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U. S. Department of Agriculture, Forest Service
FOREST PRODUCTS LABORATORY

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PROPERTIES OF WOOD THAT DETERMINE THE SERVICE GIVEN BY EXTERIOR PAINT COATINGS

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The Forest Products Laboratory has been studying the painting characteristics of softwoods since 1924. Experiments were conducted by exposing panels of 18 kinds of softwood lumber on test fences at 11 exposure stations in different parts of the country, and painting the surfaces of the panels with two representative kinds of white, exterior house paint. The panels were inspected at intervals to observe the course of disintegration of the coatings.

The study shows that paint coatings last much longer on some wood surfaces than on others and reveals the properties of wood that exert most influence on paint behavior. The study also indicates the direction in which improvement in paint service on wood should be sought. The findings can be presented here to best advantage by first describing certain characteristics of wood and then discussing their bearing on paint service.

Classifications of Lumber

By Species

Lumber is cut from trees of many different species and the grouping by species or closely related species is retained in merchandising because in general each species has more or less characteristic average properties and finds uses accordingly. A sharp distinction is made in practice between hardwood lumber, which comes from deciduous trees, and the softwood lumber from evergreen trees. Only softwoods need be considered here because the lumber used for the exterior of buildings is almost entirely of that kind.

In choosing lumber for a particular purpose, let us say house siding, paintability is only one of a number of

factors to be considered, and not necessarily the most important one. Ability to stay in place, ease of working and of nailing, durability, cheapness, and availability in the desired pattern must be given consideration varying with circumstances. No wood excels in all respects and none in common use is deficient in all of them.

Within each species there is a considerable range in properties, not only in lumber cut in different forest regions, but also in that from neighboring trees or even from different parts of the same tree. Consequently there is much overlapping in properties between species; for instance, dry western yellow pine is usually heavier than redwood and lighter than Douglas fir, but the lightest boards of pine weigh less than the heaviest ones of redwood and the heaviest boards of pine outweigh the lightest ones of fir. The painting characteristics depend largely upon such properties as density and therefore vary widely within species. From the technical point of view it is far more convenient in discussing painting characteristics to classify the woods according to their properties rather than by species, but the classification by species must be considered also as long as wood is bought and sold that way.

By Grade

In commerce, lumber of each species is subdivided into grades on the basis of the number and size of defects appearing on the surface of the boards. The highest grade admits only boards of clear lumber practically free from defects. Several of the higher grades are known collectively as the select grades; they contain only "lumber of good appearance and finishing qualities" and are the ones most likely to be used where painting is important. The common grades permit more defects and usually go into concealed parts of structures or are remanufactured, the defects being largely cut out.

The defects that have most influence on painting characteristics are knots, pitch pockets, pitch streaks, pitch, and loose grain.

By Grain

Wood has an oriented fibrous structure, that is, it has grain. Most of the fibers in a board are arranged parallel to the long axis of the tree or log from which the board is cut. Surfaces cut at right angles to the axis of the log cut through most of the fibers transversely and are known as end-grain surfaces. Only the ends of boards present end-grain surfaces.

A series of rough, concentric rings can be seen on the end of a log. They are the annual growth rings, one of which marks each year of the tree's life. Each annual ring in a softwood, or coniferous tree, consists of a soft, light-colored part termed the springwood, and a horny, dark-colored part termed the summerwood. If the principal surfaces of a board lie in planes that run approximately radially to the annual rings they are edge-grain surfaces and the board is an edge-grain board. Both surfaces of an edge-grain board are practically alike. If the principal surfaces of the board lie in planes approximately tangent to the annual rings they are flat-grain surfaces and the board is a flat-grain board. The two surfaces of a flat-grain board differ in important characteristics that will be pointed out later; the side that was nearer the bark of the log is the bark side, the other the pith side.

Lumber cut mostly from relatively small trees consists predominantly of flat-grain boards. In cutting lumber from large trees that yield a high proportion of clear lumber it is possible to turn out a predominance of edge-grain boards and to sell edge-grain lumber separately from mixed edge and flat grain.

By Heartwood and Sapwood

In many species the older wood nearer the center of the tree differs in color and in content of certain chemicals from the wood nearer the bark of the tree. The former is the heartwood, the latter the sapwood. Heartwood is usually less readily permeable to liquids than sapwood, often much more durable against decay, and is immune from blue stain fungi.

Select grades of lumber come from the outer parts of the log and therefore include much of the sapwood. Some species contain so little sapwood that there is little of it in clear commercial lumber, but other species contain much sapwood. In general there is more sapwood in lumber from small trees than from older and larger trees of the same species.

Microscopic Structure of Wood

Structure Cellular, Not Labyrinthine

The painting characteristics of wood are profoundly influenced by its porosity; from one-half to more than three-

fourths of the volume of dry wood is air space. Wood structure is cellular, not labyrinthine, so that the porosity is more nearly like that of the honeycomb, in which there is no communication between cells, than like that of a heap of marbles or a bundle of rods, in which there is unobstructed, though much involuted passageway throughout the entire volume of enclosed air space.

