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Preservative Treatment of Hardwoods: A Review

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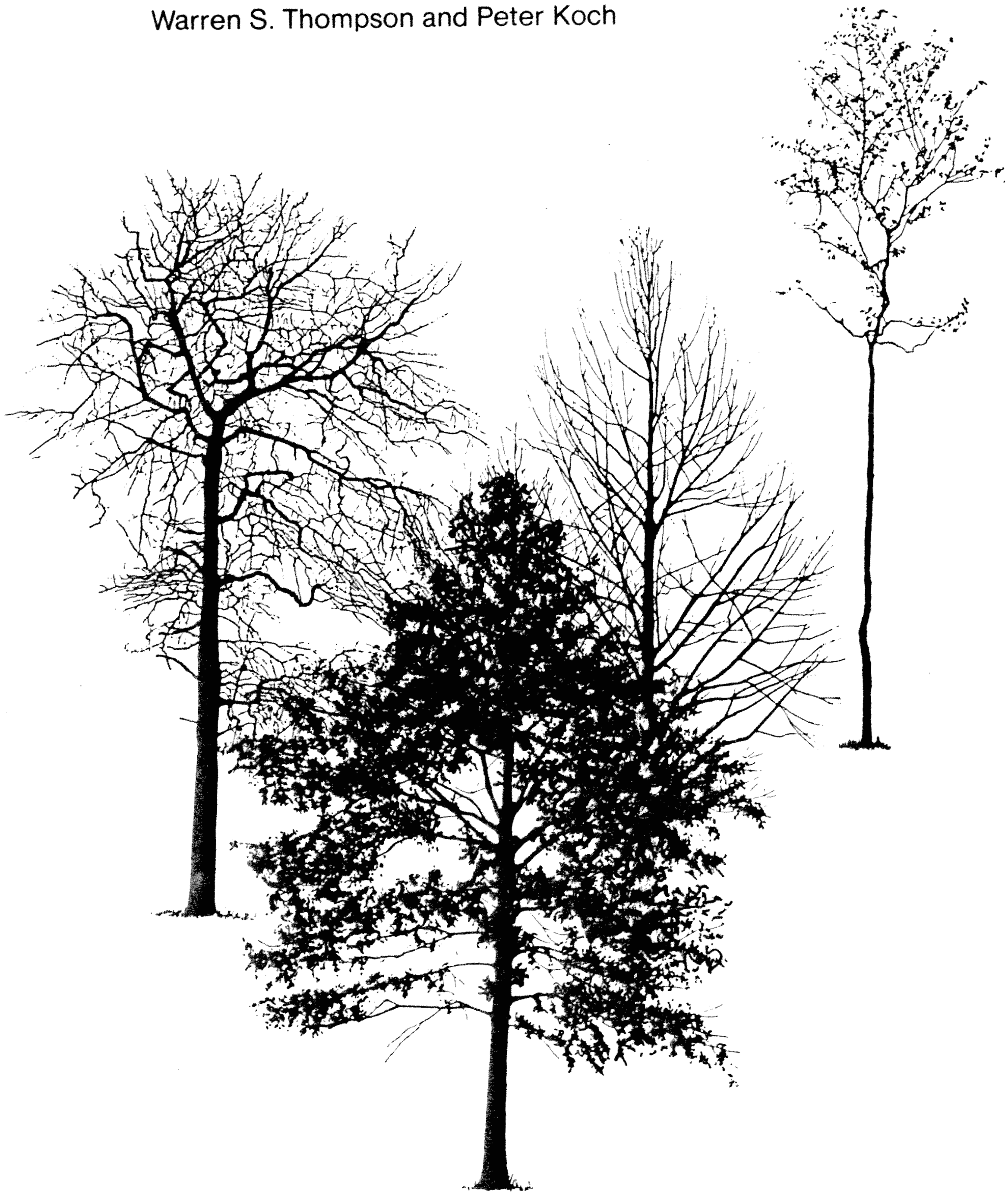

SUMMARY

Increasing demand for softwoods, now supplying two-thirds of the wood volume annually treated with preservatives in the United States, presages major increases in hardwoods treated by the wood processing industry. The wood industries of Northern Europe, Australia and other areas where, as in this country, hardwoods are relatively abundant, are treating hardwoods for a wide range of products. This report reviews information basic to the treatment of some 56 American hardwood species with more than a dozen preservatives by variations of five pressure and four non-pressure treatment methods, together with data from softwood tests of materials and methods for which hardwood test results are not available. Also reviewed are data on impregnation of hardwoods for stabilization and to improve resistance to fire.

American hardwoods available for treatment are primarily in sizes and qualities unsuitable for high grade sawn products, but usable for crossties, posts, mine timbers, piling, pallets, laminated wood, fiberboards, and flakeboards. Some hardwood species with low specific gravities are easily treated at pressures and for durations similar to those used for softwoods of like density; heavy hardwoods are more difficult to treat and require longer impregnation times and higher pressures. Hardwood species differ widely, however, in their individual requirements.

Available chemicals and technology protect hardwood crossties from decay for service lives of 25 to 50 years; much current replacement in rail lines results from physical wear rather than decay. Somewhat shorter service lives may be expected from posts, which are normally more severely exposed, but for most species treatment can extend service life by 10 to 25 years. A number of non-pressure treatments and a variety of preservatives are widely used in post treatment.

For products in less severe exposure, the same chemicals can be used in lighter applications, or other chemicals selected to minimize undesirable effects such as altered color, stickiness, or toxicity to mammals. Thus life of boxes and pallets used for storage in damp situations can be greatly extended, and exposed woodwork can be impregnated for protection against insects and decay, and to improve fire resistance.

For applications in plywoods, particleboards, flakeboards, and fiberboards, chemicals must be compatible with adhesives which give strength to the panels. This requirement limits the choices of usable chemicals, but for most applications treatments with selected chemicals appear feasible, though some loss of strength may be involved. Further research is desirable in this field to more precisely define acceptable combinations of chemicals and adhesives.

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INTRODUCTION

Hardwoods constitute about one-third of the timber resource of the United States, and occupy slightly over half of the Nation's commercial timberland. Occurring mainly in the East, they predominate over two-thirds of the eastern forest acreage. Although varying widely in many characteristics and often of high value in large, clear sizes, most hardwood trees tend to be small, crooked, and defective. Over much of the South they occupy sites on which pines could be grown more profitably (table 1, fig. 1). In both the South and the Northeast, stands of hardwoods, even on the better hardwood sites, contain much material of marginal value for traditional uses.

One way to make optimum use of the hardwood resource is to emphasize use of those products, such as fiberboard and particleboard, whose quality is not a direct function of stem quality. Another is to use small hardwoods for the production of treated products, such as fence posts, mine timbers, landscape timbers, and similar items, for which stem size and quality are not of critical importance.

Hardwood crossties currently account for about one-third of the 330 million cu ft of wood treated annually in the United States. This volume represents essentially all of the commercial production of treated hardwood products except for some mine timbers, highway posts, and oak piling. Other markets for treated wood, such as utility poles, fence posts, and sawn products, have long been satisfied by softwood species, principally the southern pines and Douglas-fir, because of their favorable form, availability in a wide range of sizes, and relatively uniform treating properties. This pattern of utilization tends to be unique to the United States. Treated hardwoods are used extensively for a range of products in Australia, New Zealand, Africa, Asia, Scandinavia, and parts of Europe where the supply of hardwoods is large relative to that of softwoods.

While treated commercially mainly for railroad ties and piling, hardwoods have been studied extensively in terms of their permeability to preservatives, their performance in ground-contact service, and the anatomical and biological factors which influence these properties. Related studies have provided information on impregnation of hardwoods for stabilization and fire resistance. Additional research is needed. Thus, Hatfield (1959) stressed the need for research to ascertain treatability of little used species of wood. He pointed out that lack of uniformity of treatment and inadequate penetration and retentions were common problems with many hardwood species. A substantial body of literature has evolved from the long-term and continuing interest in this subject. It identifies some of the problems and opportunities associated with the preservative treatment of hardwoods and the performance of hardwoods under adverse biotic conditions. Much of the literature describes results on hardwood species important on non-pine sites (table 2); because these results are, for the most part, pertinent to pine-site hardwoods, they are summarized in this report.

Table 1.—*The major hardwood species on pine sites in the South*

Common name	Botanical name
Ash, green	*Fraxinus pennsylvanica* Marsh.
Ash, white	*F. americana* L.
Elm, American	*Ulmus americana* L.
Elm, winged	*U. alata* Michx.
Hackberry	*Celtis* sp.
Hickory	*Carya* sp.
Maple, red	*Acer rubrum* L.
Oak, black	*Quercus velutina* Lam.
Oak, blackjack	*Q. marilandica* Muenchh.
Oak, cherrybark	*Q. falcata* Michx. var. *pagodaefolia* Ell.
Oak, chestnut	*Q. prinus* L.
Oak, laurel	*Q. laurifolia* Michx.
Oak, northern red	*Q. rubra* L.
Oak, post	*Q. stellata* Wangenh.
Oak, scarlet	*Q. coccinea* Muenchh.
Oak, Shumard	*Q. shumardii* Buckl.
Oak, southern red	*Q. falcata* Michx.
Oak, water	*Q. nigra* L.
Oak, white	*Q. alba* L.
Sweetbay	*Magnolia virginana* L.
Sweetgum	*Liquidambar styraciflua* L.
Tupelo, black	*Nyssa sylvatica* Marsh.
Yellow-poplar	*Liriodendron tulipifera* L.

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Figure 1.—*Typical stand of hardwoods mixed with southern pines. The hardwoods, deemed unmerchantable, have been girdled to deaden them and thereby accelerate growth of the pines.*

FACTORS AFFECTING TREATMENT QUALITY

Amenability of wood to preservative treatment depends upon numerous factors related to pre-treatment processing, such gross characteristics as sapwood thickness, and anatomical characteristics related to type, number, distribution, and size of its various structural elements. Variation in permeability to preservatives among species is almost always associated in part with differences in anatomical structure and the presence or absence of infiltrated materials. Variation within species may be due to many factors, including ratio of sapwood to heartwood, moisture content differences, and tree-to-tree differences in the amount and distribution of tyloses.

The fact that heartwood of all species is much less permeable than sapwood has a profound influence on the quality of preservative treatments of sawn products. Properly seasoned wood of all species is more easily penetrated by pressure processes than unseasoned wood; the drier the wood the deeper the penetration. Radial penetration of water-borne preservatives virtually stops at the point where free water is present. Freshly cut wood of most species can be properly treated only with difficulty, if at all.

Wood-Related Factors

Anatomical Structure.—The size, distribution, and condition of vessels are the most important basic factors affecting the preservative treatment of hardwoods. (See McMillin and Manwiller (in press) for an atlas of anatomical features of stemwood from the hardwood species listed in table 1.) Open pores (vessels) are the principal avenues for initial penetration in such species as red oak. White oak and other species whose vessels are wholly or partly occluded by tyloses or infiltrated substances are difficult to treat. The degree to which tyloses block penetration of preservatives varies with species. Tyloses in a few species, including American beech and some species of oak and hickory, are thin-walled and can be ruptured during treatment of the wood, thus permitting penetration. In other species tyloses are scattered and their effect on pre-

Table 2.—*Hardwood species common on non-pine sites, for which preservative treatment data are available*

Common name	Botanical name
Aspen, bigtooth	*Populus grandidentata* Michx.
Aspen, trembling	*P. tremuloides* Michx.
Basswood	*Tilia* sp.
Beech, American	*Fagus grandifolia* Ehrh.
Birch, river	*Betula nigra* L.
Birch, sweet (or black)	*B. lenta* L.
Birch, white	*B. papyrifera* Marsh.
Birch, yellow	*B. alleghaniensis* Britton
Blackgum	*Nyssa sylvatica* Marsh.
Box elder	*Acer negundo* L.
Butternut	*Juglans cinerea* L.
Cherry, black	*Prunus serotina* Ehrh.
Cottonwood	*Populus deltoides* Bartr.
Elm, slippery	*Ulmus rubra* Muhl.
Elm, rock	*U. thomasii* Sarg.
Elm, cedar	*U. crassifolia* Nutt.
Hickory, mockernut	*Carya tomentosa* Nutt.
Hickory, shagbark	*Carya ovata* (Mill.) K. Koch
Honey locust	*Gleditsia triacanthos* L.
Maple, silver[1]	*Acer saccharinum* L.
Maple, red[1]	*A. rubrum* L.
Maple, sugar	*A. saccharum* Marsh.
Oak, bur	*Quercus macrocarpa* Michx.
Oak, California blue	*Q. douglasii* Hook. & Arn.
Oak, overcup	*Q. lyrata* Walt.
Oak, pin	*Q. palustris* Muenchh.
Osage-orange	*Maclura pomifera* (Raf.) Schneid.
Pecan	*Carya illinoensis* (Wangenh.) K. Koch
Pecan, bitter	*C. aquatica* (Michx. f.) Nutt.
Persimmon	*Diospyros virginiana* L.
Poplar, aspen	*Populus* sp.
Redgum	*Liquidambar styraciflua* L.
Sycamore	*Platanus occidentalis* L.
Tupelo, water	*Nyssa aquatica* L.
Walnut, black	*Juglans nigra* L.
Willow, black	*Salix nigra* Marsh.

[1]Soft maples.

servative treatment is proportional to their frequency (Teesdale and MacLean 1918).

When vessels are blocked by tyloses or extraneous deposits, penetration may occur through such prosenchymatous tissues as fibers. Teesdale and MacLean (1918) concluded that hardwood rays, unlike those of softwoods, are not important in transverse distribution of preservatives. Behr et al. (1969), however, reported that, while longitudinal parenchyma is unimportant as a reservoir for preservative in most species, ray parenchyma retains significant amounts and is an important avenue for radial penetration in some species. Similarly, Greaves and Levy (1978) found CCA-type preservative in relatively high concentrations in ray tissue of several hardwoods. Bosshard (1961) likewise found creosote in ray tissue of beech—both as droplets and as a film on lumen walls. In areas of low retention the rays held most of the creosote. Narrow rays seem more important in preservative movement than wide rays such as occur in oak and beech.

Passage of preservatives through fibers and other prosenchymatous tissue is much slower and far less extensive than through vessels because hardwood pits are poorly developed. Teesdale and MacLean (1918), however, found it relatively important in certain species, such as hickory. They found the type and arrangement of the various structural elements more important to treatability than earlywood-latewood differences.

All recent work confirms Teesdale and MacLean's (1918) finding that vessels are important in the preservative treatment of hardwoods. Behr et al. (1969) reported latewood vessels more important as reservoirs of preservative than earlywood vessels, presumably because of the smaller diameter of the former; the ability of a capillary, such as the lumen of a vessel, to hold liquid varies inversely with diameter of the capillary. Perforation plates between vessels were often coated with or contained preservative when the vessel was not filled. These investigators stated that the magnitude of preservative adhesion to wood may be of importance in determining its effectiveness and contribute to differences in efficacy among species.

Teesdale and MacLean (1918) found fibers to be unimportant as avenues for preservative penetration unless the vessels were occluded. Reports by Liese (1957) that hardwood pit membranes are incapable of transmitting preservative because they contain no pores tend to support this conclusion. Côté (1963), however, observed that, while no openings were visible in basswood pits, the pits were nonetheless permeable to treating solution. Ernst (1964) found that fibers are important in determining the permeability of certain hardwoods, and Behr et al. (1969) found evidence of fiber-to-fiber movement of liquids via pits and concluded that fibers, as well as vasicentric and vascular tracheids in species containing these elements, are important reservoirs of preservative in treated wood. It appears, therefore, that the permeability of most hardwoods is attributable largely to their vessels, the fibers contributing little because of small lumen size and poor network of interconnecting pits—but this generalization is not true of all hardwoods.

Lack of agreement among investigators on the importance of different cell and tissue types to wood permeability may be due in part to natural variations among species. Thus, rays apparently are important avenues for preservative penetration in some species and not in others (Behr et al. 1969). Work of Levy and Greaves (1978) and Dickinson et al. (1976), who studied the distribution of preservative among tissue types in several species, revealed that each species has its characteristic distribution pattern. Some of the 10 hardwoods studied treated primarily through the rays, for others the principal avenues for penetration were the vessels, and for still others both rays and vessels were important.

Species.—Teesdale and MacLean (1918) studied creosote penetration and retention in heartwood and a few sapwood samples of 25 hardwood species. All samples were similarly seasoned to identical moisture contents, and were similarly treated. On the basis of their results they grouped the species into three treatability classes (table 3).

Sribahiono et al. (1974) reported that species could be placed less laboriously in the three classes defined by Teesdale and MacLean (1918) by treating specimens with 0.5 percent keystone oil red dye in mineral spirits by a vacuum impregnation technique and determining longitudinal penetration of the dissected specimens.

Siau et al. (1978) classified southern hardwoods into similar groups based on the ease of treatment with methyl methacrylate monomer using a vacuum process. Ease of treatment was evaluated in terms of the fractional void volume filled by monomer (table 4.)

They reported that treatability was generally well correlated with permeability and varied inversely with

Table 3.—*Tested species grouped according to difficulty of impregnation (Teesdale and MacLean 1918)*

Basis for grouping	Group I	Group II	Group III
Depth of penetration at 100 psi[1]			
Lateral	Complete	Variable	. . . .
Longtitudinal, inches	>8	4-8	2.5−
Retention of creosote, pcf[2]	12+	7-10	6−
Tyloses	Absent	Present, closure incomplete	Vessels occluded by tyloses
	Ash, green	Aspen, bigtooth	Beech
	Ash, white	Chestnut	Oak, bur
	Basswood	Elm, rock	Oak, white
	Beech	Hackberry	Sweetgum
	Birch, river	Hickory[3]	
	Birch, sweet	Maple, silver	
	Birch, yellow	Maple, sugar	
	Cherry	Sycamore	
	Elm, American	Willow, black	
	Elm, slippery		
	Hackberry[4]		
	Maple, silver[4]		
	Oak, chestnut		
	Oak, red		
	Sweetgum[4]		
	Tupelo gum[4 5]		

[1]Psi—pounds per square inch.
[2]Pcf—pounds per cubic foot.
[3]Vessels closed by tyloses, but creosote penetrated through fibers and tracheids.
[4]Samples were sapwood; all others were heartwood.
[5]Probably *Nyssa sylvatica* Marsh.

Table 4.—*Southern hardwoods grouped by difficulty of impregnation with methyl methacrylate monomer by vacuum process (Siau et al. 1978)*

Easy (0.8+ of voids filled)	Moderate (0.4-0.8 of voids filled)	Difficult (less than 0.4 of voids filled)
Maple, red	Ash, green	Hackberry
Sweetbay	Elm, American	Oak, black
Sweetgum	Elm, winged	Oak, blackjack
Tupelo, black	Hickory	Oak, post
Yellow-poplar	Oak, cherrybark	Oak, white
	Oak, laurel	
	Oak, northern red	
	Oak, scarlet	
	Oak, Shumard	
	Oak, southern red	
	Oak, water	

specific gravity. Thus, the average specific gravities of the "easy", "moderate", and "difficult" groups were 0.51, 0.69, and 0.74, respectively.

