water vapor, originating inside the structure, on the back side of siding, and (3) water draining behind siding from roof leaks, faulty gutters, or ice dams. Water on the back side of the siding dissolves extractives and runs off the back side of the siding onto the front side of the siding below it, where it evaporates and leaves red streaks (Figure 14).

Extractives bleed is another appearance problem, but unlike fade and gloss, extractives bleed is dependent on wood species. Film integrity is not compromised unless extractives interfere with the cure of the finish. *Finish formulation has no effect on run-down extractives bleed.* Back-priming siding prior to installation, having wide roof overhang, and using rain-screen siding installation minimizes run-down extractives bleed. *Finish formulation does affect diffused extractive bleed.* Eliminate diffused extractives bleed by formulating primers that are chemically incompatible with water-borne extractives and slow diffusion of water. Blocking extractives bleed requires that the chemistry of the finish be incompatible with the chemistry of the extractives. Generally, this means "not soluble." Stain-blocking primers were traditionally oil-alkyd formulations. One reason that latex-based primers aren't as effective is that they are more porous to water than oil-alkyds—even after they coalesce.

Stain-blocking primers have been developed to minimize diffusion of water-soluble extractives from western redcedar and redwood into finish top-coats. Other wood species may have a different mix of extractives (Figure 15). Figure 15 shows extractive bleed from the heartwood of radiata pine through an oil-alkyd primer and two latex top-coats. The extractives in radiata pine are probably soluble in organic solvents. Just as it is difficult to stop extractives bleed from knots because knots exude water-soluble and solvent-soluble extractives, extractives in the heartwood of pine, spruce, and fir may diffuse through primers designed to block water-soluble extractives from western redcedar.

Test requirements have increased in recent years because wood species traditionally used for exterior siding and trim are being replaced by imported wood species. As with testing for mildew, testing for extractives bleed may be more conclusive under controlled laboratory conditions. It may be possible to get results in several weeks using small wood wafers (e.g., 75x100x6 mm, radial, longitudinal, tangential). Wafers could be mounted in a device similar to the blister box having high RH and temperature on the inside and low RH and temperature on the outside. Use several wood species, including some highly colored hardwoods, such as northern red oak (*Quercus rubra*) or black walnut (*Juglans nigra*). Keep in mind, you are developing a test to ensure a robust product, therefore, stress it in every way possible. As with other tests, keep complete records of test conditions to enable comparisons among tests. Use many replicates to ensure that results aren't swayed by unusual pieces of wood.

Cracking, Flaking, Peeling (Interphase)

Cracking, flaking, and peeling are failures of the finish and the interphase between finish and substrate, and when they occur, the protecting quality of the finish has been compromised. In addition, fixing these degradations requires extensive substrate surface preparation and, in some cases, complete removal of the finish. These failures occur on film-forming finishes such as paints, solid-color stains, and semitransparent stains (if they form a film on the surface). Cracking, flaking, and peeling result from a combination of factors involving the substrate (e.g., species, growth-rate, density, grain-angle, and surface texture) and the finish (e.g., adhesive properties, toughness, flexibility, glass-transition temperature, coefficient of thermal expansion, and thickness of the coating). The mechanisms of failure usually involve many of the following factors:

- Grain raise of an abrupt-transition species, particularly on the pith side of smooth flat-grain lumber
- Insufficient film build
- Brittle film
- Weathered wood surface
- Weathered or chalky film
- Water

How these factors interact could be the subject of a separate paper, so I will give the short version! For good paint performance, films need to be 4-6 mils (0.10-0.13 mm) thick and be flexible over a temperature range of –20° to +50° C, films need to be applied to sound wood, and the wood should have gradual transition between early- and latewood.

However, to test paint, it's not this simple. At one extreme, paint vertical-grain saw-textured all-heartwood western redcedar using stain-blocking primer and two top-coats of acrylic latex (seal end grain with primer) and place on test fence vertically facing south. Do this early in your career—the paint will last more than 30 years (Figure 7). At the other extreme, place a single top-coat of a short-oil alkyd on flat-grain (pith side) of smooth Southern Pine and get your results the same week!