The cellular elements of softwood structure consist very largely of tracheids, which are long, narrow tubes running vertically in the tree. They are roughly from 2 to 4 mm. long by less than 0.03 mm. wide. There are also shorter elements, termed the ray cells, which run along radii of the tree trunk and at right angles to the tracheids. Tracheids and ray cells are not merely bundled together; they are firmly embedded in a continuous matrix, the middle lamella, so that there are no spaces between elements through which liquids may move. The air enclosed in wood is mostly enclosed within the tracheids and wood cells. These cavities are not completely isolated from each other as in a honeycomb, however, because their walls are penetrated by small pits, covered by membranes, in which there are ultramicroscopic openings about 0.00002 mm. in diameter, large enough to permit liquids to pass slowly, but far too small to admit paint pigments.

In the pines, spruces, larches, and Douglas fir, there are scattered through the structure certain long channels, called resin ducts, running both vertically and radially. These afford long, relatively large passageways provided that they are not obstructed with resin. The true firs, hemlocks, cedars, cypress and redwood do not normally have such resin ducts.

Springwood and Summerwood

The reason why the annual growth rings are readily distinguishable in wood is clearly revealed in the microstructure because the tracheids of the springwood and summerwood differ strikingly from each other. In springwood the tracheids are roughly square in cross section, with thin walls and large voids; in summerwood the tracheids are flattened and have thick walls with small, thin voids. The enclosed air space in springwood occupies roughly 80 per cent of the total volume while in summerwood it amounts to somewhere near 40 per cent. Although summerwood has only half the capacity for holding liquids that springwood has, nevertheless liquids move through it much more readily than they do through springwood.

Pieces of wood differ widely in the width of their annual rings, usually expressed as number of rings per radial inch and in the proportion of springwood and summerwood in each annual ring. If the tree grew rapidly, the annual rings are wide. A high ratio of summerwood to springwood makes wood heavy and strong. Ring width and proportion of summerwood are the most important determining factors in paintability.

Chemical Composition of Wood

Wood Substance

The principal substances out of which the cellular structure of wood is built are probably identical in chemical composition in all woods and the proportions in which they occur vary only slightly between species, between springwood and summerwood, and between sapwood and heartwood. These chemicals will be spoken of collectively as wood substance.

Wood substance consists principally of cellulose and lignin. Cellulose is a very complex carbohydrate, essentially a polymer of sugar, into which it can be resolved by hydrolysis. Lignin is a very complex organic material, possibly aromatic in character, whose molecular structure is still a matter of speculation and which is very likely to prove a mixture of compounds rather than a pure substance.

The walls of the wood cells are made of the cellulose, which is present in thread-like fibrils woven together in spirals inclined more or less to the long axis of the cell. Part of the lignin is interspersed in this cellulosic fabric where it fills in the chinks between threads more or less completely. The rest of the lignin forms the middle lamella which is the matrix in which the wood cells are embedded.

Swelling of Wood Substance

Wood substance is a typical elastic jelly. It is not soluble in ordinary solvents and is inert toward linseed oil, turpentine, petroleum oils, and benzene. Many liquids are imbibed by wood substance, cause it to swell, and diffuse through it. Water is the most important of these liquids; others include methanol, ethanol, acetone, and some of the esters used as solvents or plasticizers for nitrocellulose lacquers. Wood substance imbibes and is swollen by these

substances not only on contact with the liquids themselves but from contact with the vapors. The amount imbibed and the extent of the resulting swelling vary with the nature of the liquid or vapor and with the partial pressure of the vapor in the surroundings. Thus there is a definite equilibrium moisture content for wood substance at each relative humidity and temperature. Probably there is also a corresponding swelling equilibrium for wood substance also, but in practice what we observe is the change in dimensions of a piece of wood, not the swelling of the wood substance itself. Only a fraction of the total swelling expresses itself in a change in dimensions of the piece as a whole because much of it is absorbed in plastic deformation within the wood structure. As a result, both the magnitude of the gross change in volume and the amount of radial and tangential swelling (longitudinal swelling is small) vary markedly with the manner in which the change in moisture content is brought about as well as with the difference between initial and final moisture content. Still more important is the fact that such behavior as warping, cupping, checking, and weathering of wood depend more upon the manner in which changes in moisture content and in swelling take place than they do upon the amount of the changes concerned. Paint coatings therefore exercise a marked influence upon such behavior of wood even though they may not prevent change in moisture content from taking place.

Extractives in Wood

Besides wood substance, wood contains extraneous constituents which can be removed fairly easily by extraction with suitable solvents. These extractives are variable in nature and in amount, differing not only between species, but between different parts of the same tree. The extractives are conveniently classified into those soluble in organic liquids like ether and those soluble in water.