Cook (1978) studied directional penetration by pressure impregnation of short bolts in a commercial retort with a 5.3 percent solution of pentachlorophenol in a petroleum solvent, using resin coatings to restrict preservative movement to the transverse or longitudinal directions. Although his treating schedule was too mild to provide for penetration into refractory species, the method has promise for use in future studies.

Permeability.—Permeability of wood to liquids is a function of anatomical structure. The presence of cell deposits and incrustations on the membranes of pits connecting wood cells is a major factor in resistance to penetration of liquids. Various methods of improving permeability have been tried, including chemical treatments to extract material from the pit membrane or degrade the pit membrane itself. Sodium chlorite, pulping liquors, acids and bases have been tested (Nicholas 1977). All degrade the wood and reduce its strength. None are effective in heartwood, where permeability is most limited.

Biological treatments using fungi and bacteria, while used successfully on southern pine, are also effective only in sapwood. Enzymes (cellulase, pectinase, etc.) have been successfully used to improve permeability, without strength loss, of sapwood but not of heartwood. Greaves and Barnacle (1970), for example, reported that infection by microorganisms increased the permeability of slash pine and *Eucalyptus diversicolor* to creosote. This effect was attributed in both instances to depletion of cell contents in ray tissue and alterations of bordered pits by enzymes of invading organisms.

Cech (1971) and Cech and Huffman (1972) improved the seasoning and treating properties of refractory woods such as spruce (*Picea* sp.) by compressing boards from 5 to 15 percent of their thickness between pressure rolls (table 5). Nicholas and Siau (1973) applied the process to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with equal success. Retention and penetration of creosote in spruce increased more than 50 percent when Cech and Huffman (1972) compressed boards 15 to 20 percent before treatment.

Cech (1971) hypothesized that the compression treatment increased premeability by damaging pit membranes. This theory is supported by electron micrographs showing splits in some pit membranes, and by Nicholas and Siau's (1973) observation that radial compression is more effective than tangential.

Tesoro and Choong (1976) measured the permeability of nine hardwoods and three softwoods to both liquids and gas. For every species except cottonwood, heartwood was less permeable than sapwood. Longitudinal water permeability of the hardwood specimens that had been dried and resaturated was nine times greater than that of specimens that had never been dried.

Table 5.—*Effect of transverse compression on retention and penetration of creosote into eastern white spruce (Picea glauca* (Moench) Voss*) (Cech and Huffman 1972)*

Compression	Retention		Penetration	
		Fraction of controls	Fraction of cross section	Fraction of controls
percent	*pcf*[1]		*percent*	
0	3.4	....	20.8	....
10	4.6	135.3	24.6	118.3
15	5.5	161.8	32.8	157.7
20	5.2	152.9	31.5	151.4

[1]Pounds per cubic foot.

For soft maple the increase was 59-fold. Similar results were not obtained with softwoods because of extensive pit aspiration during drying.

In the Tesoro and Choong (1976) study, correlation was high between various measures of permeability and treatability of all hardwoods except semi-ring porous species, notably black willow and cottonwood. This was not true, however, for softwoods. Interestingly, permeability to water was the best indicator of treatability with copper sulfate, while permeability to gas was the best index for predicting treatability with creosote.

In other studies involving nine hardwoods and six softwoods Tesoro et al. (1966) found positive linear relationships between the logarithm of lateral air permeability and both creosote retention and depth of penetration. The correlation coefficient for permeability and retention level for the pooled results of hardwoods and softwoods was 0.847; that for permeability and depth of penetration was 0.687. Both values were significant at the 1 percent level. There was no significant difference between the regression curves for hardwoods and softwoods at the 1 percent level. Their data are presented in table 6.

Thomas (1976) conducted anatomical studies in an effort to determine the differences among sweetgum, hickory, and blackgum heartwood in degree of penetrability to fluids. He reported that blocking of intervessel pits, isolation of vessels from fibers, parenchyma, tyloses, and low vessel volume induced flow along heartwood fibers. He attributed the fact that hickory is moderately difficult to treat to the minor role played by vessels in preservative distribution, due to tyloses which obstruct liquid flow.

Tyloses and encrusted pit membranes in both vessels and fibers of sweetgum heartwood were found to halt liquid flow effectively, thus accounting for the difficulty of treating this species. By contrast, black tupelo heartwood lacks tyloses, contains little encrustation, and is relatively easy to treat.

Longitudinal and transverse permeabilities of cottonwood were determined with nitrogen gas by Isaacs et al. (1971) to fall within the range of 0.109-13.81 darcys and 0.0014-0.0715 darcys, respectively[1]. Surprisingly, sapwood of cottonwood was less permeable than its heartwood. Permeability was correlated with specific gravity in heartwood but not in sapwood. Permeability was not correlated with extractive content nor with treatability with creosote. Retentions of creosote varied widely among samples.

Measurements of the relative and absolute permeability[1] of willow, sweetgum, and tupelo were made by Tesoro et al. (1972). They reported that the pattern of relative permeability of these woods resembled that of oil-bearing rock. When the relative permeability to water was zero, that to oil was not equal to one. For any given level of saturation, the sum of the relative permeabilities of the two fluids was always less than unity except where the flowing phase—either oil or water—completely saturated the specimen. A small increase in the level of oil saturation resulted in a major increase in the relative permeability to oil; likewise, a small decrease in water saturation of a specimen occasioned a sharp decrease in the relative permeability of wood to that fluid. Oil flow through a specimen displaced only a small portion of the water.

[1]The Darcy unit is a measure of permeability; high values indicate greater permeability than low numbers. Relative permeability values are not corrected for viscosity of the flowing medium; absolute permeability is relative permeability multiplied by the viscosity of the flowing medium.

Movement of liquids into hardwoods and the anatomical and physical factors affecting it have been reported by Rosen (1974a, 1974b, and 1975a) and Rosen and vanEtten (1974). They found that bound moisture uptake is proportional to the square root of the time required for bound water to increase from the initial moisture content to two-thirds of the fiber saturation point. Bound and free uptake of organic solvents by red oak and black walnut were linear with the square root of time up to two-thirds of maximum adsorption.

Processing-Related Factors

Quality of treatment, as judged by preservative distribution and retention, varies widely among species because of the factors discussed above. Variation in treatment quality within a species, while perhaps due in part to some of these same factors, is most influenced by pretreatment processing and by treating conditions themselves. Wood may be incised and must be dried preparatory to all except diffusion treatments. The results achieved in pressure treatments are functions of the pressure and temperature employed. Treatment duration is important in both pressure and non-pressure processes.

Treating Conditions.—Within limits, preservative retentions achieved by pressure treatments vary inversely with moisture content of the wood and directly with temperature and pressure. Thus, for example,

Table 6.—*Mean transverse air permeabilities and retentions and depth of penetration of creosote for selected wood species*[1]. *(Adapted from Tesoro et al. 1966.)*

Species	Type of wood	Permeability	Retention	Depth of penetration
		cm³/sec-cm-atm	*g/cc*	*mm*
Balsam fir (*Abies balsamea* L. Mill.)	Sapwood	0.0094	0.19	2.86
Maple	Heartwood	.0110	.31	6.94
Hickory	Sapwood	.0036	.15	4.34
Hickory	Heartwood	.0032	.19	5.15
Ash	Sapwood	.0130	.23	4.70
Larch (*Larix* sp.)	Sapwood	.0037	.13	2.05
Larch	Heartwood	.0031	.05	0.66
Spruce	Sapwood	.0072	.23	3.88
Pine (*Pinus* sp.)	Sapwood	.0350	.36	. . .
Pine	Heartwood	.0068	.14	. . .
Aspen	Heartwood	.0590	.44	4.95
Cherry	Heartwood	.0062	.06	1.08
Douglas-fir	Sapwood	.0440	.17	5.78
Douglas-fir	Heartwood	.0022	.14	2.17
Oak	Heartwood	.0062	.05	.73
Mahogany (*Swietenia mahogani* Jacq.)	Heartwood	.0018	.02	.19
Baldcypress (*Taxodium distichum* (L.) Rich.)	Heartwood	.0390	.44	6.03
Teak (*Tectona grandis* L. F.)	Sapwood	.0008	.04	.17
Teak	Heartwood	.0000	.03	.20
Basswood	Heartwood	.1900	.51	6.36

[1]Each measurement is the average for four replicated samples.

a direct relationship has been found between treating pressure within the range of 0 to 800 psi and preservative retention (Walters 1967). Retentions also varied directly with preservative temperature, so that increasing temperature from 100 to 200°F effected a 28 percent increase in adsorption. Siau (1970) likewise has shown that adsorption of preservative by wood species having a range of permeabilities increases directly with treating pressure and inversely with solution viscosity. Retentions obtained with the various species were in the same order as their permeabilities. Retentions of 91 and 78 percent of void volume were achieved by the full-cell process with Douglas-fir and white oak heartwood, respectively, when a pressure of 1,000 psi was used.

The relationship between treating pressure and preservative adsorption is anchored to wood structure. The size openings available for preservative movement in wood varies widely among species and between sapwood and heartwood. Size of openings determines the pressure required to insure an adequate treatment. Siau (1971) calculated the pressure needed to force various liquids through different pore sizes. He found that the smallest pore that could effectively be filled with water using the highest gauge pressure available at most commercial treating plants (200 psi) has a radius of 0.10 μm (Nicholas and Siau 1973). Stamm (1967, 1970) showed that many species have pore radii that are considerably smaller than that value. The effect of pore size on adsorption is shown dramatically in figure 2. The breaks in the curves (e.g., Douglas-fir) were shown by Nicholas and Siau (1973) to correspond to radii of pores through which the liquid could be forced by the pressure involved.

The effect of pressure is not necessarily the same for all species. Akhtar and Walters (1974) reported changes in retention in white oak from 4.59 pcf to 8.67 pcf, a difference of 89 percent, accompanied pressure increases in the range of 150 to 600 psi. For red oak, however, the corresponding increase over the same pressure range was 17 percent, from 16.66 pcf to 19.48 pcf. Differences between these species were confirmed by Rosen (1975b) at pressures from 200 to 2015 psi; increased retention with higher pressure was more pronounced for white oak than for red oak. Degree of impregnation, expressed as a percentage of the theoretical maximum retention, was linearly related to the logarithm of treating pressure.

Incising.—Relatively few wood species are sufficiently permeable for consistently uniform penetration and desired retention of preservatives. To expedite penetration and retention of preservative solution, wood surfaces of moderately to difficultly permeable species may be incised by roller-mounted knives, leaving variously patterned longitudinal cuts, usually less than 1 inch long and 1 inch deep (fig. 3). Many sawn

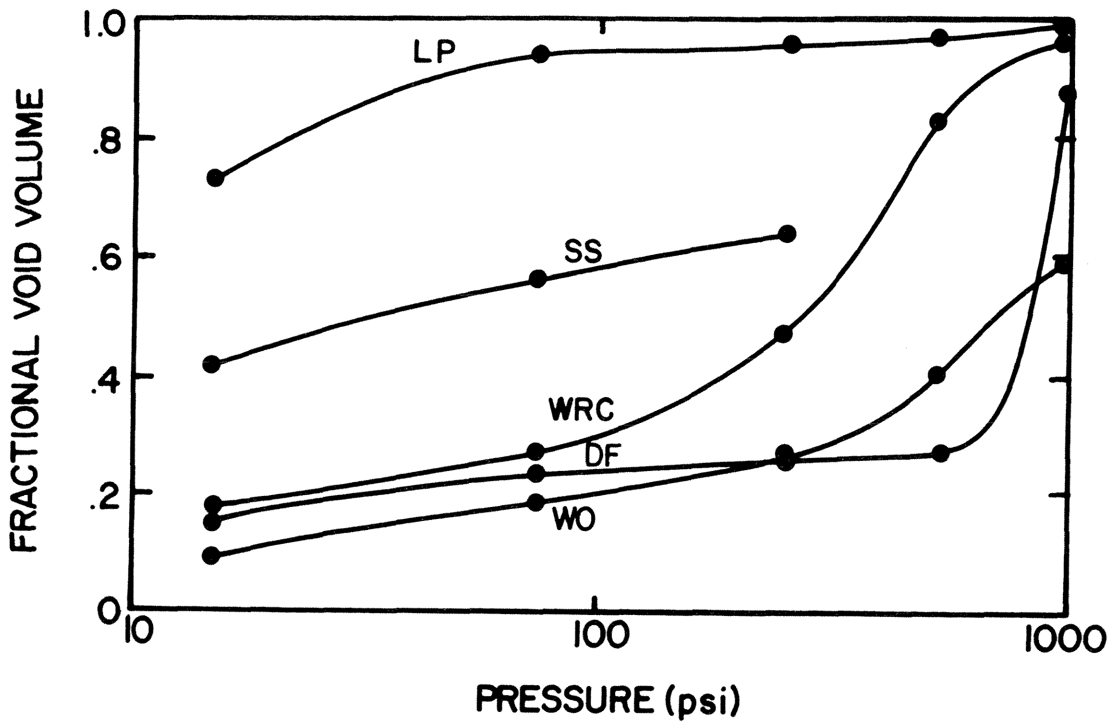

Figure 2.—*Effect of treating pressure on permeability of several species to a hydrocarbon oil with a viscosity of 1.0 poise. LP denotes longleaf pine (*Pinus palustris *Mill.); SS, sitka spruce (*Picea sitchensis *(Bong.) Carr.); WRC, western redcedar (*Thuja plicata *Donn.); DF, Douglas-fir; WO, white oak. (Drawing after Siau 1970.)*

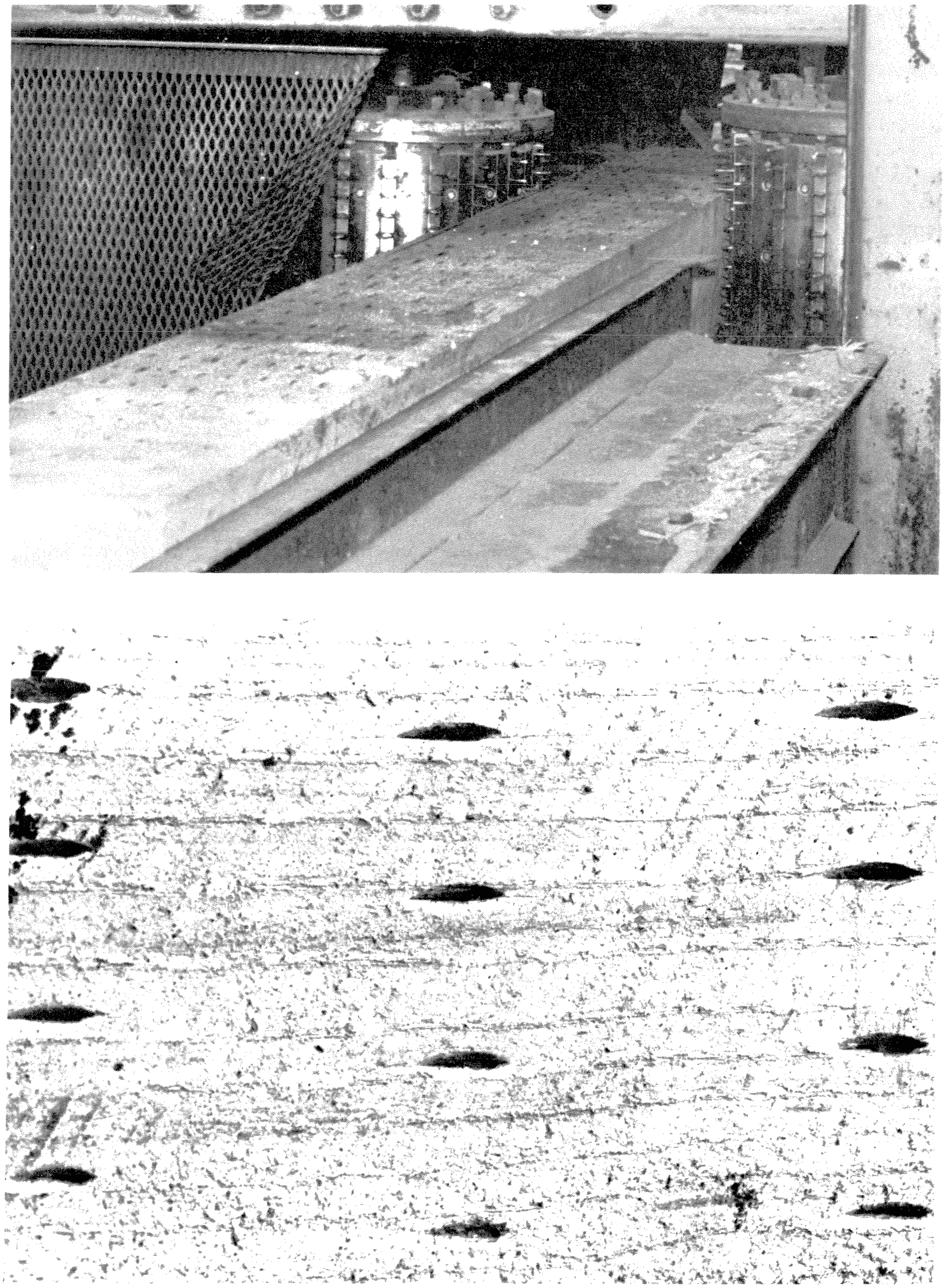

Figure 3.—*Incising of refractory species to increase retention and depth of penetration of preservative. (Top) Greenlee drums designed for 56 incisions per square foot. (Bottom) Incisions measure about ¾-inch long and ¾-inch deep.*

products, hardwood crossties among them, are routinely incised, regardless of species, because sapwood of some species and heartwood of most hardwoods are difficult to treat adequately. Round stock may or may not be incised depending upon species.

Perrin (1978) has reviewed the history and practice of incising. That it has accomplished its original purpose to increase penetration and retention into refractory species of wood (Bellman 1968) is attested to by numerous reports. Increases in treatment quality effected by incising of eucalyptus (Johanson 1975), Japanese oak (Anonymous 1955), and other hardwood species (Kanehira and Taniguchi 1960; Chudnoff and Goytia 1967) clearly demonstrate the importance of the process. Typical data from Graham (1956) on the effects of incising on preservative treatment of six softwoods are given in table 7. Incising improved both penetration and retention of creosote in several of the species. Similar results have been reported earlier by MacLean (1930).