We need reasonable tests that give consistent results in a reasonable time. This may involve a series of different tests. I recommend testing free films of paint polymers with and without pigments and other additives. In addition, place these finish formulations in field tests. This enables you to develop an extensive database of film properties and outdoor finish performance. As the database increases, compare film properties of new formulations with those in the database to save time and money. Marginal formulations could be screened out prior to conducting lengthy field tests.

To develop a film-property/paint-performance database, use free films to determine properties (e.g., glass-transition temperature, coefficient of linear expansion, effect of pigments and other additives). Research on free films can help in understanding the limitations of the polymer system. Keep in mind, dimensional changes in wood are large and vary with species, grain angle, and EW/LW. Use many replicates and several wood species. Note that as the November temperature in Winnipeg begins to approach –10° to –20º C., the wood is increasing in MC (the temperature is near the dew point, therefore the RH is near 100%). Wood outdoors swells in the winter, but the paint is contracting. The two materials are on a collision course (maybe a bit of an over-statement)! Conversely, winter temperatures in Vancouver seldom are cold enough to stress paint films.

To get the most value from field tests, test paints where the weather is variable. You need four seasons, such as found in the upper Midwest in the United States, to stress paint films on wood. Develop databases on performance from a variety of different species, growth rates, and grain angles. Perform tests on preweathered wood having different grain angles. Choose a range of substrates. Don't try to match wood grain. It's not possible! Instead, use more replicates. Photograph wood prior to finishing, immediately after the finish cures or coalesces, and periodically as the painted wood ages (monthly, if possible). Use color to show defects, particularly if the photographs will be analyzed using image analysis. Test paint adhesion periodically during exposure (after 1, 2, or 3 years, for example). Although the test is destructive, adhesion tests can indicate changes at the wood/coating interphase and can be used to estimate how long the film will remain intact (Williams et al. 2002). Possible tests include 90° and 180° peel, tensile and shear, fracture mechanics, and peg-pull-off tests (Williams et al. 1987, 1990, Knaebe and Williams 1993, Knaebe et al. 1996).

Failures caused by cracking, flaking, and peeling should be evaluated using bathtub plot concepts. You may find juvenile failures caused by raised grain, inadequate film thickness, and defects in the film followed by an extended period with little noticeable change. End-of-life failures may not begin until many years after the painted wood is placed in test.

“To seal or not to seal end grain, that is the question.” We often seal the end grain of painted boards for our tests and, of course, paint companies recommend that their customers seal the end grain. In the real world, maybe your customers actually do it. However, maybe they don’t! If end grain of test boards is not sealed, peeling often occurs near the end of the boards; if boards aren’t sealed in the real world, peeling often occurs near the end of the boards. You should consider this when developing your test protocol. Maybe you shouldn’t seal the end grain. Unsealed end grain challenges the coating and may speed results. Lack of a sealer may permit juvenile failure, maybe it won’t.

Film Integrity (Thickness)

Properties of free films may change with thickness of the film; therefore determine properties for a range of film thickness representative of the spread rates on wood. Spread rate vary depending on species and surface texture. Spread rate often varies from one board to another within the same species. Getting a consistent film thickness is difficult. You can finish a section of a board with a known amount of finish, but the finish absorbs differently into different boards to give different film-build. Alternatively, you can paint until refusal to get similar film-build on different boards, but then you have different amounts of finish. Both methods give useful information. Some paint companies prepare both types of specimens. My preference is to let the substrate determine the amount of finish and record the amount applied. Second and third coats tend to be more consistent than the primer coat.