The ether-soluble extractive of longleaf and slash pines is a resin containing the volatile oil turpentine, which consists mostly of terpene hydrocarbons, and the non-volatile substance rosin, which consists largely of abietic acid. The other pines and Douglas fir contain resins of similar composition. Other softwoods contain such resins only in small amounts if at all, except when they occur in local deposits in the tree-like pitch pockets. Western red cedar, redwood, the true firs, hemlocks, spruces, and larches ordinarily contain only small amounts of ether-soluble extractives. Port Orford cedar, eastern red cedar, Alaska cedar, and cypress contain characteristic oils soluble in ether but quite different in chemical nature, lacking an acidic substance analogous to rosin.

It is known that heartwood and sapwood may differ materially in the amount and particularly in the composition of the extractives present. It is not known whether there is more or less extractive present in summerwood as compared with springwood.

The water-soluble extractives include tannins and other complex organic substances of an aromatic nature, some of them highly colored, carbohydrates, organic acids like formic, acetic, and their homologs, traces of organic nitrogen compounds, and mineral constituents of wood ash. The amount and nature of these extractives vary widely between heartwood and sapwood and, in some species at least, in the heartwood from different parts of the same tree. During the drying of wood, under some circumstances, these extractives may tend to concentrate at the surfaces.

Object of Painting Wood

The painting characteristics of wood must be considered with due regard for the object for which wood is painted. Painting is done to secure and maintain a desired appearance on surfaces exposed to view. There are at least three factors in appearance, namely, color, texture, and line. Exterior wood surfaces must be kept painted wherever color with smooth texture and straight, snug lines are desired; they may be kept varnished where the natural wood color and grain together with smooth texture and snug lines are wanted; they may be kept stained or thinly painted where color with rough texture and broken lines are preferred; and they may be left without surface treatment where the neutral color, shaggy texture, and irregular lines of weather-beaten wood give the effect selected. In general, architectural considerations dictate that different patterns of lumber be used according to the effect desired. Thus siding nailed with the planed side out is almost always painted when any pretense of keeping up appearances is made, but if nailed sawed side out or if shingles are used, the surface is rarely painted and may either be stained or left to weather naturally.

In considering painting, therefore, we are striving to maintain a colored opaque coating intact, presenting a smooth surface, with straight, snug lines. The effect is marred if the smooth wood surface is permitted to check badly or roughen by weathering, for ordinary painting does not restore a surface with smooth texture. Likewise warping, cupping, and loosening of the boards must be prevented if

snug lines are to be retained. The paint coating must therefore protect the wood against weathering to keep up the desired appearance.

Influence of Wood Properties During

Application of Paint

The first coat of paint applied to new wood is very largely consumed in filling the voids, leaving a level, nonabsorptive surface on which subsequent applications can build a coating. However, even though one-half to three-fourths of the volume of wood is void, a comparatively small amount of paint is required for priming it. A plaster wall takes two or three times as much paint as wood. The cellular structure of wood in contrast to the granular structure of plaster accounts for the difference, because in wood, penetration beyond the voids in those cells cut open in making the surface can take place only through the very fine openings in the pit membranes.

End-grain wood surfaces consume much more paint than edge or flat-grain surfaces because the long tracheids stand at right angles to them. However, not much end-grain wood need be painted. There is little if any difference in the consumption of paint between edge and flat-grain surfaces. Light wood, with its greater content of voids, consumes measurably more paint than heavy wood, though the difference is not much greater than the individual variation between painters in applying paint and it is largely compensated if the customary recommendation is followed of mixing the priming coat relatively richer in turpentine than in linseed oil for heavy woods than for light ones. Undoubtedly there would be a marked difference in spreading rate of paint between springwood and summerwood if we had the two kinds of surfaces to paint separately.

The liquids of paint penetrate more deeply into wood than do the pigments, as can be proved by adding an oil-soluble red dye to the paint before application and later examining the depth to which the red color penetrates. The ratio of solids to liquids in the paint remaining at the surface is thereby upset, so that a paint that dries with a glossy film on glass or metal, dries with a dull film on wood. Judged by the effect on gloss, more oil is thus filtered off in springwood than in summerwood, but penetration is found to be deeper in summerwood. The paradox is not mysterious, for the void capacity of summerwood is only half that of springwood.

Penetration of oil as deeply as possible has long been held desirable in painting wood. There seems to be no good reason for so believing, however, because paint fails soonest on the summerwood, into which oil penetrates deepest.

Extractives present in cypress and redwood tend to retard the drying of some paints on these woods, especially in the presence of much moisture or low temperatures. The fact is of no serious practical import, for experiment proves that coatings applied to these woods under conditions giving pronounced retardation of drying can not be distinguished in later exposure from coatings applied under good drying conditions. From the point of view of theory, however, the fact is probably significant, for these woods are among those upon which paint coatings last longest even when they have rather wide bands of summerwood.

Normal and Abnormal Conditions

of Exposure

In considering the behavior of paint coatings on wood, sharp distinction must be drawn between normal and abnormal conditions of exposure. Under normal conditions moisture in large amounts gains access only to the painted surface for short times during wet weather. Under abnormal conditions much moisture gains access to the backs of the painted boards, usually for fairly long intervals. The results of abnormal conditions will not be discussed here; it need only be said in passing that trouble from abnormal conditions may be experienced with any kind of paint, on any kind of wood, and may arise very early in the coating's history. The failure may take one or more of several forms. The coating may blister and peel, which are easily recognized, or it may scale, which is often hard to distinguish from scaling under normal conditions with some paints. The coating may become discolored with water-soluble extractives from the wood or with dirt and stains carried by the water from other sources within the structure. The coating may become discolored by blue stain fungi growing in sapwood, and finally, under prolonged or repeated exposure to abnormal conditions, the wood beneath the coating may rot.