Beneficial effects of incising on checking were reported by Harkom (1932) who found incising at the rate of 56 incisions per square foot before air-drying reduced serious checking by 21, 23, and 61 percent in birch, maple, and beech ties. Henry (1970) and Franciosi (1956, 1967) found that the beneficial effects of incising were still evident after 10 to 18 years in service. Graham and Estep (1966), however, reported that checking after treatment in all incised Douglas-fir spar crossarms in their study exposed untreated heartwood.

Conditioning.—Maximum preservative retention is a negative function of moisture content for woods of the same specific gravity. Walters (1967) found that sweetgum specimens with a moisture content of 8 percent adsorbed 2.3 times as much preservative during high-pressure treatments as specimens with a moisture content of 25 percent.

Conditioning treatments are applied to reduce the moisture content of stock to a level at which it will accept the requisite amount of preservative and permit radial penetration at least to the deepest limit of the zone within which samples are collected for retention determinations. Air-drying is the most common method of conditioning large items, such as crossties. Because air-drying requires large inventories of stock, Boulton drying and vapor drying are being used by an increasing number of plants.

Boulton drying is applicable to any stock destined for treatment with an oily preservative. Basically, the process involves the use of the preservative itself as a heat-transfer medium and a vacuum to reduce the boiling point of water. Temperatures up to 220°F and vacuum of 14 to 24 inches of mercury are employed (Graham 1980). Vacuums in this range correspond to boiling points of water of 152°F to 182°F. Duration of the Boulton process varies with product size and initial moisture content, but typically ranges from 20 to 60 hours. Wood can be dried to a moisture content below the fiber saturation point by this method. Representative moisture content data for Boulton drying of Douglas-fir pole sections for 43 hours are shown below (Graham and Womack 1972; Graham 1980). Kiln-drying for 43 hours provided an almost identical moisture gradient.

Inches from surface	Initial moisture content	Moisture content after Boulton drying
	Percent	
1	103	31
2	71	31
3	44	35
4	34	33
5	34	32
6	33	30

Similar results can be obtained with hardwood crossties, although the target moisture content for this product is generally 40 to 45 percent, somewhat higher than that shown for Douglas-fir.

Vapor drying has been used almost exclusively to condition hardwood ties since its development in the

Table 7.—*The effect of incising on the creosote treatment of several Oregon conifers (Graham 1956)*[1]

Species	Average preservative penetration		Average preservative retention	
	Incised	Nonincised	Incised	Nonincised
	inches		*pcf*	
Libocedrus decurrens Torr.	1.0	0.7	17.1	12.1
Abies magnifica A. Murr.	.9	.6	14.7	10.7
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.	1.5	1.5	17.8	19.5
Tsuga heterophylla (Raf.) Sarg.	1.2	1.1	16.1	16.0
Tsuga mertensiana (Bong.) Carr.	.7	.6	14.3	14.0
Picea sitchensis (Bong.) Carr.	1.4	1.3	13.5	11.0

[1]These conifers, like most pine-site hardwoods, are refractory and must be incised to get acceptable retentions of preservatives. The retention values reflect heavy preservative adsorption in a thin band of sapwood.

1940's. Carried out in the preservative treatment retort, the process exposes the wood to hot vapors of organic solvents such as xylene. Drying temperature depends upon the composition of the heat transfer medium used, but generally is within the range of 280° to 320°F. Drying times are short, generally 12 hours or less. Typical data showing the reduction in moisture content with time effected by vapor drying of a charge of green oak crossties are shown in table 8. According to Hudson (1949), moisture content bears a linear relationship to vapor drying time that is expressed by the equation:

$$\text{Log C} = -0.0304t + \text{Log I},$$

where C is final moisture content, t is drying time, and I is initial moisture content.

Steaming, though less efficient than Boulton or vapor drying, may also be used to condition certain species of wood. The unseasoned wood is exposed to live steam at 245°F, followed by vacuum. Duration varies with size and moisture content, but is usually 8 to 20 hours. A volume of water equivalent to 4 to 8 pounds per cubic foot is typically removed. Assuming an initial moisture content of 80 percent, an 8-pound removal per cubic foot would leave wood having a specific gravity of 0.52 with a residual moisture content of 56 percent. Steaming is not permitted with oaks, the species group that comprises at least 50 percent of the volume of hardwoods that receive commercial preservative treatments annually.

Stock intended for non-pressure treatment is normally air-dried to 30 percent moisture content or less.

Table 8.—*Data for typical charge of oak crossties seasoned by the vapor-drying process (Hudson 1949)*[1]

Time	Cumulative water removed	Moisture content
hours	*pounds/cu ft*	*percent*
	Wood Exposed to Hot Vapor	
0	....	77.6
1	.26	76.9
2	1.12	74.5
3	2.13	71.7
4	3.12	69.0
5	3.86	66.7
6	4.86	64.2
7	5.61	62.1
8	6.42	59.9
9	7.19	57.8
10	7.93	55.8
11	8.51	54.2
12	9.14	52.5
	Vacuum After Heating in Vapor	
2	11.50	46.0
	Final Vacuum	
1	12.38	43.6

[1]Charge was composed of 2,804 cu ft (814 ties) and retained an average of 0.48 pcf of drying agent.

WOOD PRESERVATIVES

Preservatives of the Past and Present

The first successful wood preserving process was patented by Kyan in 1832. It involved immersing wood in a solution of mercuric chloride. Similar use of copper sulfate and zinc chloride followed in 1837 and 1838, respectively. Creosote was patented as a preservative in 1836; but it was not used commercially until 1839, when Bethell developed a pressure process for injecting preservatives into wood.

Creosote was first used in the United States in 1865 to treat railroad ties, and it and its solutions with coal tar and petroleum continue to be used for that purpose almost to the exclusion of other preservatives. Pentachlorophenol was patented as a preservative in 1931, but was little used until World War II, when creosote was in short supply. Other oil-borne wood preservatives include copper naphthenate and copper-8-quinolinolate, patented in 1948 and 1963, respectively, but little used commercially at present. Copper naphthenate has the potential for "heavy-duty" use in ground-contact service, but its undesirable physical properties and high cost have limited its use. Copper-8-quinolinolate is also too expensive for wide-scale commercial use, but is used to treat container stock used by the food industry, since it is the only preservative that is permitted in contact with food products.

Fluor-chrome-arsenate-phenol is the oldest of the commercially successful water-borne salt formulations, having been patented in 1918. It was followed, in order, by acid copper chromate (ACC) in 1928, chromated copper arsenate (CCA) in 1938, and chromated zinc chloride (CZC) and ammoniacal copper arsenate (ACA) in 1939. The commercial use of fluor-chrome-arsenate-phenol has decreased from about 7 million pounds in 1966 to less than 250 thousand pounds in 1977. Chromated zinc chloride and acid copper chromate are used mainly on lumber for above-ground service; together they accounted for less than 1 percent of wood treated in 1977 (American Wood Preservers' Association 1978). CCA and ACA are widely used by the wood preserving industry today.

Creosote, pentachlorophenol, and two inorganic salt formulations, CCA and ACA, the only preservatives widely used commercially for ground contact service in the United States, accounted for 47, 24, and 28 percent of the 330 million cubic feet of wood treated in the United States in 1978[2]. Creosote is used principally to treat railroad ties, piling, and poles, accounting for 97, 83, and 28 percent of these products in 1978

[2]U.S. Department of Agriculture. 1980. Biological and economic assessment of pentachlorophenol, inorganic arsenicals, and creosote. Report of the USDA-States-EPA Preservative Chemicals Assessment Team. Final draft report.

Table 9.—*Volume of wood treated in 1978 by product and preservative*[1]

Product	Preservative			
	Creosote	Penta	CCA and ACA	Total
	thousand cu ft			
Railroad ties	103,138	449	3,498	106,085
Poles	18,237	41,905	4,038	64,180
Piling	9,993	1,154	943	12,090
Lumber, timbers	10,780	21,209	73,317	105,306
Fence posts	4,584	10,983	4,461	20,028
Other	7,855	4,296	7,646	19,797
Total	154,587	79,996	92,903	327,486

[1]U.S. Department of Agriculture. 1980. Biological and economic assessment of pentachlorophenol, inorganic arsenicals, and creosote. Report of the USDA-States-EPA Preservative Chemicals Assessment Team. Final draft report.

(table 9). The principal products treated with pentachlorophenol are poles, posts, and sawn products, other than ties, 64, 55, and 20 percent of which are treated with that preservative. CCA and ACA jointly account for 70 percent of all lumber treated in the United States and the use of these preservatives for poles, posts, and piling is increasing rapidly.

Creosote is used straight or blended with coal-tar or petroleum. Its use with petroleum is confined almost entirely to tie production. Pentachlorophenol may be applied as a solution in any of a wide range of petroleum solvents, depending upon the end use of the product. It is also applied, mainly on utility poles, in such volatile solvents as methylene chloride and liquified petroleum gas.

ACA is an ammoniacal solution of arsenic and copper which, upon evaporation of ammonia, forms an insoluble precipitate of copper arsenate in the wood. CCA is an acid solution of copper oxide, chromic acid, and arsenic acid which react *in situ* to form a complex of relatively insoluble precipitates. Various salts of chromium and copper may be used instead of chromic acid and copper oxide in formulation of CCA preservatives. Three formulations designated as Type A, Type B, and Type C, are currently recognized by the American Wood-Preservers' Association (1977). Their compositions are shown below.

Ingredient	Percent composition		
	Type A	Type B	Type C
CrO_3	65.5	35.3	47.5
CuO	18.1	19.6	18.5
As_2O_5	16.4	45.1	34.0

CCA Type C is most widely used and it probably will, in time, entirely displace the other two formulations.

While creosote and waterborne salts are equally efficacious in preventing biological deterioration, tests show that salt-treated wood is much more prone to split, check, and deteriorate with weathering. Either preservative prevents decay in crossties, but most replacements are due to mechanical failure; creosote treatment delays the need for such replacements. Creosote appears to impart water repellency that lowers moisture content and reduces moisture-content cycling between wet and dry periods, especially while ties are exuding preservative (Hedley 1973). Over a period of years, however, this effect declines and water adsorption of creosote-treated ties approaches that of salt-treated ties.

Salt-treated ties are also reported to cause more corrosion of iron fasteners, and to be more conductive of electricity than creosoted ties, a matter of concern in railroads where electrical-signal systems are used.

Efforts to improve the weathering properties of salt-treated ties include a CCA emulsion to reduce rapid uptake of water (Belford and Nicholson 1968, 1969). The product reduced splitting of ties, performing in a manner comparable to a heavy oil treatment. The CCA addition is described as a solution of long-chain, petroleum-hydrocarbon fractions containing non-ionic surface-active agents and a light-petroleum fraction solvent that is self-dispersing in the CCA solution. After injection into wood, the emulsion is reported to break and the hydrophobic materials to be deposited on the inner surfaces of the cell cavities. Levi et al. (1970) reported that autoradiography revealed these hydrophobic materials in the earlywood rays of pine sapwood. The water repellents were effective to a depth of at least 1 inch.

Pretreatments with petroleum solvents have not improved the weathering characteristics of salt-treated ties (Hedley 1973). However, a light treatment of hardwood ties with a heavy oil or with creosote did (data from Hickson's Timber Products, Ltd. *in* Cooper 1976). Salt-treated ties subsequently treated to a 2.5 pcf retention with 3:1 diesel oil in creosote performed better in long-term service tests than ties conventionally treated with a 50:50 creosote-petroleum blend. Whether this double-treatment process is currently used commercially is unknown.

Laboratory and field tests indicate that 2.5 to 3.0 percent concentrations of pentachlorophenol in a heavy petroleum solvent protect hardwoods against decay as well as 50-50 blends of creosote and petroleum or coal tar (Baechler 1947a; Blew 1950; Olson et al. 1958). Long-term weathering characteristics of ties treated with this preservative need further study.

Retentions Needed to Protect Hardwoods.—The amount of chemical required to adequately protect wood from decay and insect damage varies with wood species, exposure conditions, and type of preservative. (See discussion under heading EFFICACY OF PRESERVATIVE TREATMENTS.) Table 10 is intended to give the reader some indication of equivalency—

with important reservations, as follows. There are only three heavy-duty preservatives (four if the relatively expensive copper naphthenate is included) suitable for soil-contact service: pentachlorophenol, CCA-ACA, and creosote. The other two listed in table 10 are recommended only for above-ground service. Acid copper chromate (ACC), however, is permitted for ground-contact service of non-critical items such as fence posts.

Of the preservatives listed in table 10, only creosote and CCA-ACA are suitable for softwoods and only creosote for hardwoods in marine (salt water) use. Retentions and assay zones for this type of service are (American Wood Preservers' Association 1977):

Preservative and species or species group	Retention in assay zone	Assay zone
	Pcf	*Inches*
Cresote		
Southern pine	20	0 to 3.0
Douglas-fir and oak	10	0 to 2.0
CCA-ACA		
Southern pine	2.5	0 to 0.5
	1.5	0.5 to 2.0
Douglas-fir	2.5	0 to 1.0

CCA and ACA are not recommended for hardwood marine piling.

Retention by hardwood lumber, timbers, and crossties is determined by gauge readings or weight gain rather than by assay. Only two species groups are covered by current standards of the American Wood-Preservers' Association: oak (white and red) and gum (sweetgum and black tupelo).

While assay zones are defined in standards for southern pine poles, these definitions have no application to hardwood poles; hardwood poles are not used in the United States and no standards have been written for them.

New Preservatives and Preservative Systems

Other preservative systems, or modifications of existing ones, are being developed in response to the increasing cost of oil-borne preservatives and their petroleum solvents. Concern about environmental restrictions that may be imposed on the four major preservatives has further expedited the search for new ones with low mammalian toxicity which meet requirements of economy and effectiveness.

An oil-water-emulsion solvent system for pentachlorophenol that significantly reduces petroleum requirements has been developed. Initial test results of this new solvent system are promising[3]. Alkylammonium compounds developed in New Zealand are being studied for possible use in the United States. They have proven acceptable for above-ground use and are

Table 10.—*Retentions of six classes of preservatives in assay zones for approximately equivalent protection of hardwoods*[1]

Preservative	Service above ground	Service in soil contact
	-----*retention, pounds/cu ft*-----	
Creosote[2]	6.00	8.00
Pentachlorophenol[3]	.25	.40
Chromated copper arsenate (CCA)[4] or ammoniacal copper arsenate (ACA)[4]	.25	.40
Copper naphthenate[5]	.40	.75
Acid copper chromate (ACC)[4]	.25	.50[6]
Chromated zinc chloride (CZC)[3]	.45	not recommended

[1]Protection of piling against marine organisms requires higher preservative retentions of creosote than those shown. None of the other preservatives is recommended for use in salt-water exposure of hardwoods.
[2]Retention of whole creosote.
[3]Retention of anhydrous chemical.
[4]Retention of anhydrous chemical, oxide basis.
[5]Retention of copper, as metal.
[6]Recommended only for non-critical items in soil content, e.g., for fence posts.

being tested for ground-contact service. A water-solubilized form of copper-8-quinolinolate appears to have promise for use in above-ground applications.

Preservative systems whose toxic mechanisms are operative outside the body of the invading organism have been investigated. The use of chelating agents to inactivate the micronutrients required by fungi for growth was first suggested by Zentmyer (1944) and tested against wood-decay fungi by Baechler (1947b) and Thompson (1964a). Success of this method depends upon inactivation of the trace elements in wood, as well as those from other sources, such as the soil, to which the fungus has access. Hence, it does not work. This is likewise true—for the same reason—of attempts to dethiaminize wood and hence deny to fungi this essential growth factor (Gjovik and Baechler 1968). Efforts to treat wood with materials that chemically inhibit the cellulase enzymes secreted by fungal hyphae, thus preventing decay from occurring, have also failed (Reese and Mandels 1957; Thompson 1965).

METHODS OF PRESERVATIVE TREATMENT

Wood may be preservative treated by either pressure or non-pressure processes. Pressure impregnations involve the application of 50 psi pressure or more in large cylinders to force preservative liquid into the wood (figs. 4 and 5). Pressure treatments account for

[3]Hatcher, D. 1979. Private communication.

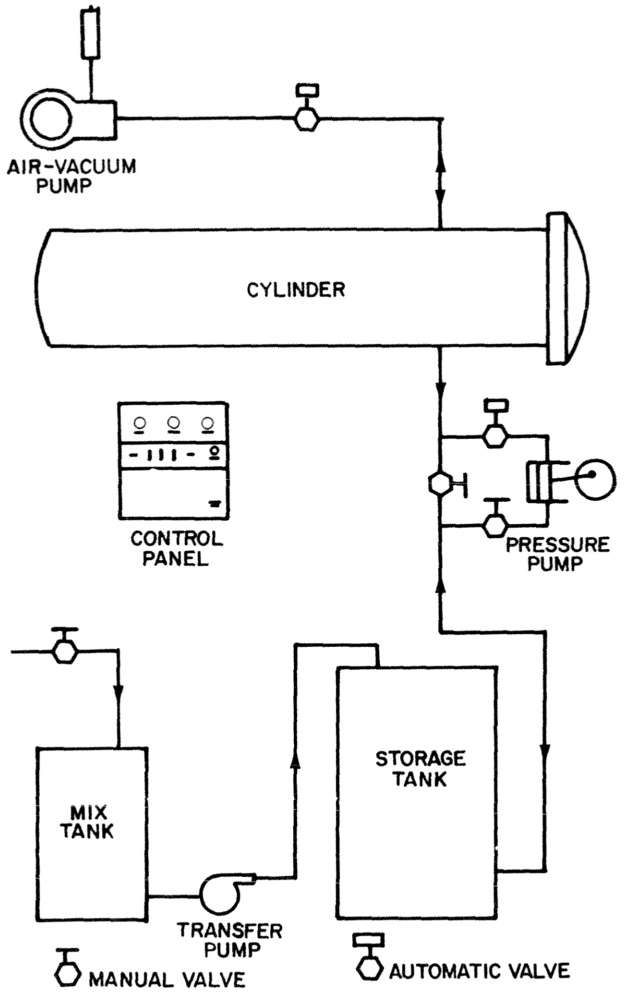

Figure 4.—*Schematic diagram of piping, storage tanks, and treating cylinder (retort) for pressure-impregnating wood with preservative. The air vacuum pump permits the cylinder to be evacuated before admission of the preservative, during a drying cycle (boiling under vacuum), or following the pressure cycle and drainage of the preservative.*

more than 95 percent of the wood treated in the United States by all processes except brush, dip, and spray. The remainder is treated by various non-pressure processes that include thermal, diffusion, cold soak, and vacuum methods. Brush, dip, and spray methods are also used, but not for material intended for ground-contact service. Products treated by these latter methods include millwork, which alone accounts for 60 million cubic feet of wood[2].