Finishes may form films and/or penetrate wood, and the extent to which they penetrate wood differs depending on finish formulation. All finishes can flow into the lumina of cut cells and vessels at the surface, but some can also infiltrate voids in wood cell walls. Molecular weight of the resin (size of resin molecules) determines whether the resin infiltrates the cell wall or merely flows into the lumina. Oil and oil-alkyd resins can penetrate wood at two levels; they can easily flow into the cut lumina and they are small enough to infiltrate wood cell walls near the surface. The molecular weight of resins in latex paint is too large to allow latexes to infiltrate cell walls; resins merely flow into cut lumina. Likewise, pigments are too large to infiltrate the cell wall, but pigments can be carried into the lumina along with oil-alkyd or latex finishes. Infiltration of oil-alkyds into cell walls modifies the properties of the wood at the wood/paint interphase, thus decreasing stress on the film. Decreased stress on the film may be why brittle oil-alkyds perform well. Resins in oil-based semitransparent stain absorb into cell walls, leaving just enough resin to “glue” pigments to surface.

As you develops tests, take into account the different ways that finishes interact with the substrate surface to form films. This can lead to different modes of finish failure. Semitransparent stains may flake and peel if they are too thick. A test protocol for them should include a range of film thickness to determine maximum film thickness to avoid flaking. This may vary with wood species and polymer system.

4. Designing Experiments with Lasting Value

As you design studies, consider the following situation. An addition was built onto the barn pictured in Figure 16. The portion of the barn having board and batten siding is original; the portion having gaps between siding is new. After completing the addition, the mural was painted. The paint on the new section started to fail within a couple months, and the owner took the picture after one year. Note that the extensive paint failure occurred only on the new addition (Figure 16, bottom). Why this difference? I consider this a juvenile failure. How does you test for this type of failure? First, consider possible causes of the failure. The old section of the barn had paint on it at the time the mural was painted, whereas the new section had been allowed to weather for several months. Failure is a combination of water and poor adhesion to weathered wood. The battens protected the edges of the boards from rain, but edges of the boards on the new addition were exposed to rain. In addition, moisture may have moved from inside (from livestock and hay) to outside on the section lacking battens. These types of failure cause customer dissatisfaction. Paints must be able to perform on many types of substrate (such as hardwoods, softwoods, weathered, unweathered), and the limitation(s) of formulations must be discovered using a range of substrates. Design experiments to determine juvenile and end-of-life failures.

Many of the field studies I have conducted over the years have been single experiments. I felt like I was starting each experiment from scratch. I did little to compare data from one experiment to another, and in fact for most of the experiments, it was not possible. This has changed. Researchers at FPL now design experiments to answer specific questions and use computer systems to store and manipulate data. The database includes a record of the weather during the tests and digital photographs of specimens taken periodically (monthly for one of our studies).

In our statistical designs, researches at FPL consider within-board and board-to-board variability within a particular species. We are designing experiments so that we can compare data from different experiments. We select substrates according to test requirements. For example, we are determining effects of grain angle, growth rate, and specific gravity of loblolly pine (*P. taeda*) on several paints. The object of this study is to evaluate a particular species. If we were testing paint, we would replicate this study with several other species (Douglas-fir, western redcedar, and red oak, for example). Each board has six finishes and each parameter (such as density, growth rate) has six to eight "replicates." We use boards having a range of wood properties to give a robust test that represents the range of growth rate and specific gravity typical for this species (Figure 17). Specific gravity of the boards ranges from 0.53 to 0.73, growth rate from 3 to 19 rings/in (1 to 7 rings/cm). We photograph each section of each board (72 boards) monthly in the laboratory under consistent lighting (Figure 18). Although we are using only one wood species (*Pinus taeda*), for this study, entering performance evaluations into a standard database will enable us to compare the results with future tests and other experiments currently underway.

Accelerated Weathering Chambers

Accelerated weathering chambers consisting of a UV radiation source and water spray have been used for decades to test paint. They are a valuable tool for getting answers quickly for specific types of paint degradation. Keep in mind that weathering chambers are just one of many tools available and the data obtained from them is just part of the dataset. As mentioned previously, weathering chambers can be used to evaluate gloss and fading. To some extent, they can stress paint films to cause cracking, flaking, and peeling, particularly if a wood species having large dimensional change is used for the test and the duration of water spray is long enough to achieve a cyclic dimensional change. We have used 4 h water spray/day and this can stress paint films quite well. In my opinion, there is no "best" cycle. Choose a cycle to stress the wood/paint system to achieve the experimental goals. As with field tests, we shouldn't just hang stuff in the weathering chamber and see what we get!