Early Part of Normal Exposure

Not Influenced by Wood

Under normal conditions of exposure the behavior of paint coatings during the early part of their service life is not materially influenced by the kind of wood surface upon which they are applied. The rate of loss in gloss, the collection of dirt, the development of chalking and fading, the time when paint checking begins, and the distinctive pattern of the checking depend upon the kind of paint, the climate, the local conditions of exposure, and perhaps to some extent upon the manner of application, but they are not influenced to any important extent by the wood.

By way of exception to this generalization it may be said that occasionally chalking and fading proceed more rapidly over springwood than over summerwood, so that the grain of the wood is revealed by the appearance of the coating over it. Such behavior is here regarded as due to inadequate priming and therefore to poor craftsmanship in painting, because well-painted surfaces do not so behave. Further exception may be made of loose grain appearing on flat-grain boards that are turned pith side out, which will be discussed later.

The nature of the wood surface begins to influence the behavior of coatings when they reach the point in their deterioration at which they no longer protect the wood adequately against weathering and when they begin to disintegrate by crumbling, flaking, or scaling, leaving parts of the wood surface bare. From this point on, under present painting practices, it may fairly be said that the kind of wood surface rather than the composition of the paint dominates the behavior of the coating and determines when repainting is in order.

Influence of Wood on Ultimate

Failure of Coatings

Paints as we now use them fail ultimately either by (1) inadequately protecting the wood so that it begins to weather check, cup, warp, or pull away from fastenings, or (2) crumbling, flaking, or scaling, leaving parts of the wood bare. As would be expected, the wood surfaces on which failure by inadequacy of protection is first noticed are the

surfaces having the greatest tendency to develop weathering defects. Failure of the coating to remain intact starts over the summerwood and a stage is usually reached, if the exposure continues long enough, when all the summerwood is bare while the springwood remains covered. The amount and distribution of summerwood is therefore the predominant influence in failure of the coating to remain intact.

Influence of Species

Chart 1 summarizes the results by species of an extensive series of field tests by the Forest Products Laboratory. Two kinds of paint were used, for each of which a separate tabulation is made. There is far more difference in the life of coatings of the same kind of paint on different woods than between the two paints on any wood.

The woods are divided into four groups on the basis of the results in this test; I, those woods on which paint protected and remained intact longest; II, those on which it remained intact but failed sooner in protection than was found for group I woods; III, those on which paint failed in both protection and integrity sooner than on group I woods; IV, those on which paint failed soonest, especially in integrity.

Influence of Density and Ring Width

Chart 2 shows that the classification by species follows fairly closely the average density of the species. A still closer parallel would be brought out if the chart could show ring width as well as density in their bearing on the results. The photograph, Figure 1, illustrates how ring width modifies density in determining coating integrity. The four boards shown are all flat grain and of the same species of wood. They were taken from paint test panels and planed to remove the remnants of the coatings and reveal the nature of the surface. Boards A and B held paint well, boards C and D poorly. Board A is both light in weight and narrow-ringed, board D is heavy and wide-ringed. Boards B and C are equal in density but B is narrow-ringed while C is wide-ringed.

As already pointed out, there is much variation within many species in density and ring width and it follows that there is a corresponding variation in painting characteristics. Density and ring width consequently are a far