Pressure Processes

Pressure processes are differentiated by the air pressure applied to the wood before impregnation with a preservative. The full-cell process employs an initial vacuum to obtain maximum retention of preservative (fig. 6). The empty-cell processes employ either atmospheric pressure (Lowry Process) or higher air pressures of 15-75 psi (Rueping Process) (fig. 7). Hydrostatic or pneumatic pressures of 50 to 200 psi are imposed on the system and maintained until the desired gross injection of preservative has been achieved. The pressure is then gradually returned to atmospheric level and the excess preservative returned to storage. The treated wood may be subjected to a final vacuum or steaming and vacuum of short duration to remove surplus preservative from the surface of the wood.

The treating process and conditions employed and the preservative retention are determined by the species of wood, the preservative used, and the service conditions to which the wood will be exposed. Refractory species, such as white oak, require higher treating pressures than permeable species like southern pine. Treating temperatures of 210°F to 239°F are used to reduce the viscosity of creosote, while those used with pentachlorophenol-hydrocarbon solutions range from ambient to 220°F, depending upon the hydrocarbon (heavy petroleum, mineral spirits, or liquified petroleum gas). Target adsorption determines which of the two pressure processes is used. Products such as marine piling must be treated by the full-cell process to obtain the high preservative retention of 20 pcf required. Water-borne preservatives also are applied by the full-cell process. The empty-cell process is used for products, such as utility and construction poles, for which retentions of 6 to 12 pcf are needed.

Modifications of the basic pressure treating process that involve different pressure and temperature regimes from those in common usage have been explored at pilot-scale levels. Pressures in the range of 600 to over 2,000 psi have been used in these studies in an effort to improve the treatment quality achieved with refractory hardwood species (Walters and Guiher 1970; Akhtar and Walters 1974) and to obtain maximum loading of monomers in stabilization treatments (Rosen 1975a). In addition, oscillating pressure and vacuum treatments and other variations have been studied for possible beneficial effect on treatment quality. Some innovations and special applications of pressure methods that have been tried—some successfully and some not—are discussed in following sections.

Solvent Recovery Processes.—Two relatively new pressure treating processes receiving commercial application are unique in that the preservative—pentachlorophenol—is injected into wood in volatile solvents which are subsequently recovered and reused. The more commercially successful of these is the "Cellon Process" developed by Koppers Company, Inc., that employs liquified petroleum gas as the solvent. The other process was developed by Dow Chemical Company and uses methylene chloride as the solvent. The treating cycles employed with both processes are similar to those used with pentachlorophenol in oil,

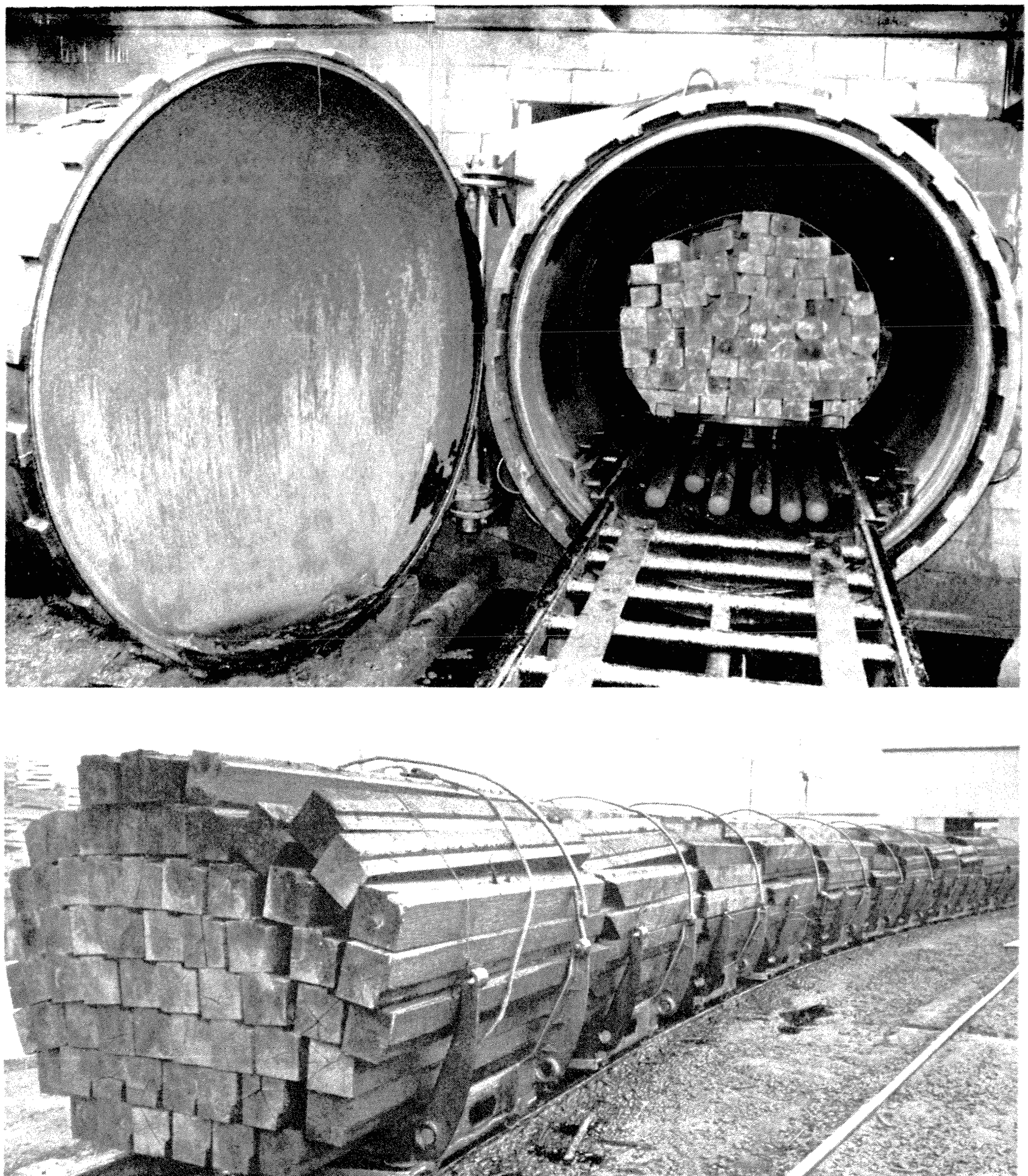

Figure 5.—*Commercial operation for pressure-impregnating wood with preservative. (Top) Frontal view of 7- by 130-foot retort ready for discharge. (Bottom) Freshly pulled charge of creosote-treated hardwood crossties.*

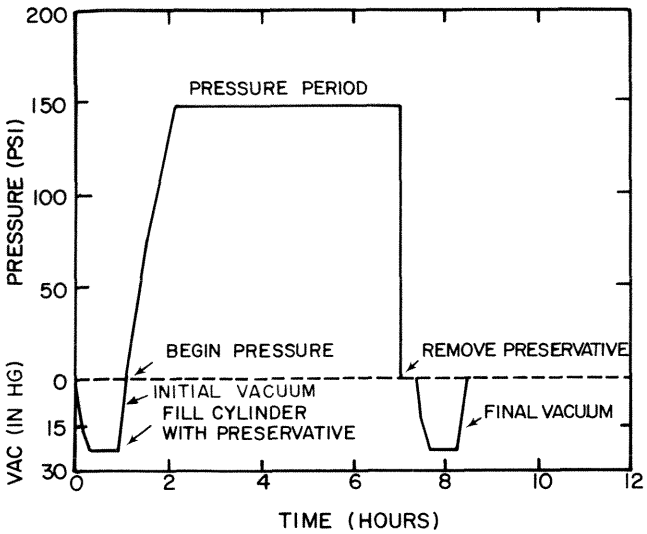

Figure 6.—*Schematic showing the treating schedule for full-cell treatment.*

except that each has a solvent-recovery step following the pressure period. Wood treated by these processes retains its natural appearance and can be used where cleanliness and paintability are requirements. Neither method is used to any significant extent in the treatment of hardwoods.

Modified Empty-Cell Process.—A modified empty-cell treatment for use with CCA-type preservatives was developed by Kelso[4] as an alternative to the conventional full-cell treatment currently used by industry (fig. 8). Impregnation is accomplished by either the Rueping or Lowry processes. After the desired gross adsorption is achieved, the preservative is removed from the retort while simultaneously maintaining a pressure such that kickback of the preservative solution in the wood is prevented. Fixation of the preservative is accelerated *in situ* by admitting to the retort either water or steam and maintaining a temperature of about 220°F for a period of 1 to 4 hours, depending upon the size of the items in the charge. Upon completion of the fixation period, the pressure is reduced and kickout of the spent preservative solution allowed to occur. Moisture contents of stock treated by this process are typically only one-third that of wood treated by the conventional full-cell process. In addition, the process permits rapid sequential treatment of wood with dyes, water repellents, stabilizing chemicals, or other preservatives.

Oscillating-Pressure Techniques.—Efforts to improve treatment quality of refractory species by sequential changes in pressure have generally been unsuccessful. An oscillating pressure technique, in which pressure (120 psi) and vacuum (28 inches of mercury) were alternated repeatedly throughout a 22-hour impregnation cycle, did not improve retention and penetration in the heartwood of either hardwoods or softwoods (Blew et al. 1961). However, the process did improve sapwood treatment in sweetgum over that achieved by conventional treating processes.

Work by McQuire (1964) indicates that the oscillating pressure method may have potential in the treatment of green wood, but not for dry wood. Its efficacy with green wood is attributed to exchange of wood water and preservative during the alternate pressure and vacuum cycles and to an increasing flow rate which accompanies the removal of air bubbles from the pores during the vacuum phase (Nicholas and Siau 1973).

Use of Shock Waves and Ultrasonics.—Low frequency shock waves and ultrasonics were investigated to improve the treatment of wood. The use of shock waves, induced by striking the retort with a hammer, produced some improvement in the treatment of oak crossties (Burdell and Barnett 1969). This effect was attributed to deaspiration of pits and dislodging of air bubbles from the pores (Nicholas and Siau 1973). Penetration of refractory woods was not improved.

The use of ultrasonic waves while wood is immersed in a liquid at atmospheric pressure can result in a significant increase in adsorption of certain liquids (Borkin and Corbett 1970). The improvement mechanism is thought to be the formation and removal of minute air bubbles, resulting in the removal of air-liquid interfaces which block penetration of liquids.

Pressure Treatment of Crossties.—Although hardwoods, in the form of crossties, constitute a large fraction of the total volume of wood pressure treated annually in the United States, treatment-response data for individual species are limited. Current standards (American Wood Preservers' Association 1980a) for the treatment of hardwood crossties with creosote and its solutions specify the following minimum retention and penetration values for the species groups shows:

Species group	Retention	Penetration
	Pounds/cu ft	
Red oak	8	65 percent of annual rings
White oak	Refusal	95 percent of sapwood
Sweetgum and black tupelo	10	1.5 inches or 75 percent of sapwood
Beech, birch, maple	7	85 percent of sapwood
Ash, hickory	Refusal	95 percent of sapwood

Determination of actual retention values by assay is not part of this standard. Hence, data are usually available only for cylinder charges, based on calculated retentions and, where required, checks of penetration on sample pieces.

[4]W. C. Kelso, Jr. Unpublished data. Mississippi For. Prod. Lab., Mississippi State Univ., Mississippi State.

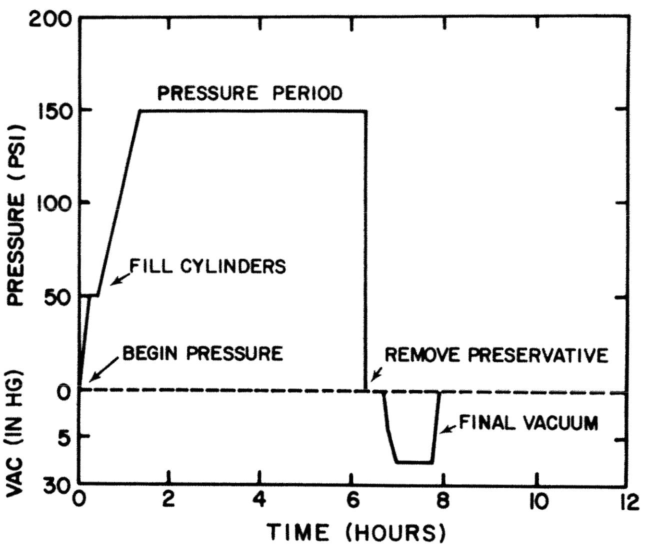

Figure 7.—*Schematic showing the treating schedule for empty-cell treatment.*

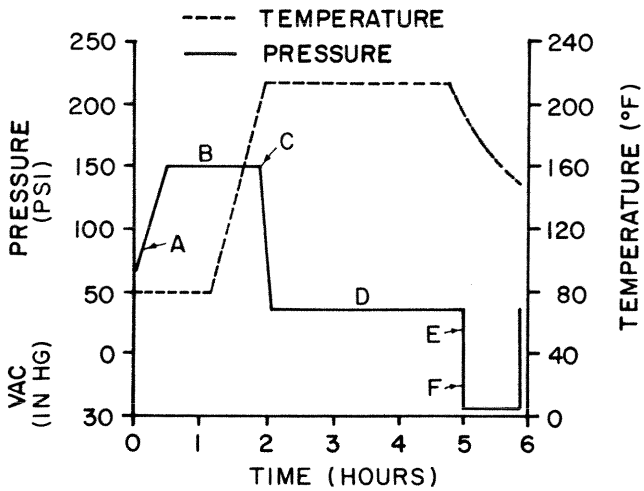

Figure 8.—*Treating cycle used to treat southern pine pole sections with CCA by a modified empty-cell process. (A) Initial air pressure and fill cylinder. (B) Pressure period. (D) Maintain pressure sufficient to prevent loss of preservative from wood during fixation period. (E) Release pressure and recover kickback from wood. (F) Final vacuum.*

Figure 9.—*Typical thermal treating plant. A boiler (not shown in photo) supplies steam to heat coils in the bottom of the tank at left. The tank at right is for cool preservative. Wood is transferred between tanks manually or by hoist mounted on adjacent pole.*

Table 11.—*Summary of creosote penetration and retention in hickory crossties by method of seasoning (Taras and Hudson 1959)*

Investigator	Seasoning method and time	Moisture content at treatment	Penetration	Retention
		percent	*inches*	*pounds/cu ft*
Hudson (1954)	Air drying (6 months)	34	1.0	4.8
Shinn (1955)	Air drying (15 months)	26	1.3	6.0
Vaughan[1]	Controlled air seasoning[2] (11 days)	43	1.3	6.0
Hudson (1951)	Vapor drying (12 hours)	35	1.7	6.4
Collister (1955)	Vapor drying (15 hours)	20	1.8	11.7
Diechman (1954)[3]	Vapor drying (15 hours)	32	2.2	9.0
Huffman (1958)	Vapor drying (3 days)	32-47	2.2	5.5

[1]Vaughan, J. A. 1954. The use of hickory for railroad crossties. Southern Wood Preserving Company Rep., File 11-A-5 HTS.

[2]Process for slow drying of poles and crossties. See Vaughan (1954, 1955).

[3]Diechman, M. W. 1954. Vapor drying and treatment of hickory crossties. Unpublished report, Taylor-Colquitt Company.

Federal specification TTW-571 is more explicit and provides that, for species not covered either in that document or in AWPA specifications, penetration of heartwood faces will be not less than 0.4 inch in lumber and 0.5 inch in timbers.

The relative abundance and favorable mechanical properties of hickory have prompted extensive research on its suitability for crossties. Its reputation for excessive checking and splitting and for being difficult to treat has concentrated much research on seasoning and treating properties (Taras and Hudson 1959).

Investigators generally agree that moisture content of hickory should be between 20 and 40 percent for adequate retention and penetration (table 11). Seasoning and treating properties of hickory appear to be similar to those of the red oaks. Huffman (1958) found that degrade of hickory ties during seasoning in some studies was no worse—and in some instances was less—than that for other dense species such as the oaks.

In contrast, uneven distribution of creosote in pressure-treated, 4-inch-square hickory timbers was reported by Lund (1966). Despite an average retention of 9.6 pcf, only 46 percent of the treated stock had commercially acceptable penetration. Eighty-five percent had penetration skips, mostly associated with mineral streaks at worm galleries and other injuries. Skips present following treatment were not reduced by preservative migration over a 5-year period.

Pressure Treatment of Posts.—While the literature on treatment of hardwood posts deals principally with non-pressure treatments, some retention values for pressure treatments of post-size material with creosote by the empty-cell process are available (table 12). No penetration data accompanied these values. The retention values for all species met or exceeded the minimum recommended retention for softwood posts (American Wood Preservers' Association 1980b); there are no standards for hardwood posts.

Cook (1978) pressure treated 22 species of hardwood (table 13) with pentachlorophenol in a petroleum solvent conforming to P-9, Type A (American Wood-Preservers' Association 1977) by an empty-cell process with a maximum pressure of 100 psi for 50 minutes. This treatment regime is very mild for hardwoods, in terms of both pressure and duration. Retentions in the outer 0.25 inch varied greatly, the soft hardwoods generally having greatest retentions in this zone. In only six species was penetration deep enough to estimate retention in the 0.25- to 1.0-inch zone.

Non-Pressure Processes

Non-pressure processes are employed both commercially and by individuals for farm and ranch uses. Conditioning of stock is usually by air-drying and for most purposes the wood must be seasoned to a moisture content of 30 percent or less prior to treatment. Diffusion-type treatments are applied to unseasoned wood. Thermal and cold-soak treatments are the non-pressure processes most frequently employed commercially. In both, the wood is exposed to the preservative in an open vessel.

Thermal Process.—In this process wood is immersed in hot preservative for a fixed period of time—usually

4 to 12 hours—followed by exposure to preservative at ambient conditions (fig. 9). Variations of this treatment include use of separate vessels for the hot and cold baths and using a single vessel to which hot or cold preservative can be pumped as appropriate. A few small operators in the South leave the stock in the hot tank so that wood and preservative cool together.

Pentachlorophenol in petroleum is the preservative normally used with the thermal process, but other preservatives, notably creosote, may also be used. In the past this process was used extensively because creosote, the principal preservative, was too viscous at ambient temperature. Availability of pentachlorophenol and copper naphthenate which can be applied by cold-soaking has reduced use of the thermal process; thus the data base for thermal treatment is limited. Retentions of creosote and 5-percent pentachlorophenol solution achieved with thermal and cold-soak treatments, respectively, are shown in table 14. The numerous sources of these data do not permit more than a general interpretation of results. Retentions obtained with the thermal process for creosote are generally higher than those for pentachlorophenol obtained by cold soaking. By both processes the soft hardwoods appear to be more easily treated than the dense hardwoods.

Putnam (1947) investigated the treatability of bottomland hardwoods in Mississippi, using residence times of 1½ to 2 hours in the hot bath and 15 to 60 minutes in the cold bath. Satisfactory treatments were obtained in posts of ash, cypress (*Taxodium distichum* (L.) Rich.), elm, hackberry, honeylocust, maple, overcup oak, water oak, pin oak, pecan, persimmon, sweetgum, and willow. Results with cottonwood were unsatisfactory.