Keep in mind that the radiation intensity and water spray vary from one portion of the chamber to another, and measuring the irradiance that each specimen receives is not possible. Therefore, evaluating specimen response in terms of radiation dose and comparing different experiments are difficult.

5. Conclusions

Finished wood is a complicated materials system. Finish performance may depend on interactions between the finish and wood substrate. As you develop test methods, consider these interactions and use them to increase the robustness of your test, accelerate the degradation, or target a particular degradation mode (e.g., using redwood and radiata pine to test stain blocking qualities of a new primer). Supplement fields tests with laboratory tests, and when possible, substitute laboratory tests for field tests. Think of each test as part of a larger program so that you develop a database containing all tests and supporting data. Eventually, you will be able to "mine" the database to augment data from later experiments and in some cases avoid doing extensive outdoor exposure tests.

Just a thought in closing: "Our tests may measure minimal performance to meet our minimal expectations."

6. Acknowledgment

I thank Alex Wiedenhoeft for Figure 3 and helping to prepare Table 1.

7. Literature

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Table 1. Painting Characteristics of Common Wood Species							
		Shrinkage (%)[b]					
Wood species	Specific gravity[a] green/dry	Tangential	Radial	Paintability (latex paint)	EW/LW transition	Is LW greater than about 1/3 of GR	Color of heartwood
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[c,d]	0.45/0.48[e]	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[e]	0.47/0.51[e]	8	5	III	A	Yes	Light brown
Western white	0.36/0.38	7.4	4.1	I	G	No	Cream
Redwood[f]	0.38/0.40	4.4	2.6	I	A	No	Dark brown
Spruce[g]	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/poplar/ cottonwood	0.36/0.40	7.0-9.2	3.5-3.9	I	D	NA	Pale brown
Basswood	0.32/0.37	9.3	6.6	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]Value obtained by drying from green to ovendry.
[c]Lumber and plywood.
[d]Coastal Douglas-fir.
[e]Loblolly, shortleaf, specific gravity of 0.54/0.59 for longleaf and slash.
[f]Redwood is listed as I because its LW band is very narrow
[g]Spruce. Values are for Engelmann spruce; other species are similar.
A = Abrupt-transition softwood, G = gradual-transition softwood, R = ring-porous hardwood, D = diffuse-porous hardwood, SR = semi-ring porous hardwood, Y = yes (typically), N = no (typically), NA = not applicable, Y/N = yes or no (depending on the specimen). In ring-porous hardwoods, the growth rate (number of rings per inch) will determine the relative proportions of earlywood and latewood.

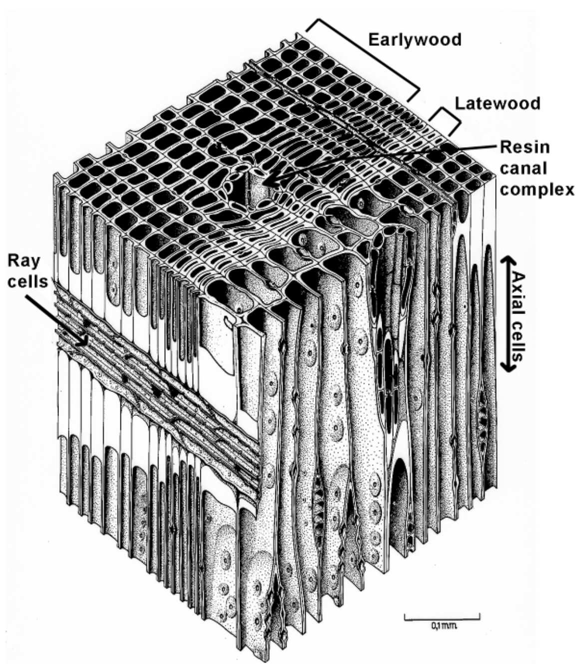

Figure 1. Illustration of a typical softwood showing axial and ray cells, earlywood and latewood, and a resin-canal complex