WHITE LEAD PAINT

LEAD AND ZINC PAINT

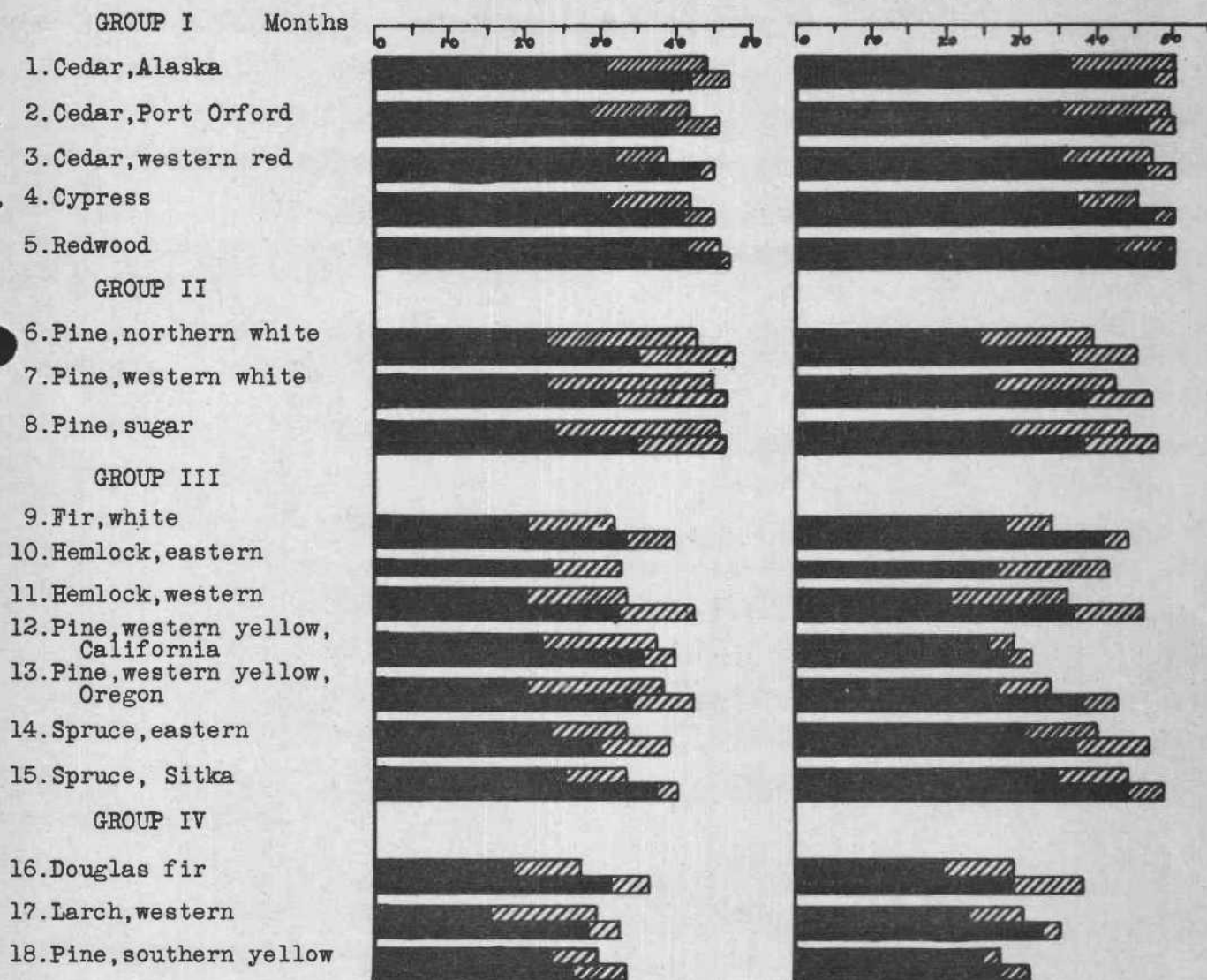


Chart 1.--Representing for the different woods the average time elapsed before repainting was needed to maintain (a) the integrity of the coating, (b) adequate protection against wood weathering. For each species the upper half of each bar represents flat-grain panels, the lower half edge-grain panels, except that for eastern hemlock only flat-grain panels were tested. The whole length of the bar, that is, the solid plus the crosshatching, represents the time for repainting when coating integrity only is considered; the solid part alone represents the time for repainting when protection of the wood is considered also