Cold-Soaking.—This process involves simply placing wood in a vessel, covering it with preservative solution, and allowing it to soak until it adsorbs the appropriate amount of preservative, as determined by weight gains (fig. 10). It has been used extensively to treat fence posts and lumber for farm and ranch uses, and in some research tests. The process is normally used with pentachlorophenol solutions, but other preservatives, including water-borne salts, may also be used.

Table 12.—*Creosote retentions in hardwood posts treated by a pressure process (Kulp 1961)*

Species	Retention
	pounds/cu ft
Elm, American	9.1
Hickory	9.7
Maple	6.5
Oak, black	6.6
Oak, blackjack	7.9
Oak, northern red	5.9
Oak, white	6.0
Sweetgum	9.7

Table 13.—*Retentions of pentachlorophenol by hardwood post sections treated by a pressure process*[1] *(Cook 1978)*

Species	Retention of pentachlorophenol	
	0.25 inch	0.25-1.0 inch
	pounds/cu ft	
1. Sweetbay	0.56	. . .
2. Black Tupelo	.52	0.17
3. Yellow-poplar	.50	. . .
4. Sweetgum	.48	.23
5. Red maple	.37	. . .
6. American elm	.36	. . .
7. Post oak	.34	.06
8. Scarlet oak	.26	. . .
9. Shumard oak	.26	. . .
10. Black oak	.26	. . .
11. Green ash	.26	. . .
12. Hackberry	.26	. . .
13. Blackjack oak	.26	. . .
14. Cherrybark oak	.25	. . .
15. Water oak	.23	. . .
16. Hickory, true	.22	.02
17. White ash	.22	. . .
18. Winged elm	.21	. . .
19. Southern red oak	.20	.05
20. Northern red oak	.20	. . .
21. White oak	.18	.05
22. Laurel oak	.17	. . .

[1]Because treatments were very mild, these values reflect relative difficulty of treatment rather than typical effective treatments for these species.

Preservative retentions obtained by cold soaking vary widely among species and with moisture content. Some control over retention by permeable species can be exercised by adjusting the period of immersion. Retentions achieved with refractory species usually represent a compromise between the adsorption desired and the maximum feasible soaking period. Retention of 6 pcf of 5 percent pentachlorophenol solutions, the minimum allowed for ground-contact service by the American Wood Preservers' Association (1980b), is seldom achieved in oak and certain other species by non-pressure treatments. Retentions after cold soaking obtained in selected studies are summarized in table 15 for 16 of the hardwood species commonly found growing on southern pine sites.

The retention data presented are for pentachlorophenol in petroleum solvents and represent many different studies. Pretreatment moisture content and treating solution temperature are unknown. Differences among species are apparent. Retentions for the oaks, elm, and hickory were generally less than 5.0 pcf while those for the soft hardwoods—red maple, sweetgum, black tupelo, and yellow-poplar—were generally greater than 5.0 pcf. These groupings agree reasonably well with the categories in tables 3 and 4 developed by Teesdale and MacLean (1918) and Siau et al. (1978), respectively. There is a tendency for the retention values to vary

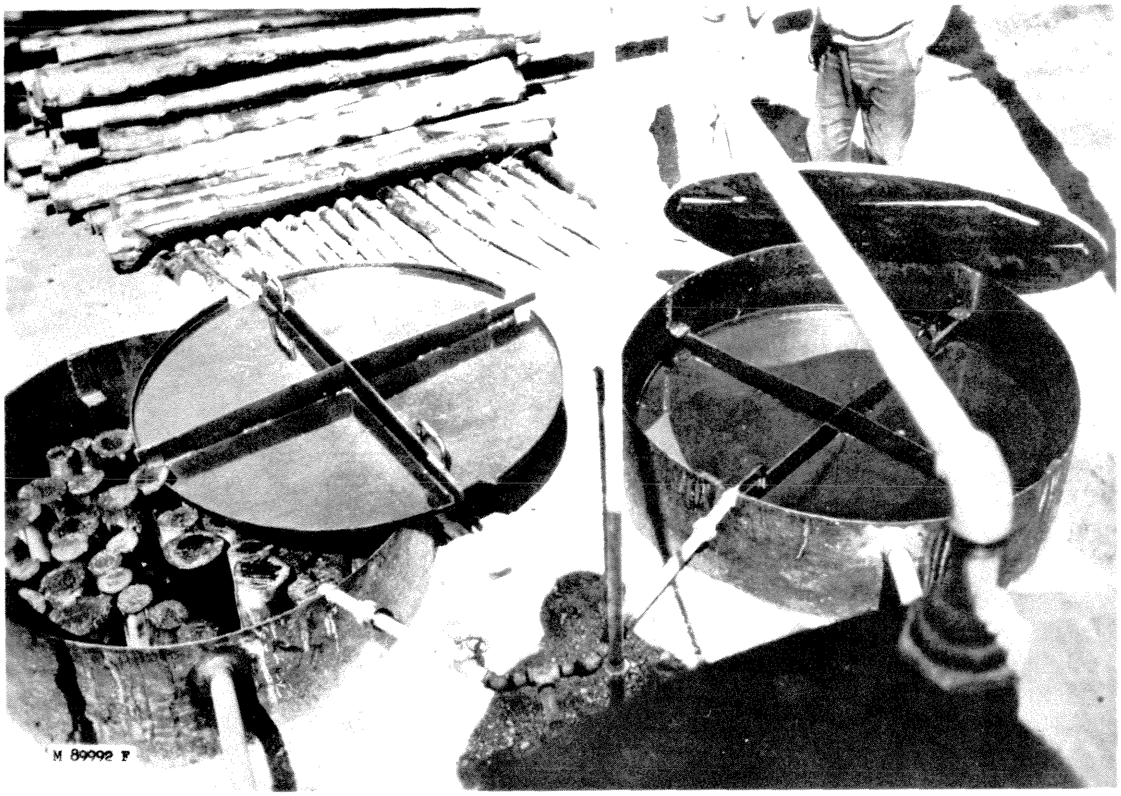

Figure 10.—*Preservative treating plant equipped to employ the cold-soaking process. Tank tops are equipped with latch mechanism to hold wood submerged. Piping arrangement maintains preservative level desired in tanks. Wood is charged manually or with the aid of a hoist.*

Table 14.—*Retention of creosote applied by the thermal process and 5 percent pentachlorophenol by cold-soak treatments in hardwood fence posts.* (Data from Kulp 1966; Gjovik and Davidson 1975.)

Species	Retention	
	Thermal	Cold soak
	pounds/cu ft	
Ash, green	8.9-11.9	6.1 (2)[1]
Ash, white (butts only)	5.1[2]	......
Basswood	6.1[2]	2.4[2]
Beech	8.5	......
Elm, American	8.0	......
Hackberry	8.0-12.7	3.5 (5)
Maple, red	8.2	7.0 (2.6)
Oak, blackjack	4.1	4.5 (8.1)
Oak, overcup	6.1-9.5	5.2 (5)
Oak, northern red	2.4	4.2 (2.8)
Oak, water	8.4-9.6	......
Oak, white	2.4	......
Pecan, bitter	6.0-8.9	5.2 (5)
Persimmon	7.9	3.9 (2)
Sweetgum	9.9-11.0	5.6 (2.7)
Tupelo, water	8.6	5.8 (4.5)
Tupelo, black	7.2	......
Willow, black	8.4	3.8 (2)
Cottonwood	10.0	6.3 (4)

[1]Numbers in parentheses are treating times in days.
[2]Pounds per post.

inversely with specific gravity. Green ash is an exception in all three tables, its retention of preservative being greater than predicted by its specific gravity.

Diffusion Treatments.—These processes apply waterborne salt formulations to unseasoned wood by diffusion. In the traditional application, the treating solution contains a single salt of a metal, such as copper sulfate or zinc chloride. Such treatments have generally been unsatisfactory for exterior exposure because of rapid loss of the preservative by leaching.

In a variation called **double diffusion** (Baechler et al. 1959), the wood is soaked successively in two different aqueous inorganic salt solutions. The two components react within the wood to form relatively insoluble, toxic precipitates. A retention of 0.4 pcf by double diffusion is adequate for soil-contact service and is not subject to leaching. One pcf of leachable salts (e.g., zinc chloride) is more than adequate for protection, but an excess is needed to compensate for leaching.

Another diffusion process studied extensively in the South (Anonymous 1960) employs a solution of a single salt, such as zinc chloride, and green, unpeeled posts. The posts are placed vertically in a shallow pail containing the quantity of solution calculated to provide a net retention of about 1 pcf of the salt in the posts (fig. 10). The ends of the posts are reversed when about one-half of the solution has been adsorbed and the process is continued until the solution is adsorbed. This process provides somewhat better protection for wood in exterior service than conventional diffusion treatments with zinc chloride because the bark inhibits leaching of the preservative as long as it remains intact.

Yet another variation of the diffusion process employs as the preservative a water-soluble salt or salt formulation in dry or paste form. The preservative is spread over the surface of unseasoned, peeled wood, which is then dead-piled and covered to reduce loss of moisture. The preservative diffuses into the wood during a treating period that ranges from a few days to more than 2 weeks, depending upon the product involved.

Diffusion treatments have potential in the treatment of hardwoods because retentions comparable to those obtained by pressure processes are attainable. The double-diffusion process, in particular, is promising because of the long-term protection afforded by the heavy metal complexes formed in the wood.

In studies conducted by Baechler et al. (1959), fence posts cut from several hardwood species were soaked first in a solution of zinc sulfate and arsenic acid and then in a solution of sodium chromate. Exposure periods were 1, 2, and 3 days in each solution. Total retentions of anhydrous salt by species for each exposure period are shown below (Vick et al. 1967):

Species	Retention 1 day	Retention 2 days	Retention 3 days
	Pounds/cu ft		
Yellow-poplar	1.99	2.97	3.15
Sweetgum	1.93	2.41	2.88
White oak	1.27	1.50	2.26
Red oak	1.04	1.57	2.07
Hickory	.39	.70	1.03

Retentions for cypress and southern pine, which were also included in the study, were of the same order of magnitude as those for the hardwoods. Heating the first solution accelerated chemical uptake and, except for white oak (1.69 pcf), red oak (1.60 pcf), and hickory (0.78 pcf), the adsorption was higher than would be desired in practice.

In other work reported by Baechler and Roth (1964), the double-diffusion treatment with copper sulfate and sodium arsenate provided good retention and adequate to excellent penetration in birch, maple, basswood, California blue oak, and bluegum (*Eucalyptus globulus* Labill.) when these species were soaked one day in each of the two solutions. They concluded that this process seems to offer promise as a method of treating hardwoods. However, the authors emphasized that several investigators have shown that certain decay fungi frequently associated with decay of hardwoods are

Table 15.—*Preservative retention in hardwood posts treated by cold soaking in pentachlorophenol-petroleum solutions. (Data from Kulp 1966; Gjovik and Davidson 1975.)*

Species and treating period (days)	Retention
	pounds/cu ft
Ash, green	
2	6.1
Elm, American	
2	3.2
4	3.2
5	2.5
Hackberry	
2	4.4
5	3.5
Hickory	
2	3.8
3.7	4.3
5	3.6
Maple, red	
0.5	2.5
1	5.4
2	5.8
2.2	5.7
3.5	9.5
Oak, black	
2	2.7
Oak, blackjack	
6.3	4.1
8.1	4.5
Oak, chestnut	
2	8.7
2.8	5.6
Oak, northern red	
2.8	2.6
4	4.4
Oak, post	
2	3.2
3	3.1
. . .	5.7
Oak, scarlet	
1.8	3.9
Oak, southern red	
2	5.9
. . .	4.8
Oak, white	
2	2.4
3.9	5.3
. . .	6.1
Sweetgum	
.25	5.0
1	5.7
2	5.1
3	6.0
4	4.5
6	7.2
Tupelo, black	
.2	7.4
.5	5.5
4	4.4
Yellow-poplar	
1	5.4
1.4	5.2
2	6.6
3	6.1
6	8.8

relatively resistant to inorganic preservatives. They surmised that chemical costs probably will be higher in treating hardwoods than in treating softwoods because of that fact.

Boone et al. (1976) found that penetration and retentions by aspen, soft maple, and red oak lumber were generally not satisfactory when the conventional double-diffusion process was used. However, a modified process, using a heated first bath followed by partial drying, gave very good results. Retentions achieved in aspen and maple exceeded those obtained by pressure treatment.

Modified double-diffusion processes were also used successfully by Johnson and Gonzales (1976) to treat several tropical hardwood species. The first solution was 10 percent copper sulfate and the second was 2.25 percent sodium arsenate and 3.25 percent sodium chromate for green material and 4.5 percent sodium arsenate and 6.5 percent sodium chromate for partially seasoned material. Retentions in the outer ½-inch of sawn material, principally sapwood, ranged from 0.14 to over 1.0 pcf, oxide basis, depending upon treatment schedule, species, and whether or not the specimens were incised. Retentions for all species were considered adequate to provide a high degree of protection for ground-contact service in the tropics. Similar results were obtained by Smith and Baechler (1961) in exploratory treatment studies of Hawaiian-grown fence posts. Promising results were obtained with silk oak (*Grevillea robusta* A. Cunn.), bluegum (*Eucalyptus globulus* Labill.), *Eucalyptus saligna* Sm., and *Eucalyptus robusta* Sm.). Skolmen (1962, 1971), however, treated these same species by double diffusion and reported only a marginal improvement in service life after 10 years of field testing in Hawaii.

Table 16.—*Preservative retention of inorganic salts by hardwood posts treated by diffusion processes. (Data from Kulp 1966; Gjovik and Davidson 1975; Baechler et al. 1959.)*

Species	Retention
	pounds/cu ft of anhydrous chemical
Elm	0.90
Hickory	.30[1]
	.70[1]
Maple, red	1.10
Oak, black	.65
Oak, blackjack	.70
Oak, post	.90
Oak, red	.89
	1.56[1]
Oak, white	.87
	1.70[1]
Sweetbay	.94
Sweetgum	1.14
	2.40
Tupelo, black	.89
	.52[1]
Yellow-poplar	1.43
	2.95

[1]Denotes double-diffusion treatments. All other values are for end diffusion.

Retention values for diffusion treatments of posts of some of the hardwood species that grow on southern pine sites are given in table 16. End diffusion values, being easily controlled to target retentions, tend to be lower than those for double diffusion. Posts treated by double diffusion tend to be overtreated. For both diffusion treatments, differences between refractory and permeable species are much less pronounced than with cold-soak and thermal treatments.

Behr (1964) treated American elm and aspen fence posts with anhydrous salts of copper sulfate, followed by disodium arsenate and/or sodium dichromate. The chemicals were applied under a plastic bandage to the debarked butt portion of green posts. Copper sulfate was applied first and left in contact for 6 to 13 days. Disodium arsenate and sodium dichromate were then applied to a wet paper towel inside the plastic bandage and the bandage rewrapped. The posts were then stored for several months. Distribution data for the preservative are given below; values have been converted to an oxide basis.

Species and assay zone	CuO	As_2O_5	CrO_3
		Pounds/cu ft	
American elm			
First ¼-inch	0.273	0.285	0.065
Second ¼-inch	.023	0	.004
Third ¼-inch	.004	0	0
Aspen			
First ¼-inch	.233	.396	.160
Second ¼-inch	.021	.003	.010
Third ¼-inch	.004	.001	0

Total retention was comparable to that attained by double-diffusion treatments, but most of the salts were concentrated in the outer ¼-inch of wood. Better results were achieved with aspen than with American elm. Behr recommended the procedure for groundline treatments of poles in service.

Dip, Brush, and Soak Treatments.—Extensive, long-term testing has shown that surface treatments applied by dipping, brushing, and spraying are efficacious in preventing deterioration of wood in above-ground exposure (Verrall 1961). Benefits vary with the preservative, treating method, solvent, presence or absence of a water repellent, wood finish, and exposure conditions. Two- to threefold increases in service life in above-ground, exterior exposure can be achieved by 3-minute dips with such preservatives as pentachlorophenol and copper naphthenate (2 percent copper) (Verrall 1953; 1959; 1961). The efficacy of such treatments for such items as pallets has also been verified (Nethercote et al. 1977).

Superficial treatments are also extensively used on unseasoned lumber to prevent stain, mold, and decay during seasoning (Lindgren 1930; Lindgren et al. 1932; Verrall and Scheffer 1949). Such treatments fall outside those activities normally considered to be wood preservation, and hence are not covered here. Likewise, protection of logs (Burkhardt and Wagner 1978) and chips (Bois et al. 1962; Silberman 1970; Eslyn 1973) in storage fall outside the subject matter considered.

EFFICACY OF PRESERVATIVE TREATMENTS

International Overview

Hardwood crossties constitute a significant fraction of the total volume of wood treated annually in the United States. Practically all crossties are treated with creosote (fig. 11). Almost a century of use has shown that a broad range of hardwood species, when properly treated with creosote solutions, perform satisfactorily in rail lines. Average service life of crossties ranges from 25 to 50 years, depending upon location; increasingly, tie failure is caused by factors unrelated to biological deterioration.

Performance data for hardwood products treated with preservatives other than creosote and for hardwoods in other ground-contact service is less extensive. Available data show an uneven pattern of performance ranging from good to bad, perhaps reflecting in part differences among species and among treating methods employed.

Definite information is generally lacking on the specific organism responsible for failure. In general, the white-rot fungi are the most important causes of decay in hardwoods. Some of these organisms (e.g., *Coriolus versicolor* L. per Fr.) are much more tolerant of certain preservatives than are brown-rot organisms (Thompson[5]; Gjovik[6]). Soft-rot fungi, which destroy wood despite preservative loadings that prevent decay by *Basidiomycetes,* are increasingly recognized as important in decay of hardwoods in ground-contact service.

In Europe and Australia hardwoods with high absorption and deep penetration of water-borne salts are rapidly attacked by soft rot. Some authorities recommend that salt-treated hardwoods not be used in ground contact (Bergman 1977).

Noting that in tropical climates soft rot is the primary cause of failure of treated wood in ground contact, especially hardwoods, Levy (1978) recommended use of softwoods for poles where a choice is available. Soft-rot damage to improperly treated softwood poles, however, has also been reported (Henningsson et al. 1976).

Greaves and Levy (1978) found evidence that low levels of CCA preservative in the fibers of hardwoods may be responsible for poor performance. Eight of the

[5]Thompson, W. S. 1975. Unpublished data. Miss. For. Prod. Lab., Miss. State Univ., Mississipppi State, Miss.

[6]Gjovik, L. R. 1980. Personal communication with W. S. Thompson.