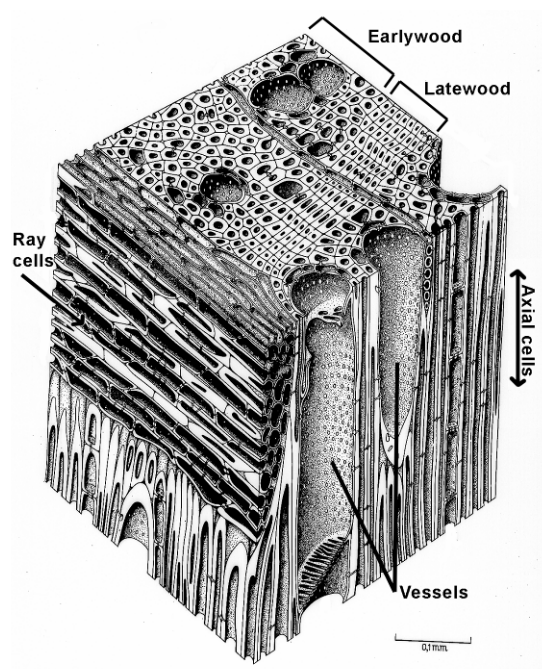

Figure 2. Illustration of a typical ring-porous hardwood showing axial and ray cells, earlywood and latewood, and vessels

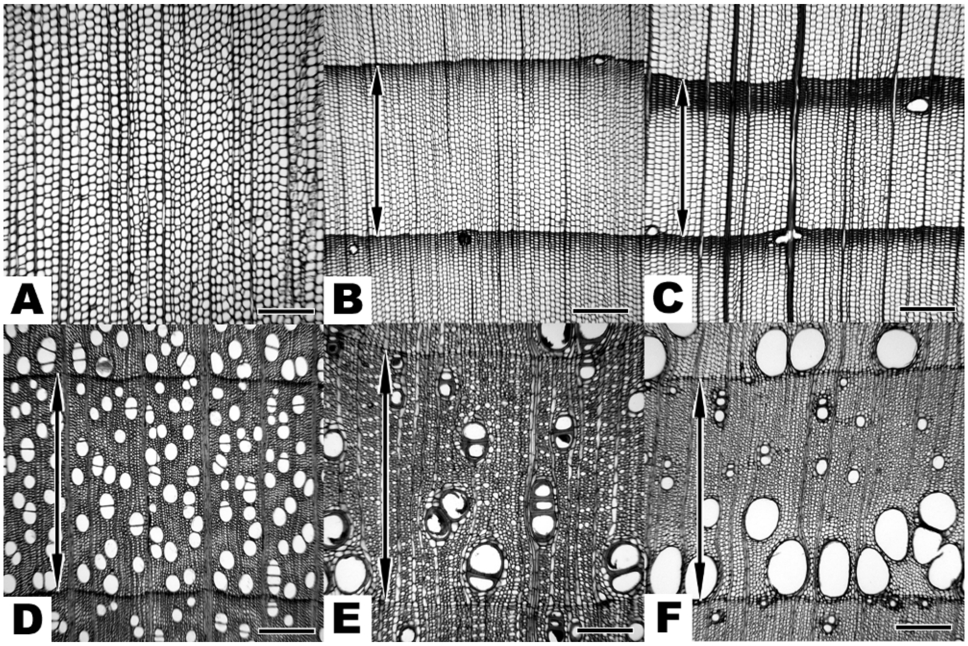

Figure 3. Cross section micrographs of a tropical softwood (A), white spruce (*Picea glauca*) (B), Douglas-fir (C), sugar maple (*Acer saccharum*) (D), persimmon (Diospyros virginiana) (E), and white ash (*Fraxinus americana*) (F)

Figure 4. Lateral and end-grain surfaces of eastern white pine (left) and western redcedar (right)

Figure 5. Lateral and end-grain surfaces of Douglas-fir (left) and loblolly pine (right)