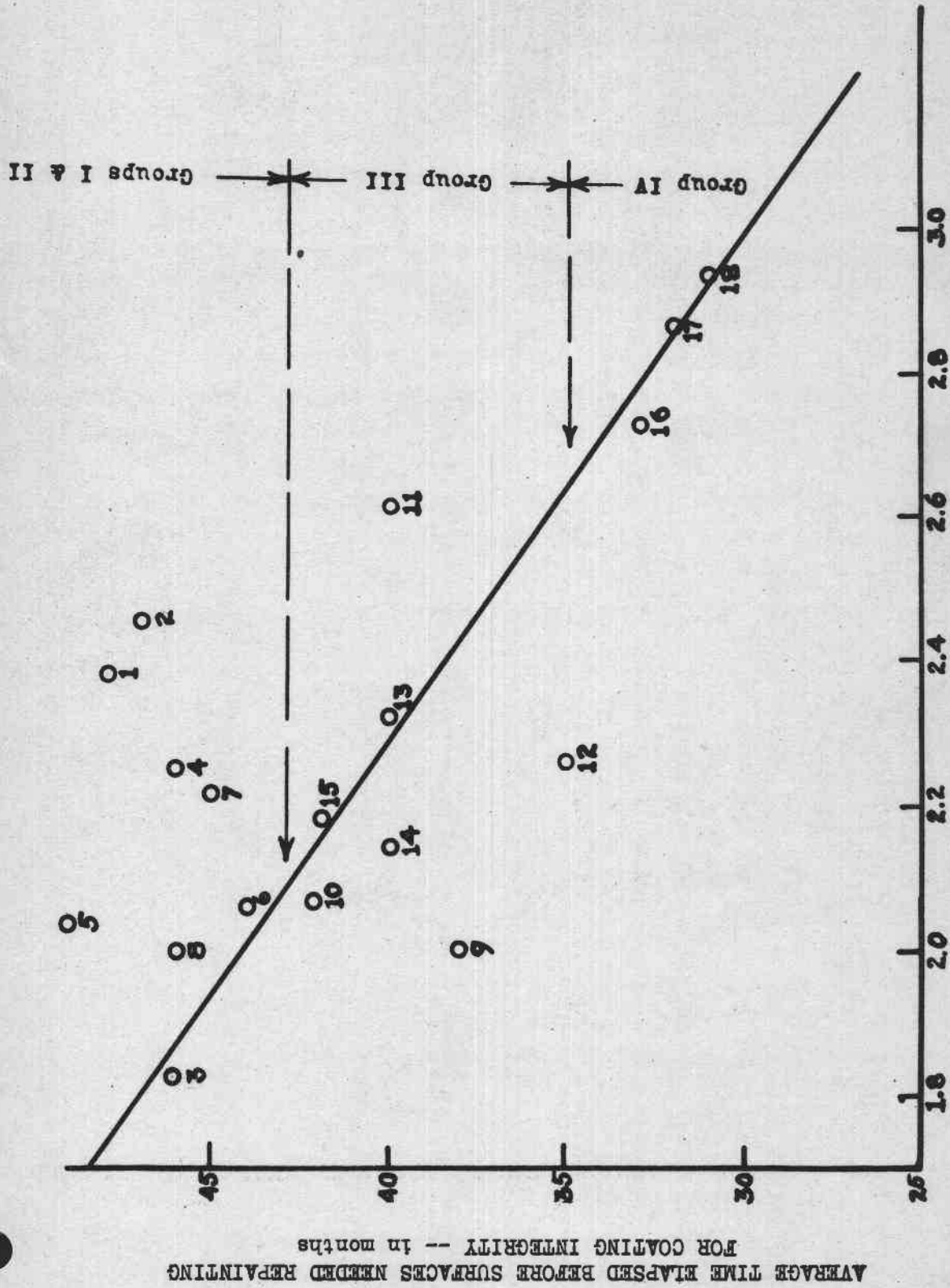


Chart 2.--The relation between repainting time and weight of dry wood in the panels tested for the different species. The key to the numbers is given in Chart 1