Figure 11.—*Hardwood crossties, shown here air-drying prior to treatment, account for about one-third of the 330 million cu ft of wood treated annually in the United States.*

10 hardwoods studied showed skewed CCA distribution patterns among vessels, fibers, and ray tissues. The pattern evident for CCA as a whole was also found individually for copper, chromium, and arsenic. Fibers contained much less CCA than either vessels or rays at all depths studied and ranged as low as 9 percent. The two species which showed uniform distribution performed satisfactorily in field tests.

On a different level, Dickinson et al. (1976) investigated the distribution of copper, chromium, and arsenic within individual wood cells where a normal CCA treatment protected softwood from both soft rot and *Basidiomycetes* and hardwood from *Basidiomycetes* only. Even a double treatment failed to protect the hardwood from soft rot. Elemental distribution of copper within tracheid and fiber walls, determined by electron-probe microanalysis, was as follows (data for chromium were similar):

Wall layer	Relative amount of copper	
	Softwood tracheids	Hardwood fibers
	----- *X-rays emitted/second* -----	
S_3	239	6.8
S_2	222	4.9
S_1	224	6.1
Middle lamella	183	5.4

Unlike the uniformly well treated tracheids, the fibers were poorly treated, with lowest quantities of preservative in the S_2 layer, where soft-rot fungi attack wood by forming distinctive cavities. Concentrations of copper, chromium, and arsenic were much higher in ray cells than in fibers.

Levy (1978) cited three reasons for the apparent preferential attack of hardwoods by soft rot.

1. High content of pentosan and other hemicelluloses easily utilized by soft rot.
2. Poor penetration of the fiber cell walls by the preservative.
3. High wall-to-lumen volume ratios in fiber cells resulting in low retention of preservative in fiber walls even at normally adequate retentions in pound/cu ft of wood.

Hulme and Butcher (1977), however, found no major differences in the gross or cellular distribution of CCA preservatives between hardwood and softwood specimens.

Tamblyn (1973) reported that in field trials at eight sites in Australia and New Guinea involving both eucalyptus and pine poles, and several preservatives, soft rot had seriously deteriorated the hardwood after only 6 to 8 years. He concluded that retentions of the best preservatives providing satisfactory protection in temperate climates are inadequate for some hardwoods in ground-contact service in the tropics.

By contrast Aston and Watson (1976) reported that in numerous parts of Africa creosote-treated eucalyptus has performed extremely well. They cited a power line near Pretoria, in which no poles failed during a 40-year period. They also reported similar results in Malaysia with *Shoria* sp treated with CCA. Purslow (1975) reported no failures in 44-year-old beech stakes treated with creosote or CCA and installed at Princes Risborough in England. In field trials in Scandanavia, however, beech and other hardwood species performed poorly when treated with either organic or inorganic preservatives (Henningsson 1974).

Investigations by Sorkhoh and Dickinson (1976) on the cause of early failure of treated hardwoods confirmed the findings of others (Tamblyn 1973; Henningsson et al. 1976; Levy and Greaves 1978; Greaves and Levy 1978), that soft-rot fungi are the causal organisms. Cavities were forming in the S_2 layer of the cell walls of six species within 3 days to 2 weeks following inocculation of samples. Treatment with CCA reduced neither the incidence of cavity formation nor the time required for their development. In similar studies Liese and Peters (1977) found that hardwood specimens treated with either copper or chromium were more heavily attacked by soft-rot fungi than those treated with both metals.

Those interested in performance records of salt-treated railroad ties outside the United States will find the following publications useful: Cooper (1976), Ellwood (1956), Krzyzewski (1973), Borup (1961), Hedley 1973).

Service Data in North America

North American service data for treated hardwoods are concerned mainly with crossties and fence posts. These two products represent distinctly different levels of exposure. Crossties placed on well ballasted roadbeds are subject to less biological hazard than fence posts in direct contact with soil (fig. 12). On the other hand, they are subjected to much higher levels of mechanical stress and may require replacement for causes unrelated to biological factors. Service data for the two products are thus not interchangeable.

Current estimates of service life of crossties in line are based on tests begun 30 to 50 years ago. Many preservatives then in actual or potential use have since been discontinued. For all practical purposes, only creosote and its coal-tar or petroleum solutions are employed in crosstie treatment today. A somewhat similar situation exists in the case of fence posts, although the time involved is usually shorter.

Crossties.—Average service lives of 50 years or more were reported by Blew (1963) for red oak and hard maple crossties treated with 5-12 pcf of creosote in tracks in Wisconsin compared to 6 to 10 years for untreated ties. Surprisingly, semi-refined paraffin oil

Figure 12.—*(Top) Peeled hardwood posts air drying prior to treatment. (Bottom) Treated posts installed during the years 1950-1954 near Starkville, Miss., to determine service life; some treated stakes are visible in the foreground.*

provided a service life for both species nearly as long as that for coal-tar creosote, as did a 20:80 emulsion of zinc chloride solution and creosote.

Blew attributed differences in average service life in two Wisconsin test tracks to the use of tie plates on some ties, better drainage, and less traffic at one site. In related studies, 50:50 blends of coal-tar creosote and wood-tar creosote at retentions of 7 to 10 pcf provided service lives of 23 to 44 years for slippery elm, red oak, white oak, cherry, and butternut crossties. Red oak ties treated with zinc chloride failed after an average service life of 17 years.

In other work, Blew (1966) found that service conditions as well as treatments affect the life of oak crossties. Average service life in Maryland for red oak and white oak crossties representing a variety of preservatives was 20 to 34 years and 21 to 31 years, respectively. Red oak ties treated to retentions of 8 to 10 pcf with creosote remained serviceable for about 34, 33, 21, and 19 years in Ohio, Pennsylvania, Texas, and Arkansas, respectively.

Reports of tie service life in Northern Pacific Railroad show that red oak ties treated either with straight creosote or a 50:50 creosote-petroleum blend have a service life throughout the system of 30 to 50 years (Radkey 1960). Mechanical failure was a contributing factor in the replacement of over 50 percent of these ties.

A comprehensive test of crossties in track has been underway in Canada for many years. Forty-year test data reported by Krzyzewski (1969) are summarized in table 17 by species and type of preservative treatment. It is of interest in this table that brush treatments with Osmolit (sodium fluoride and dinitrophenol) and Osmotite pastes (sodium fluoride, dinitrophenol and chromium salt) performed about as well as pressure treatments with Boliden salt or pentachlorophenol in petroleum. Only about 25 percent of all failures resulted from biological deterioration. Blew (1963, 1966) found that rail plates greatly reduced mechanical failure.

The service life of properly treated hickory ties has been shown to be equal to that of other more widely used tie species. Taras and Hudson (1959) summarized data from several studies which indicate a service life for hickory ties of 25 to 35 years. This range is very close to the estimated service life of 31 years for red oak ties included in the same track.

Bescher (1977) summarized available data on the life of creosoted crossties in mainline tracks. Tests beginning in 1909 and 1910 by the Chicago, Burlington, and Quincy Railroad showed that service life varied from 25 to 35 years, except for ash, which had only a 20-year life. Beech, sycamore, elm, red oaks, sweetgum, and black tupelo all had service lives averaging 30 to 35 years. Birch, cottonwood, hickory, pine, hard and soft maple, and white oak had 25- to 30-year service life. Crosstie life also varied significantly according to the quality of track and ballast maintenance, and with severity of traffic; crossties in tracks of a midwestern railroad that traditionally made a profit and maintained its tracks had service lives varying from 25 to 60 years depending on the amount of traffic.

Tie life is longest in side and yard tracks (60-year average), intermediate in branch lines (about 30 to 35 years), and shortest on heavily used mainline tracks

Table 17.—*Service life of hardwood crossties in Canadian railways by species, preservative, and retention (Krzyzewski 1969)*

Species	Retention	Preservative	Average service life
	pounds/cu ft		*years*
Aspen	7.2	Creosote	32.9
Red oak	.26	Zinc-meta-arsenite	23.9
Beech	.20	Zinc-meta-arsenite	21.9
Hard maple	.31	Zinc-meta-arsenite	23.5
Yellow birch	.25	Zinc-meta-arsenite	22.5
White birch	.26	Zinc-meta-arsenite	21.7
Beech, hard maple, red oak	.43	Osmotite (brush treated)	21.2
Red oak, yellow birch, hard maple	.43	Osmolit (brush treated)	21.2
Yellow birch, hard maple, beech	5.3-8.8	70/30 creosote-coal tar	27.0-31.7+
Yellow birch	8.1	50/50 creosote-petroleum	21.0+
Aspen	.....	70/30 creosote-coal tar	18.0+
Beech, birch, maple	.....	Copper naphthenate	20.0+
Birch	.40	Pentachlorophenol	17-18+
Birch	.60	Boliden salt	16.7+
Maple	.60	Boliden salt	15.7+
Red oak	.60	Boliden salt	17.0+
Aspen	7	50/50 creosote-petroleum	15-16+
Yellow birch	.30	Pentachlorophenol	15+
Hard maple	.42	Pentachlorophenol	15+

(about 25 years—possibly 35 years); on curved portions of mainline tracks, crosstie life is shortest.

In the future crosstie life may be further extended by fabricating them from two or more pieces of wood smaller than 7 by 9 inches, thus permitting more complete penetration by preservatives. One such fabrication procedure now in limited commercial use calls for dowel-lamination (no glue required) of two pieces measuring 4.5 by 7 inches into a 7- by 9-inch assembly (Howe and Koch 1976). Such two-piece crossties are more readily treated than one-piece ties. Preservative penetration from the two-piece interface, nearly equal to that from the outside surfaces, should augment protection against decay.

Tschernitz et al. (1979) described the Press-Lam process for making crossties which embodies stored-heat glue-laminating of thick-sliced veneer (0.25 inch or more thick) using residual heat of the wood as removed from the veneer dryer. They found that creosote preservative treatment was adequate for all species and treating time was only about half that for solid wood crossties.

Fence Posts.—Many service-life data for treated hardwood posts are from field installations (fig. 12) made between 1940 and 1960 at Land Grant universities and by the United States Forest Service. They involved a great number of preservative materials, methods of application, species of woods, and exposure sites.

The variables of site and method of application have complicated interpretation of these data, making it difficult to reconcile inconsistencies in results. This problem is aggravated by the large number of researchers involved and resultant lack of uniformity in treating solutions, applications, and in interpretation of inspection results (Gjovik and Davidson 1975). It often is impossible after the fact to distinguish between procedural errors and differences that are site related.

The reports available cover a range of non-pressure treating methods. Among these, the cold-soak, hot-and-cold bath, and diffusion treatments were most frequently used, but superficial brush, spray, or dip applications of preservative are also well represented.

Treatments of selected hardwood species to retentions averaging between 6 and 12 pcf by cold-soak and hot-and-cold bath process have proved satisfactory. In a study reported on by Carpenter and Bouler (1962), 85 percent of ash, American elm, honeylocust, mixed oak, bitter pecan, and sweetgum posts treated by this process with coal-tar creosote were still serviceable after 19 years' exposure in Mississippi. Sixty-three to 68 percent of cottonwood, red maple, and hackberry, but only 15 percent of the willow posts were serviceable after the same period.

Retentions of 5 percent pentachlorophenol in fuel oil comparable to those obtained with coal-tar creosote were also obtained by the same authors using the hot-and-cold-bath process (Carpenter and Bouler 1962). After 13 years' exposure, 83 to 100 percent (average 94) of posts of nine hardwood species, representing both heartwood and sapwood, were serviceable. Results for sweetgum were poorest, with 59 percent serviceable after 13 years. After being pressure-treated with creosote to a retention of 12 pcf, cottonwood posts were 100 percent and sweetgum 89 percent serviceable after 23 years; with retentions of 6 pcf, however, only 42 percent of sweetgum and 8 percent of cottonwood posts were serviceable. Carpenter and Bouler (1962) also reported that soaking of black willow and cottonwood in chromated zinc chloride provided a service life of 7 to 10 years.

Among 398 hardwood posts included in a study reported on by Walters and Peterson (1965), at least 87 percent of the green ash, black cherry, shagbark hickory, black oak, and red oak were still serviceable 21 years following a cold-soak treatment in a 5 percent solution of pentachlorophenol in fuel oil.

Green, unpeeled posts treated by end-diffusion with an aqueous solution of zinc chloride protected pine and some hardwood species for over 20 years (Toole and Thompson 1973). Over 80 percent of red oak, post oak, sweetgum, and pine posts in certain size classes were still serviceable after 20 years of exposure in a test plot in Mississippi following end-diffusion treatments that yielded retention of about 1.0 pcf (Thompson 1954). Time of harvest had some effect on serviceability, with posts cut when dormant out-performing those cut during the growing season, a result attributed to retention of bark by fall- and winter-cut posts and consequent reduced leaching of preservative.

Verrall (1959) studied the protection afforded ammunition boxes by dipping in a 5 percent pentachlorophenol solution containing a water repellent. After 4.4 years' exposure near Gulfport, Miss., the decay ratings were 2.3, 3.0, and 2.3 for sapwood of yellow-poplar, sweetgum, and tupelo gum, respectively, on a scale where 0 = no decay and 5 = destroyed. The comparable rating for southern pine sapwood was 1.8. Untreated wood of all species had ratings of 4.8 to 5.0.

Scheffer (1953) tested several fungicides against common wood-decay fungi on oak and several other species, for possible use in bilgewater in boats. The order of effectiveness was: phenylmercuric acetate, sodium pentachlorophenate, 2, 4, 5-trichlorophenol, orthophenylphenol, pentachlorophenol, boric acid + sodium dichromate, and boric acid. All were effective, but orthophenylphenol and pentachlorophenol were recommended because of their low solubility, safety in use, and low cost.

Superficial treatments of pentachlorophenol in light solvent containing a water repellent were found by Scheffer and Browne (1954) to provide a high degree of protection to sweetgum blocks exposed to *Coriolus versicolor.* This work was later verified by other studies (Scheffer and Clark 1967).

Compilations of service-life data for posts are available from the following sources:

Gjovik and Davidson (1975)	Reports on over 800 combinations of preservatives, retention levels, treatment methods, species, and exposure sites.
American Wood Preservers' Association Proceedings	Reports of Committee U-5, Post Service Records: Annually through 1969.
Anonymous (1960)	Results of studies by members of Wood Preservation Council.
Krzyzewski and Spicer (1974)	Results of Canadian post studies, 34 years.
Krzyzewski and Sedziak (1975)	Performance of treated posts.

Service-life and treating data gleaned from the aforementioned sources are shown in table 18 for selected species. Service-life for untreated wood of the same species is included in table 19. Extension of service life by preservative treatment varied principally with the preservative used and exposure site. Zinc chloride, chromated zinc chloride, and other water-soluble, nonreactive formulations generally gave poorer results than creosote or the oil-borne preservatives. Exposure site greatly affected service-life with these light-duty preservatives. Red oak posts treated by end-diffusion had a service life of 21 years in Wisconsin, but only 9 years in Mississippi. Retention of zinc chloride by the Mississippi posts at 0.95 pcf was 27 percent higher than that for the Wisconsin posts.

The double-diffusion process generally protected posts better than one-step diffusion. Service life of red oak, sweetgum, and hickory posts treated with zinc sulfate followed by arsenic acid + sodium chromate and exposed in Georgia ranged from 16 to 22 years and averaged almost 20 years (table 18). This is near the average service life of 23 years for pentachlorophenol-treated oak posts exposed in Mississippi and Alabama. Results are even better when copper sulfate replaces zinc sulfate in double-diffusion treatment (Gjovik and Davidson 1979).

The performance of copper naphthenate-treated posts was generally inferior to that for posts treated with creosote and pentachlorophenol. For example, oak posts treated with this preservative and exposed in Tennessee and Mississippi failed after only 8 to 14 years. These results indicate that solution concentration—in terms of percent copper metal—was inadequate even though gross adsorption of solution was comparable to that for other preservatives. A retention of copper naphthenate equivalent to 0.40 pcf of copper metal is needed for long-term protection of wood[2]. The copper content of treating solutions used in the studies reported was usually about 0.5 percent, too low by a factor of about 10 to provide the desired copper retention when gross adsorption was typically 4 to 6 pcf.

Service life for oaks treated with creosote, mainly by the thermal process, ranged from 27 years in Mississippi (pcf = 8.4 to 9.2), 50 years in Missouri (pcf = 6 to 11), and 40 years in Wisconsin (pcf = 4.1). These high performances appear to reflect above average treatment quality rather than the superiority of the preservative. For any given retention, pressure and thermal treatments should provide better penetration of preservative than cold-soak treatments. This trend was also evident with species other than the oaks.

Species prone to develop deep checks or splits may decay faster than split-resistant species. There is some evidence that cottonwood and willow perform more poorly than could be anticipated based on preservative retention (Hopkins 1951;Furnival 1954), probably attributable to uneven distribution of preservative.

Sweetgum is the hardwood species that has received the most attention from researchers in establishing field tests of wood preservatives. Results of tests conducted by eight state agricultural experiment stations located within the natural range of this species are listed in table 20. These data show that the two-year natural service life of this species is increased by a factor of seven or more by perservative treatment with pentachlorophenol and copper naphthenate and by a factor of about three by treatment with zinc chloride.

EFFECTS OF TREATMENTS ON WOOD PROPERTIES

Some of the treatments to which wood is subjected during preserving and stabilization treatments adversely affect its mechanical properties. Certain preservatives are themselves reported to reduce wood strength as do incising and conditioning preparatory to preservative treatment. The beneficial effects of these operations—improved quality of preservative treatments and extended service life—usually outweigh the negative effects.

Most studies of the relationship between wood strength and processing operations deal with softwood species. There are some data for hardwoods, however, and much can be inferred about hardwoods from softwood studies.

Incising

Perrin (1978) concluded that incising probably has a negligible effect on the strength properties of large items such as poles and crossties. For timbers smaller than crossties, however, the results were mixed, as indicated for Douglas-fir in table 21.