Figure 6. Forest Products Laboratory test site near Madison, Wisconsin

Figure 7. Western redcedar boards painted with oil-alkyd primer and one acrylic latex top-coat (left) and two top-coats (right) after 29 years outdoor exposure at the Forest Products Laboratory test site near Madison, Wisconsin

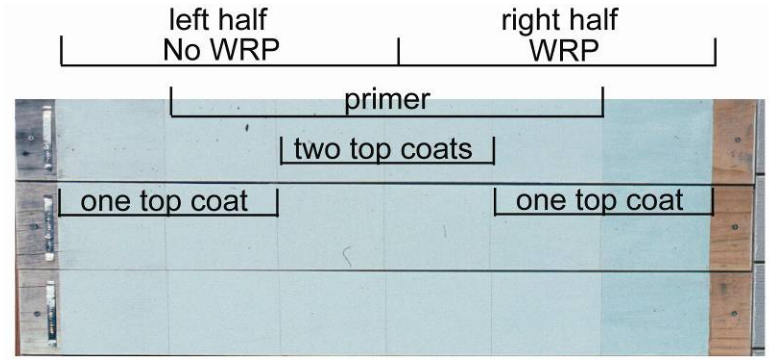

Figure 8. Painted boards showing water-repellent preservative (WRP) treatment on left half of boards, no WRP treatment on right half, and the arrangement of primer and top-coats to give primer and one top-coat, primer and two top-coats, and top-coat having no primer

Figure 9. Boards on test fence showing rain screen on the left and no rain screen on the right

Figure 10. Painted plywood with Z-flashing between panels

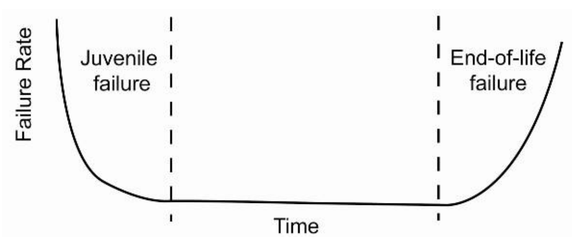

Figure 11. Bathtub plot showing juvenile and end-of-life failure rates with respect to time

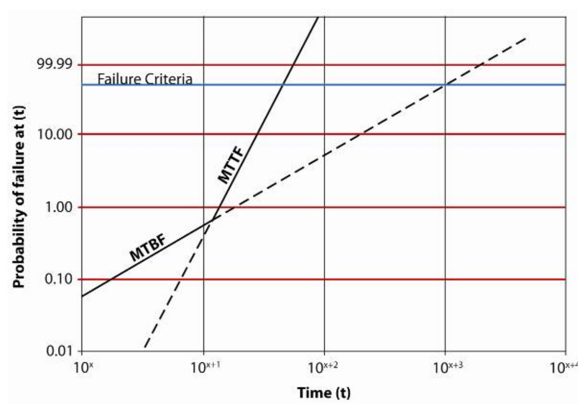

Figure 12. Probability of failure with respect to time for mean time between failures (MTBF) and mean time to failure (MTTF)

Figure 13. Diffuse extractives bleed on painted boards

Figure 14. Run-down extractives bleed on painted boards

Figure 15. Diffuse extractives bleed from heartwood of radiata pine

Figure 16. Mural on barn near Madison, Wisconsin (top); close-up of paint failure (bottom)

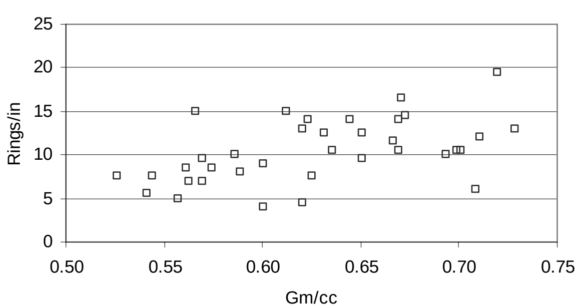

Figure 17. Rings per inch with respect to specific gravity for loblolly pine

Figure 18. Steve Lacher (right) and Sam Williams (left) photographing painted boards