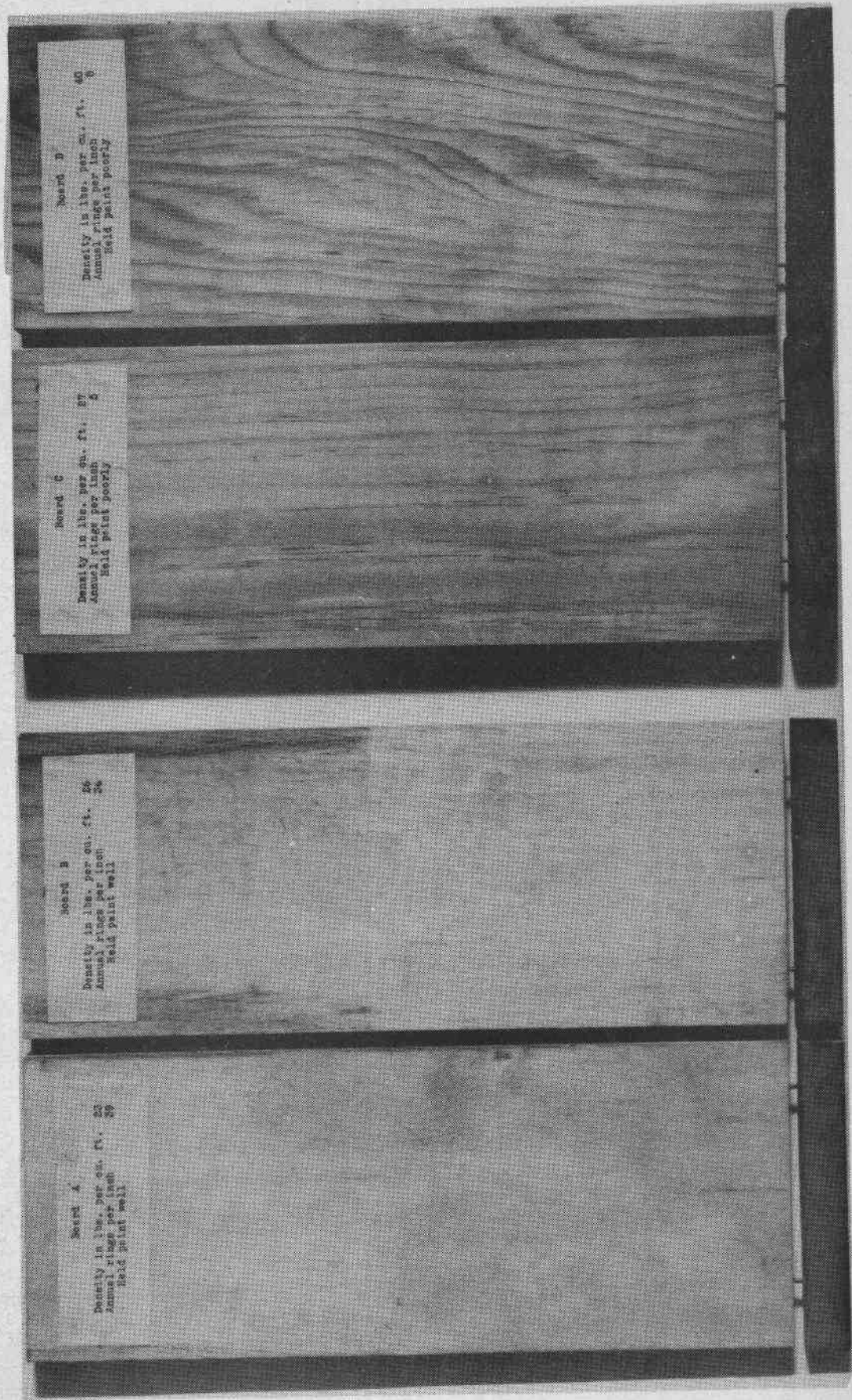


Figure 1.--Illustrating the influence of ring width and density on the behavior of paint coatings. The boards are all of the same species of wood

more precise guide to paintability than species, but woods are bought and sold by species and not by density and ring width.

Influence of Direction of Grain

Chart 1 shows that edge-grain boards are far superior to flat-grain boards, both because they require less protection against weathering and because they display their summerwood in narrow lines rather than in flaring areas and hence hold coatings intact longer.

The bark side of flat-grain boards is far superior to the pith side in many species because there is a tendency for the grain to shell out on the pith side. This is a form of wood weathering against which paint should, theoretically, afford protection. In practice, however, paint as we now use it proves inadequate. Flat-grain boards should therefore be turned bark side out.

Influence of Grade

Knots are objectionable in painted surfaces because they do not remain perfectly concealed, either because they do not remain level with the rest of the surface, because they sometimes cause the coating over them to turn yellow, because the wood of the knot may crack, or because the paint may scale over the knot. Pitch pockets and pitch streaks lead to objectionable exudation of pitch through coatings. For these reasons high-grade lumber of any species is better for painting than the lower grades.

Influence of Extractives

The position of cypress and redwood in Charts 1 and 2 seems to be more favorable than their density and ring width would predict. It has already been mentioned that these woods contain extractives that retard drying under certain circumstances and it is plausible to consider these substances as inhibitors of oxidation exercising a favorable influence on the maintenance of coating integrity.

A careful examination of Chart 1 shows that woods containing a resin with an oil-soluble acid like rosin compare with the other woods more favorably in maintenance of coating integrity for white lead paint than in integrity for lead and zinc paint. This is in line with the familiar evidence that paints containing zinc oxide are adversely affected by acids present in linseed oil.

Influence of Climate

Chart 3 shows that climate profoundly influences the durability of paint coatings, as has long been realized, but the differences between woods remain much the same. However, the amount of difference between woods of the four classes is less in the more humid climates than it is in the drier ones.

Influence of Paint Composition

The Forest Products Laboratory has tried various expedients in priming-coat procedure that have been recommended for obtaining better results on wood surfaces containing much summerwood. The proportions of turpentine and linseed oil in the priming coat have been altered greatly, thinners like benzol have been used in place of turpentine, and special priming-coat paints have been used. All but one of these expedients have either failed to alter the behavior of the coatings or have led to earlier loss of coating integrity. Aluminum paint used as a priming coat under white lead or lead and zinc paint materially prolongs the life of the coating both in protective power and in integrity, but the ultimate failure takes place by flaking from the summerwood just as it does when the paints are applied in the customary fashion.

The Forest Products Laboratory has also tried a number of supposedly harmful painting practices, such as painting wood at high moisture content (not containing free water, however), painting in humid atmospheres and in the absence of sunlight and allowing short times for drying between coats. The results seem to indicate that the bad effects of such factors in paint application have been greatly exaggerated.

The Wood Painting Problem for

Future Research to Solve

The variability in behavior of paint coatings on wood surfaces of different kinds is the wood-painting problem that must be solved before consumers of paint and of lumber can be given better paint service. To some extent selection of lumber in accordance with its painting characteristics can be practiced but improvement in this direction is limited by the facts that in choosing wood for any purpose