Table 18.—*Service life of hardwood fence posts by species, treating method, preservative, and exposure site. (Data from Anonymous 1960; Kulp 1966; Gjovik and Davidson 1975.)*

Species and treatment method (and time, hours)	Preservative Material	Preservative Retention	Exposure state	Year installed	Service life
		pounds/cu ft			*years*[1]
American elm					
Hot-and-cold bath	Creosote	11.1	Mississippi	1941	....
Cold-soaking (48)	Pentachlorophenol (10 percent)	3.2	Illinois	1942	20
Cold-soaking (120)	Pentachlorophenol	2.5	Mississippi	1953	14
Beech					
Hot-and-cold bath	Creosote	8.5	Maryland	1908	48
River birch					
Hot-and-cold bath	Creosote	....	Maryland	1908	30
Bitter pecan					
Hot-and-cold bath	Creosote	6.0-8.9[2]	Wisconsin	1941	18+
Hot-and-cold bath	Pentachlorophenol	4.3-6.7	Mississippi	1949	13
Cold-soaking	Pentachlorophenol	5.2	Mississippi	1953	21
Blackjack oak					
Pressure	Creosote	6-11	Missouri	1938	50+
Pressure	Zinc chloride	.84	Wisconsin	1938	34
Hot-and-cold bath	Creosote	4.1	Wisconsin	1938	40
Cold-soaking (105)	Pentachlorophenol	4.1	Tennessee	1949	....
Cold-soaking (195)	Pentachlorophenol	4.5	Tennessee	1949	....
Cold-soaking (47)	Copper naphthenate	4.4	Tennessee	1953	8
Cold-soaking (48)	Copper naphthenate	3.4	Tennessee	1953	12
Black willow					
Steeping	Chromated zinc chloride	....	Mississippi	1948	5
Steeping	Chromated zinc chloride	....	Mississippi	1947	10
Hot-and-cold bath	Creosote	8.4[2]	Mississippi	1941	17
Box elder					
Cold-soaking (120)	Pentachlorophenol	9.8	Mississippi	1953	18
Cedar elm					
Cold-soaking (120)	Pentachlorophenol	5.1	Mississippi	1953	26
Cottonwood					
Pressure	Creosote	6.0	Mississippi	1937	18
Pressure	Creosote	12.0	Mississippi	1937	....
Hot-and-cold bath	Creosote	12.2[3]	Minnesota	1909	30
Steeping	Sodium fluoride	.28	Montana	1926	9
Steeping	Sodium fluoride	.67	Montana	1926	13
Hackberry					
Hot-and-cold bath	Creosote	8-12	Mississippi	1941	23
Hot-and-cold bath	Pentachlorophenol	10-13	Mississippi	1948	17
Cold-soaking (120)	Pentachlorophenol	3.5	Mississippi	1953	11
Hickory					
Double diffusion	[4]	.20	Mississippi	1953	14
Cold-soaking (120)	Pentachlorophenol	3.6	Mississippi	1953	21
Double diffusion	[5]	.39	Georgia	1955	19
Double diffusion	[5]	1.0	Georgia	1955	19
Northern red oak					
Pressure	Creosote	5.8	Wisconsin	1960	....
Hot-and-cold bath	Creosote	....	Maryland	1908	36
End diffusion	Chromated zinc chloride	.75	Wisconsin	1946	21
Cold-soaking (8)	Pentachlorophenol	3.2	Wisconsin	1943	14
Cold-soaking (24)	Pentachlorophenol	3.5	Wisconsin	1943	20
Cold-soaking (48)	Pentachlorophenol	4.5	Wisconsin	1943	28
Cold-soaking (96)	Pentachlorophenol	5.8	Wisconsin	1943	36
Cold-soaking (168)	Pentachlorophenol	5.7	Wisconsin	1943	36
Cold-soaking	Pentachlorophenol	1.8[2]	Minnesota	......	33
Cold-soaking (66)	Pentachlorophenol	2.6	Illinois	1942	....
Overcup oak					
Hot-and-cold bath	Creosote	6.1-9.5[2]	Mississippi	1941	30+
Hot-and-cold bath	Pentachlorophenol	2.7-7.9[2]	Mississippi	1947	18
Post oak					
Cold-soaking (72)	Pentachlorophenol	4.2	Alabama	1948	23
Cold-soaking (46)	Pentachlorophenol	3.2	Alabama	1948	17
Cold-soaking	Pentachlorophenol	5.7	Mississippi	1956	....
Cold-soaking (48)	Pentachlorophenol	2.0[3]	Texas	1963	....

Table 18.—*Service life of hardwood fence posts by species, treating method, preservative, and exposure site. (Data from Anonymous 1960; Kulp 1966; Gjovik and Davidson 1975.)—Continued*

Species and treatment method (and time, hours)	Preservative Material	Preservative Retention	Exposure state	Year installed	Service life
		pounds/cu ft			*years*[1]
Cold-soaking (123)	Copper naphthenate	7.1	Tennessee	1954	11
Cold-soaking (72)	Copper naphthenate	7.1	Tennessee	1954	. . . .
Cold-soaking	Copper naphthenate	9.6	Mississippi	1956	. . . .
Red maple					
Hot-and-cold bath	Creosote	. . . .	Maryland	1908	32
Cold-soaking (23)	Pentachlorophenol	6.1	Tennessee	1951	15
Cold-soaking (53)	Pentachlorophenol	5.6	Tennessee	1949	22
Cold-soaking (46)	Copper naphthenate	4.3	Tennessee	1953	7
Scarlet oak					
Cold-soaking (44)	Pentachlorophenol	3.9	Tennessee	1949	. . . .
Cold-soaking (48)	Copper naphthenate	4.7	Tennessee	1953	12
Cold-soaking (55)	Copper naphthenate	5.7	Tennessee	1953	14
Cold-soaking (47)	Copper naphthenate	5.2	Tennessee	1954	. . . .
Southern red oak					
Cold-soaking	Pentachlorophenol	5.6	Mississippi	1953	. . . .
Cold-soaking	Pentachlorophenol	3.9	Mississippi	1947	23
End diffusion	Zinc chloride	.95	Mississippi	1947	9
Double diffusion	[5]	1.0	Georgia	1955	21
Double diffusion	[5]	1.6	Georgia	1955	22
Double diffusion	[5]	2.1	Georgia	1955	16
Cold-soaking (48)	Pentachlorophenol	6.2	Mississippi	1948	. . . .
Cold-soaking (48)	Pentachlorophenol	5.0	Mississippi	1956	. . . .
Cold-soaking (48)	Pentachlorophenol	6.4	Mississippi	1951	. . . .
Cold-soaking (84)	Copper naphthenate	7.6	Mississippi	1951	11
Cold-soaking	Copper naphthenate	9.2	Mississippi	1956	. . . .
Sweetgum					
Pressure	Boliden salt	.78	Mississippi	1957	. . . .
Pressure	Creosote	9.7	Mississippi	1957	. . . .
Hot-and-cold bath	Creosote	7.7	Louisiana	1909	23
Hot-and-cold bath	Creosote	. . . .	Maryland	1908	14
Pressure	Creosote	6.0	Mississippi	1937	23
Pressure	Creosote	12.0	Mississippi	1937	34
Hot-and-cold bath	Pentachlorophenol	2.3-10.0	Mississippi	1947	15
Cold-soaking (48)	Pentachlorophenol	4.9	Mississippi	1947	21
End diffusion	Zinc chloride	.95	Mississippi	1947	7
Double diffusion	[5]	1.9	Georgia	1955	19
Water oak					
Hot-and-cold bath	Creosote	8.4-9.6[2]	Mississippi	1941	27
Hot-and-cold bath	Pentachlorophenol	2.7-5.6[2]	Mississippi	1947	. . . .
Water tupelo					
Hot-and-cold bath	Creosote	8.6	Louisiana	1908-10	23
Cold-soaking (120)	Pentachlorophenol	6.5	Mississippi	1953	22
End diffusion	Zinc chloride	.94	Mississippi	1947	5
White oak					
Pressure	Chromated copper arsenate	.28	Mississippi	1957	. . . .
End diffusion	Chromated zinc chloride	.75	Wisconsin	1946	29
Hot-and-cold bath	Creosote	. . . .	Maryland	1908	37
Pressure	Creosote	8.1	Mississippi	1957	. . . .
Steeping	Zinc chloride	1.1-1.8	Wisconsin	1940	16
Double diffusion	[5]	1.3-2.3	Georgia	1955	16-21
Yellow-poplar					
Double-diffusion	[5]	2.0	Georgia	1955	19

[1]Estimated average life of posts in tests. The most common method of determination of service life is use of mortality curves (such as those developed for crossties). An estimate of service life can be made when as few as 11 percent of the posts have failed. Other authors whose data are cited in this table made no estimate of service life until 60 percent of the posts had failed. Dot leaders (. . .) in this column indicate that an insufficient number of posts had failed at the last inspection to permit an estimate of service life.

[2]Mixed round and split posts.

[3]Split posts.

[4]Copper sulfate-sodium chromate.

[5]Zinc sulfate and arsenic acid-sodium chromate.

Table 19.—*Service life of untreated hardwood posts of 16 species (Gjovik and Davidson 1975)*

Species	Form	Location of test	Service life
			years
Ash, green	Round	Halsey, Nebraska	18.7
Ash, green	Round	Miles City, Minnesota	8.6
Ash, white	Round	Madison, Wisconsin	4.3
Elm, slippery	Round	Oregon, Wisconsin	3.8
Hickory, mockernut	Round	Saucier, Mississippi	3.5
Hickory, shagbark	Round	Oregon, Wisconsin	4.0
Hickory, sp.	Round	Norris, Tennessee	4.7
Hickory, sp.	Round	Saucier, Mississippi	2.8
Maple, red	Round	College Park, Maryland	3.8
Oak, black	Round	Norris, Tennessee	2.8
Oak, blackjack	Square	Madison, Wisconsin	8.4
Oak, blackjack	Round	Ava, Missouri	6.0
Oak, blackjack	Square	Madison, Wisconsin	7.9
Oak, southern red	Round	Saucier, Mississippi	2.8
Oak, red sp.	Round	Athens, Georgia	4.3
Oak, overcup	Round	Stoneville, Mississippi	4.3
Oak, overcup	Split	Stoneville, Mississippi	5.0
Osage orange	Round and split	Childress, Texas	43.0
Sweetbay	Round	Saucier, Mississippi	1.6
Sweetgum	Round	Athens, Georgia	2.2
Sweetgum	Round	College Park, Maryland	4.2
Sweetgum	Round	Wilson Dam, Alabama	2.3
Sweetgum	Round	Saucier, Mississippi	1.8
Tupelo, black	Round	Norris, Tennessee	3.4
Tupelo, black	Round	College Park, Maryland	4.2
Tupelo, water	Round	Saucier, Mississippi	2.1

Schrader (1945) determined the effect of incising on the strength of Douglas-fir laminated beams. Beams 8 × 18 inches in cross section fabricated from 1-inch lumber and beams 8 × 16 inches prepared from 2-inch lumber sustained reductions in bending strength of from 10 to 20 percent as a result of ⅝-inch-deep incisions applied at a rate of 65 per square foot. Banks (1973) found that 2- by 2-inch samples of Norway spruce (*Picea abies L.* Karst.) lost 16 and 13 percent of their MOR and MOE, respectively, following incising to a depth of ¼-inch with 860 incisions per square foot. Similar depths and frequencies of incisions on redwood (*Sequoia sempervirens* (S. Don) Endl.) dimension sized for use in cooling towers reduced bending strength by 7 to 28 percent (Kass 1975).

From the limited data available on the effect of incising on the strength of hardwoods, it can be surmised that effects are similar to those for softwoods. A study of strength losses sustained by small hardwood posts prepared for non-pressure preservative treatment (Chudnoff and Goytia 1967) tends to confirm this. Incising at a rate of 160 incisions per square foot caused a reduction of MOR of about 14 percent.

Conditioning

Steaming.—Steaming of wood reduces water content in green stock and renders it more permeable to preservatives. It is routinely applied to southern pine and certain other conifers but less frequently applied to hardwoods. Current industry standards (American Wood Preservers' Association 1977) do not permit steam conditioning of oak because of its susceptibility to damage from this process. While steaming is permitted with other hardwoods, those that receive preservative treatment are mainly for crossties, conditioned usually by air drying, Boultonizing, or vapor drying.

Steam conditioning at the pressures and durations permitted under existing standards may cause significant strength losses in treated products. Buckman and Reese (1938), Davis and Thompson (1964), MacLean (1951), and Wood et al. (1960) show conclusively that above certain temperatures wood undergoes chemical degradation and sustains losses in strength to a degree dependent upon the duration and severity of exposure.

Wood heated in an atmosphere of steam loses weight, becomes discolored, sustains reductions in strength, and undergoes chemical degradation (Baechler 1954). At atmospheric pressure, effects are those of a mild hydrolysis, catalyzed by natural acids in the wood, becoming progressively more severe with increasing temperature and time of exposure. The carbohydrate fraction of wood, especially the hemicellulose component, is particularly susceptible to hydrolysis (MacLean 1951).

Much of the original work on the effect of steaming on the mechanical properties of wood was conducted

Table 20.—*Treating and service-life data for sweetgum fence posts. (Data from Kulp 1966; Anonymous 1960).*

Treating method (and time, hours)	Preservative Material	Preservative Retention	Age at last inspection	Exposure state	Number in test	Failure	Service life[1]
		pounds/cu ft	*years*			*percent*	*years*
Cold-soaking (26)	Pentachlorophenol	6.8	11	Mississippi	23	44	13
Cold-soaking (. . .)	Pentachlorophenol	6.3	8	Mississippi	292	41	9
Cold-soaking (48)	Pentachlorophenol	5.1	14	Georgia	23	39	16
Cold-soaking (24)	Pentachlorophenol	4.7	14	Georgia	18	33	17
Cold-soaking (72)	Pentachlorophenol	5.8	14	Georgia	25	28	18
Cold-soaking (72)	Pentachlorophenol	5.7	14	Georgia	24	4	. . .
Cold-soaking (72)	Pentachlorophenol	6.4	13	Georgia	26	8	. . .
Cold-soaking (144)	Pentachlorophenol	7.2	14	Georgia	25	1	. . .
Cold-soaking (24)	Pentachlorophenol	5.5	15	Alabama	28	14	22
Cold-soaking (6)	Pentachlorophenol	5.0	15	Alabama	27	85	11
Cold-soaking (72)	Pentachlorophenol	5.6	12	Texas	65	0	. . .
Cold-soaking (72)	Pentachlorophenol	5.6	13	Texas	98	0	. . .
Cold-soaking (72)	Pentachlorophenol	5.6	13	Texas	97	0	. . .
Cold-soaking (72)	Pentachlorophenol	5.6	12	Texas	30	0	. . .
Cold-soaking (12)	Pentachlorophenol	5.1	12	Virginia	5	80	10
Cold-soaking (48)	Pentachlorophenol	4.1	12	Virginia	11	48	13
Cold-soaking (105)	Copper naphthenate	7.0	8	Mississippi	50	18	11
Cold-soaking (24)	Copper naphthenate	4.4	14	Georgia	47	56	15
Cold-soaking (48)	Copper naphthenate	5.4	14	Georgia	24	38	16
Cold-soaking (72)	Copper naphthenate	4.2	14	Georgia	22	64	14
Cold-soaking (144)	Copper naphthenate	5.7	15	Georgia	23	52	14
Cold-soaking (0.3)	Copper naphthenate	. . .	6	Tennessee	17	35	7
End diffusion	Zinc chloride	.9	6	Mississippi	200	34	7
End diffusion	Zinc chloride	.4	12	Georgia	50	82	6.5
End diffusion	Zinc chloride	.6	10	Georgia	24	96	6
	None		. .	Georgia	24	100	3.0
	None		. .	South Carolina	21	100	1.0
	None		. .	Mississippi	24	100	2.2
	None		. .	Louisiana	25	100	2.0

[1]Estimated average life of posts in test. Dot leaders (. . .) in this column indicate that an insufficient number of posts had failed at the last inspection to permit an estimate of service life.

Table 21.—*The effect of incising on the strength of Douglas-fir timbers and ties (Adapted from Perrin 1978)*

Dimensions	Incisions per square foot	Change in strength: Bending[1] PL	Bending[1] MOR	Bending[1] MOE	SH[2]	Compression[3] CS	Compression[3] MOE	Compression[3] FS
inches	*number*	percent						
4×8	64	−8	−15	−4	. . .	−4	. . .	−7
4×8	64	−18	−15	−14	. . .	−17	. . .	−33
4×8	64	−4	−9	−4	. . .	−3	. . .	+3
4×8	64	+2	+11	−6	. . .	−5	. . .	−5
6×12	56	−2	−2	. . . .	−2	. . .	. . .	. . .
6×12	56	+1	−2	. . . .	−2	. . .	. . .	. . .
6×12	75	−2	0	−7	0	. . .	. . .	. . .
6×12	75	−4	−7	−4	−7	. . .	. . .	. . .
7×8	75	. . .	. . .	. . .	. . .	. . .	. . .	−10
7×9	76	. . .	. . .	. . .	. . .	. . .	. . .	−8
7×9	76	+6	+4	0	0	+3	0	+6
7×10	90	. . .	. . .	. . .	. . .	. . .	. . .	+17

[1]PL-proportional limit stress, MOR-modulus of rupture, MOE-modulus of elasticity.
[2]SH—shear parallel to grain.
[3]CS—crushing strength parallel to grain; MOE in compression parallel to grain; FS—compression strength perpendicular to grain.

by MacLean (1951, 1952, 1953). Following a study in which small specimens were steamed at temperatures of 250°F to 350°F for 8 to 32 hours, he concluded that shock resistance was the property most seriously affected, followed in order by MOR, fiber stress at the proportional limit, and MOE (MacLean 1953). An identical order of effect was reported by Thompson (1969a) based on bending tests of Class 6, 30-foot southern pine poles. In the latter study, MOR was reduced about 37 percent, from 7,902 psi to 5,707 psi, as a result of steaming 14 hours at 245°F.

The limited data available on hardwoods indicate they are more susceptible to damage from steaming than are softwoods. Davis and Thompson (1964) found that the residual toughness of small red oak specimens following steaming at 138°C for 120 minutes was only 60 percent of the control values, a greater reduction than those for southern pine and Douglas-fir specimens similarly treated. Chemical analyses of these specimens revealed that the reduction in strength was well correlated with changes in chemical composition. The carbohydrate fraction was more seriously degraded in oak than in either of the two coniferous species.

Kubinsky (1971) reported that compressive strength of small red oak cubes was reduced by 20 and 23 percent in the tangential and radial directions after steaming for 6 hours at atmospheric pressure. Reductions after exposure for 96 hours were 55 and 49 percent, respectively. Thompson (1969b) found a 14 percent reduction in compressive strength for southern pine piling sections steamed 16 hours at 245°F. While specimen size differed, results suggest that hardwoods are more sensitive to steaming than softwoods.

Further substantiation of this statement is provided by extensive research conducted by MacLean (1951, 1953). Weight losses resulting from heating small specimens for 17.4 days in water at 250°F were as follows for the species indicated:

Species	Weight loss
	Percent
Yellow birch	38
Yellow-poplar	37
Basswood	36
White oak	36
Sweetgum	34
Hard maple	33
Southern pine	28
Douglas-fir	25
White pine	24
Sitka spruce	24

Although this order of effect of thermal treatments was not maintained for all combinations of temperatures and heating mediums employed by MacLean (1951), the hardwoods were far more sensitive than the softwoods in all tests.

Boulton Drying. —Conditioning by the Boulton process has less deleterious effects on wood than steaming because of the lower temperatures (180-210°F) used. As in the case of steaming, strength reductions caused by the process at a given temperature are determined by the duration of the conditioning process, by species, and by the size of items involved.