WHITE LEAD PAINT

LEAD AND ZINC PAINT

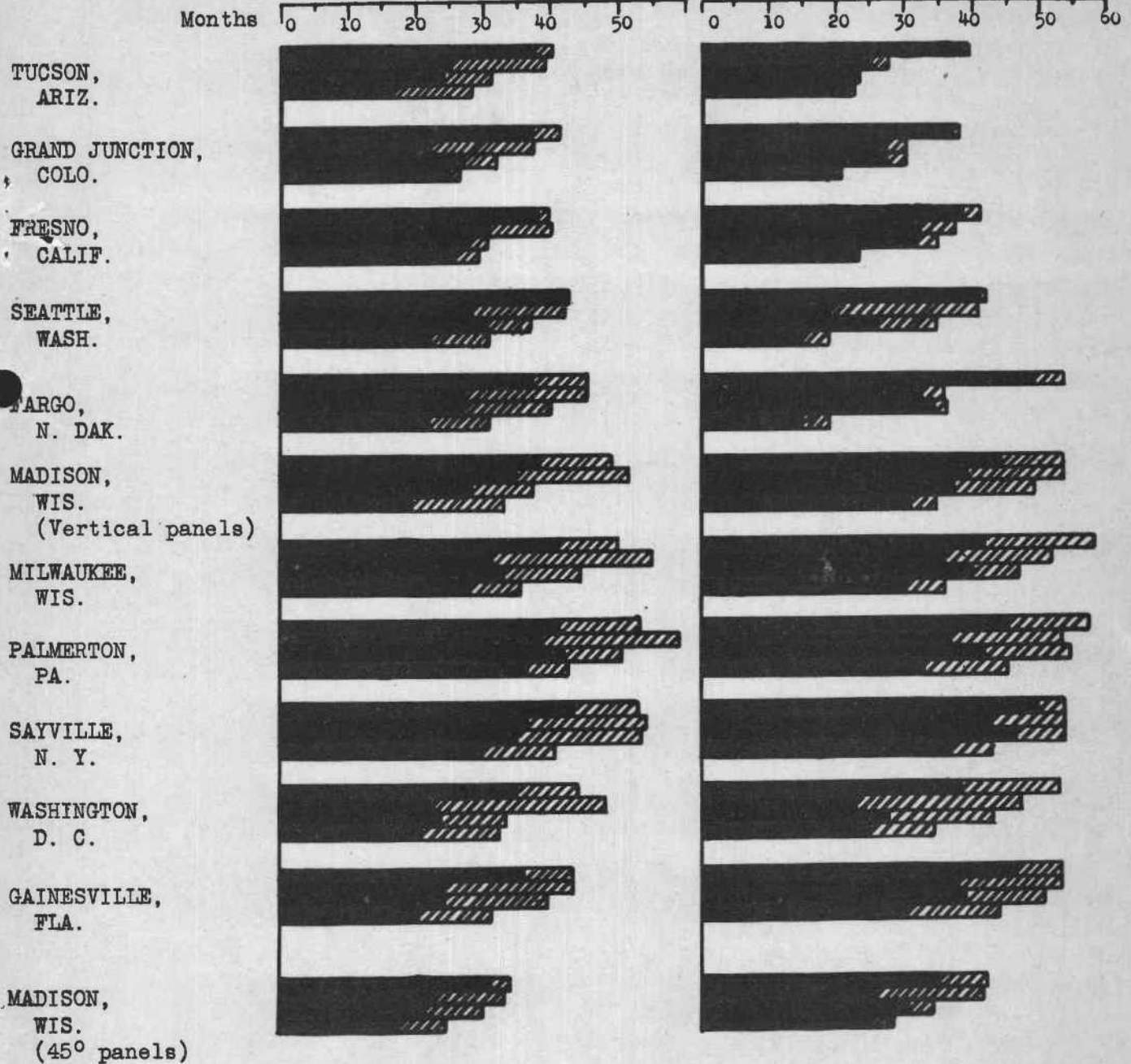


Chart 3.--Illustrating the influence of climate on the behavior of paint coatings. Each bar is divided into four parts representing respectively, beginning with the upper part, the behavior of coatings on woods of Group I, Group II, Group III, and Group IV. The whole length of the bar, that is the solid plus the crosshatching, represents the average time elapsed before repainting was needed when coating integrity alone was considered; the solid part represents the time for repainting when protection of the wood was considered also

other factors must be considered besides paintability and that most of our available lumber supply is of the kinds that contain much summerwood. Furthermore, second-growth woods are likely to be less desirable in respect to painting than the virgin stands because the trees will usually be grown more rapidly and will be cut younger. It is conceivable that some means of treating lumber to improve its painting characteristics may be invented, but there is no reason for regarding that point of attack on the problem as particularly hopeful. Improved paint or painting technic seems much more likely to furnish the solution.

A coating that would endure indefinitely is probably a vain objective and perhaps not an altogether desirable one, for most people would like to change their scheme of decoration once in a while. The ideal coating for wood, however, ought to remain an adequate protective agent against wood weathering until its appearance is so changed that repainting is clearly necessary and it ought to wear down uniformly over summerwood and springwood alike, being firmly anchored to all parts of the wood when repainting is done. Flaking from summerwood should be unknown. With such a paint, all wood surfaces would give equally satisfactory paint service.

The attainment of an ideal paint of this kind is an ambitious but by no means unpromising objective. As we see it, the problem is one of securing firmer and more permanent adhesion between coatings and wood. Probably at present aged coatings cling to wood by mechanical embedding in the rough surface, much as plaster grips lath. Summerwood, with its low void volume and very small voids, offers an uncertain support for adhesion of that kind. A true adhesion between wood substance and the matrix of the paint coating is called for. Glue sticks to summerwood, why can not paint be made to do so? The Forest Products Laboratory proposes to seek true adhesion between paint coatings and wood and invites the cooperation of the technical men of the paint industry in that quest.