Data of the effects of Boulton-drying are lacking for hardwood species. Based on the experience with other forms of thermal treatment, it is probable that they would be at least equal to those for softwoods. Data compiled by Graham (1980) on the effect of three conditioning processes on the strength of Douglas-fir sawn products are of interest (table 22). Reductions in MOR for timbers in the size range from 6 × 12 to 8 × 16 inches that were Boultonized at temperatures of 190° to 215°F ranged between 5 and 18 percent and averaged about 10 percent in tests conducted by Rawson (1927), MacFarland (1916), Luxford and MacLean (1951), and Harkom and Rochester (1930). Reductions in MOR for 1-inch and 2-inch stock exposed to the same temperature averaged almost 12 percent; items in this size class that were kiln-dried or vapor-dried in the temperature range of 220° to 250°F sustained reductions in MOR of 18 to 21 percent. Rawson's study of the effect of Boulton drying on Douglas-fir timbers was superimposed on a study of the effect of incising. The modest reduction in MOR of 6 percent attributed by the authors to the Boulton process was higher than the apparent reduction caused by incising —about 2 percent.

Reductions in MOR caused by Boultonizing for 30-foot Douglas-fir and western larch poles were reported by Wood et al. (1960) to be of the same order of magnitude as those for sawn products (table 23). Larch was the more seriously affected, showing a decrease in MOR and MOE of 17 and 20 percent, respectively. However, these values were smaller than the reductions sustained by steam conditioned southern pine, which ranged from 23 to 34 percent for MOR and 12 to 16 percent for MOE.

Vapor Drying. —The effect of this conditioning process on wood strength is somewhat greater than that of Boulton-drying because of the higher temperatures employed. Eddy and Graham (1955) found reductions in MOR of 9, 18, and 21 percent following vapor drying of 2- by 2-inch Douglas-fir at 190, 225, and 250°F, respectively. Reductions in work to maximum load were, in order, 17, 36, and 49 percent.

Strength reductions in oak and gum crossties attributed to vapor drying are of the same order of magnitude (table 24) notwithstanding the large difference in cross-sectional dimension of the test specimens: 2 by 2 inches compared to 7 by 9 inches. The MOR of untreated vapor-dried ties at 8,025 psi was about 8.3 percent less than that for matched air-dried ties. The comparable reduction for fiber stress at the proportional

Table 22.—*Effect of conditioning temperature on the modulus of rupture of Douglas-fir (Graham 1980)*

Reference	Specimen size	Reduction of MOR as fraction of control values[1]				Heat source
		140 to 170°F	190 to 215°F	220 to 230°F	250°F	
	inches	*percent*				
Eddy and Graham (1955)	2×2	...	9	18	21	Organic vapors
	2×2	4	...	...	...	Kiln drying
Graham (1980)	1×1	...	...	16	...	Organic vapors
	1×1	7	16	...	...	Kiln drying
Harkom and Rochester (1930)	6×12	...	13	...	...	Boulton drying
Kozlik (1968)	2×6	1	10	21	...	Kiln drying
Luxford and MacLean (1951)	4×8	...	4	...	...	Boulton drying
	8×16	...	9	...	...	Boulton drying
	8×16	...	12	...	...	Boulton drying
	8×16	...	7	...	...	Boulton drying
	8×16	...	8	...	...	Boulton drying
MacFarland (1916)	7×16	...	18	...	...	Boulton drying
Rawson (1927)	6×12	...	5	...	...	Boulton drying
	6×12	...	7	...	...	Boulton drying

[1]Adjusted for differences in moisture content between treated and control specimens.

limit in compression perpendicular to the grain was 11.9 percent. For reasons that are unclear, the reduction in both strength properties was increased if the ties were water soaked prior to testing. Thus, the MOR of air-dried, water-soaked oak ties was 8,320 psi compared to 6,760 psi for vapor-dried, water-soaked ties, an apparent reduction due to vapor drying of almost 19 percent. The same effect is evident in the data for gum crossties.

Effect Of Treating Cycle

Woods with low permeability sometimes sustain cell collapse under high temperatures and pressures in wood preserving. The incidence of collapse varies both within and among species, as well as with the treating conditions imposed. Thus, Rosen (1975b) found that both white oak and red oak collapsed at a pressure of 1,000 psi when the temperature was 75°F and at 500 psi when the temperature was 200°F. James (1961), however, found no collapse in red oak following pressure treatments conducted at 1,000 psi and 200°F. Likewise, Walters and Guiher (1970) successfully treated redgum (sweetgum) at 800 psi and 200°F without inducing collapse. Walters (1967) found collapse of sweetgum only in specimens subjected to pressure greater than 400 psi. It varied from slight to severe depending upon treating temperature and wood moisture content.

In red oak specimens, following treatments covering pressure and temperature ranges of 200 to 800 psi and 100 to 200°F, respectively, James (1961) detected no collapse in any of the specimens. Toughness reductions increased with the severity of treating conditions and ranged from about 6 percent (200 psi, 100°F) to about 11 percent (800 psi, 200°F).

While temperature and pressure are important, the refractory nature of collapse-prone species is a basic cause of collapse during preservative treatment. Unlike easily penetrated species, in which pressures are rapidly equalized by the flow of preservative into cell lumens, refractory species permit large pressure differentials to develop, inducing collapse of cells.

Stabilization Treatments

Rowell and Youngs (1981) noted that "there are two basic types of wood treatments for dimensional stability: (1) those which reduce the rate of water vapor or liquid absorption but do not reduce the extent of swelling to any great degree, and (2) those which reduce the extent of swelling and may or may not reduce the rate of water absorption (fig. 13). Terms most often used to describe the effectiveness of the first type of treatment are moisture-excluding effectiveness (MEE), which can be determined in either water or water vapor form, and water repellency (WR), which is a specific liquid test. The term used to describe the effectiveness of the second type of treatment is reduction in swelling (R) or antishrink efficiency (ASE). Most of the type (1) treatments have very low R or ASE values. The R or ASE values can be determined in water vapor tests or single-soak liquid test for water-leachable treatments, or in double-soak liquid tests for nonleachable treatments.

"In selecting a treatment to achieve product stability to moisture, at least three factors must be considered. The environment of the end product is the most important factor. If the product will come into contact with water, nonleachable—and perhaps even bonded—treatments will be needed. If, however, the product will be

Table 23.—*Effect of conditioning method on the strength of 30-foot poles (Wood et al. 1960)*

Species	Conditioning method	Modulus of rupture	Modulus of elasticity
		(Fraction of unseasoned controls)	
		----------- percent -----------	
Longleaf and slash pines (*Pinus palustris* Mill. and *P. elliottii* Engelm.)	Steam and vacuum[1]	−23	−12
Shortleaf and loblolly pines (*Pinus echinata* Mill. and *P. taeda* L.)	Steam and vacuum[1]	−34	−16
Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)	Boulton drying[2]	− 7	− 4
Western larch (*Larix occidentalis* Nutt.)	Boulton drying[2]	−17	−20
Lodgepole pine (*Pinus contorta* Dougl.)	Air drying	+ 4	+ 3
Western redcedar (*Thuja plicata* Donn)	Air drying	− 4	− 1

[1]Steaming conditioning was conducted at 259°F for 8.5 to 13.5 hours.
[2]Boulton drying was conducted at 195 to 210°F for 16 to 30 hours with a vacuum of 17 to 25 inches of mercury.

subjected to changes in relative humidity in an indoor environment, a leachable or water-repellent treatment might be satisfactory. The degree of dimensional stability must also be considered. If very rigid tolerances are required in a product—as in pattern wood dies—a treatment with very high R or ASE values is needed. If, on the other hand, only a moderate degree of dimensional stability is satisfactory, a less rigorous treatment will suffice. A final consideration is the cost effectiveness of a treatment. For example, the millwork industry uses a simple wax dip treatment to achieve a moderate degree of water-repellency. They would, no doubt, like a higher degree of water repellency or dimensional stability, but the cost to achieve this may not be recoverable in the marketplace. On the other hand, musical instrument makers require a very high degree of dimensional stability and the value of the final instrument can absorb the high cost to accomplish the desired results."

Readers interested in a general review of stabilization treatments such as cross lamination, water resistant coatings, hygroscopicity reduction, crosslinking, and bulking should read Rowell and Youngs (1981). Some research results specific to eastern hardwoods follow.

Typically, small specimens have been treated with polyethylene glycol or monomers, such as styrene and methyl methacrylate, which are subsequently polymerized *in situ* by heat (Siau and Meyer 1966) or gamma radiation (Siau et al. 1965). Treatment efficiency, as assessed by reduction in dimensional changes or volumetric swelling associated with changing moisture conditions, is a function of the fractional void volume of the wood filled by the chemical—a function of wood permeability and moisture content at time of treatment. Impregnation by pressure and vacuum processes has been used for treatments with monomers, while polyethylene glycol is applied by soaking unseasoned wood in a 30 to 50 percent aqueous solution of the chemical for several days or weeks, depending upon specimen size. Cost has limited the use of stabilization treatments to high-value items requiring above normal dimensional stability (Hallock and Bulgrin 1972).

Siau and Meyer (1966) reported that mechanical properties of yellow birch specimens impregnated (average loading 97 percent) with methyl methacrylate differed by curing method. Curing was by heat (68°C for 19.5 hours) or gamma radiation (0.64 megarads/hour for 4.7 to 15.6 hours). Mean compression strength was 11,700 psi for the 3 to 10 megarads treatment and 12,180 psi for heat. Values for control specimens averaged 2,905 psi. Thus, impregnations with methyl methacrylate improved compressive strength by an average factor of 4.11. Shear strength was not affected by treatment. Surface hardness was 25 percent greater in irradiated than in heat-cured specimens, ascribed by the authors to a preferential loss of monomer near the surface during heat curing. Antishrinkage efficiency was only 7.3 percent, thus suggesting that only small quantities of the monomer penetrated cell walls.

Much higher antishrinkage efficiencies—up to 80 percent—were reported by Siau et al. (1965) following irradiation curing of styrene-impregnated yellow-poplar. Retentions of 80 to 200 percent (based on ovendry wood weight) were obtained using solvent exchange and vacuum methods. Best results were achieved with dioxane, methanol, or ethanol as solvents. In later work, Siau (1969) found that volumetric swelling of up to 9 percent may occur in basswood following prolonged immersion in methyl methacrylate and styrene and after wood-polymer composites have been made using these materials. The amount of swelling was reported to be a function of temperature and moisture content of the wood. Siau et al. (1975) found that both smoke evolution and flamespread are significantly increased by the presence in wood of polymers whose structure includes benzene rings.

Table 24.—*Strength of green, air-seasoned, and vapor-dried 7- by 9-inch oak and gum crossties*[1]

Species group and condition at time of test	Modulus of rupture	Fiber stress at proportional limit in compression perpendicular to the grain
	psi	
Oak (*Quercus* sp.)[2]		
Green	9,560	804
Air-dried, water-soaked	8,320	706
Air-dried	8,754	687
Air-dried, creosoted, water-soaked	8,360	800
Air-dried, creosoted	8,920	811
Vapor-dried, water-soaked	6,760	474
Vapor-dried	8,025	605
Vapor-dried, creosoted, water-soaked	6,360	459
Vapor-dried, creosoted	8,250	611
Gum (sweetgum and black tupelo)[3]		
Green	8,604	685
Vapor-dried, water-soaked	7,500	446
Vapor-dried	7,828	490
Vapor-dried, creosoted, water-soaked	6,010	490
Vapor-dried, creosoted	7,390	792

[1]Data provided by M. S. Hudson, Spartanburg, S.C.
[2]Each value is the average of 32 tests.
[3]Each value is the average of 12 tests.

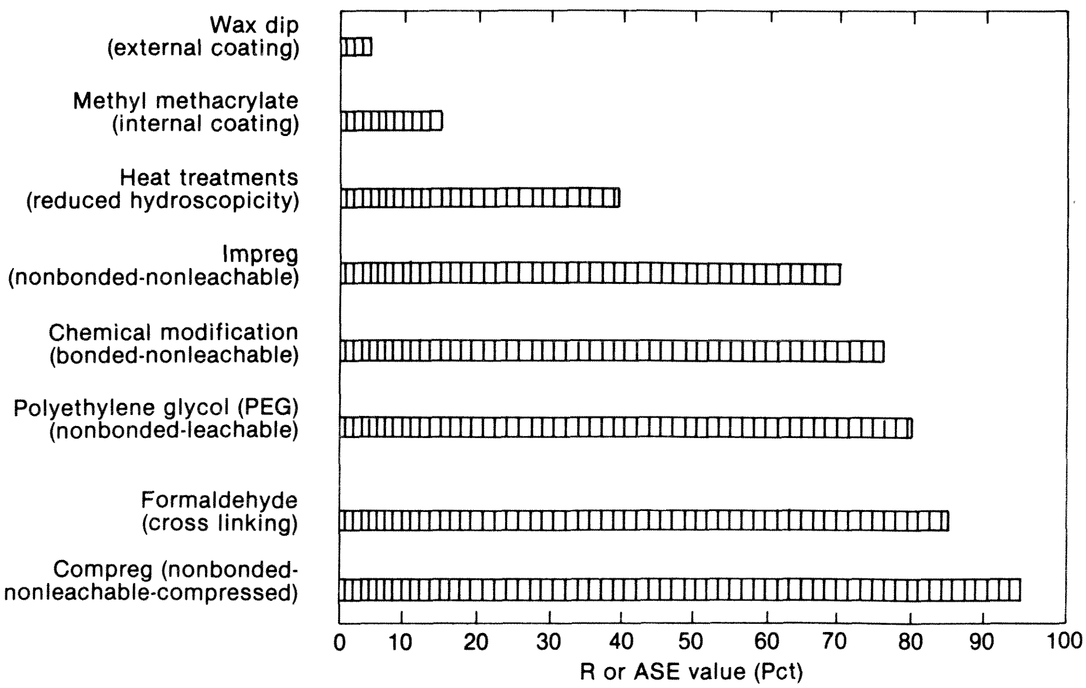

Figure 13.—*Comparison of wood treatments and the degree of dimensional stability achieved. Impreg is laminated from veneers impregnated with phenol-formaldehyde resin. Compreg is made by densifying layers of resin-impregnated veneer by application of heat and pressure up to 1,000 psi. (Drawing after Rowell and Youngs 1981).*

Unlike Siau and Meyer (1966), Loos and Kent (1968) found significant increases in shear strength of yellow-poplar following loadings of 50 to 100 percent with methyl methacrylate.

The addition of waxes to styrene and methyl methacrylate monomers prior to impregnation of wood was reported by Lan and Rosen (1978) to affect adversely the polymerized properties of the wood-polymer composite. Application of waxes to the surface of composites provided water and water-vapor resistance superior to all wax-monomer combinations.

Antishrink efficiencies of 60 to 70 percent have been reported for softwood samples treated with methyl isocyanate to weight gains of 16 to 28 percent (Rowell and Ellis 1979). Volumetric changes resulting from treatment were approximately equal to the volume of chemical absorbed, thus indicating that a chemical addition took place within the cell wall. Decay resistance was imparted by the treatment. At weight gains greater than about 26 percent, part of the chemical could be leached from the wood, and electron micrographs revealed cell-wall splitting.

Hallock and Bulgrin (1972) and Merz and Cooper (1968) have shown the efficiency of polyethylene glycol (molecular weight 1000) in reducing shrinkage and warpage of wood during drying and in service. The latter authors, who worked with black oak specimens 3 × 1½ × 1½ inches long, reported that treatment durations of 96 hours at 130°F to 150°F provide antishrink efficiencies of 50 to 65 percent and that further gains from longer treatments are of little practical significance. Hallock and Bulgrin subjected maple flooring to a treatment regime in polyethylene glycol that included solution temperatures as high as 200°F. Exposure at this temperature for 10 days produced a 22 percent retention and essentially no shrinkage upon drying.

Irradiation of wood has been employed commercially in the production of wood-polymer composites. The effect of irradiation on the mechanical properties of the wood varies with dosage and also apparently with species. Loos (1962) reported an increase in toughness of specimens of yellow-poplar for gamma radiation dosages up to about 0.85×10^5 rads. Toughness was reduced by as much as 28 percent, however, by levels in the range of 1.0×10^7 rads.

A significant increase in MOR was reported by Shuler et al. (1975) for specimens of American elm cut from saplings that had been exposed for 5 years to a gamma radiation level of 22,000 roentgens. By contrast, maximum work was decreased by all radiation levels studied by these authors.

Recommendations for Future Research.—Rowell and Youngs (1981) identified some specific research avenues that need further investigation. They noted that the "properties of coatings can be tailored to perform more duties than just water repellency. A water-repellent coating could also serve as an ultraviolet screen or flameproofing shield. It could also contain bound functional insecticides or fungicides that could protect the wood from attack by insects and decay organisms."

"In bonded bulking treatments, the bound chemical could be a fire retardant if the bonded chemical has an adequate distribution in the wood structure; thus, the treated wood would be both dimensionally stabilized and resistant to attack by termites, decay organisms, and marine organisms. Chemical modification of wood could provide a variety of nonleachable treated wood products that are both dimensionally stabilized and fire retardant or nonbiodegradable or acid and base resistant."

Complete dimensional stability of wood (R or ASE = 100) has never been achieved, and perhaps never will be; there is much yet to be learned about wood-moisture relationships (Rowell and Youngs 1981).

Effect Of Preservatives

Solid-Wood Products.—The pH of treating solutions of some water-borne preservative formulations must be maintained within certain limits to prevent precipitation of the heavy-metal salts of which they are composed. Some of the solutions may be quite acid. Thus, for example, chromated copper arsenate (CCA) solutions may have a pH as low as 1.9, and the acidity of acid copper chromate (ACC) solutions may range from pH 2.0 to 3.9. By contrast, ammoniacal copper arsenate (ACA) is quite alkaline since solutions of this preservative must contain a weight of ammonia equal to 1.5 to 2.0 times the weight of the copper oxide; copper oxide comprises 47.7 percent of the dry weight of the formulation.

The effect of the pH of the treating solution and, indeed, the effect of the preservative salts themselves on wood properties have not been clearly defined. Thompson (1964b) investigated the effect of CCA, ACA, and ACC on the toughness of sweetgum, yellow-poplar, and black tupelo veneer for retention levels of 1 to 4 pounds per cubic foot. Toughness of sweetgum and yellow-poplar was not significantly affected by the treatments. Black tupelo, however, sustained important reductions in toughness, the values varying with retention. At retentions greater than about 1.0 pound per cubic foot, embrittlement was observed in specimens of all species; yellow-poplar was least affected. Subsequent analyses of the specimens revealed that the chemical composition of the wood, particularly carbohydrate content, was altered by high retention of all three preservatives.

Additional evidence that high retentions of salt-type preservatives may reduce the shock-resistant properties of timbers was supplied by Wood et al. (1980). Specimens cut from southern pine pole sections treated

Table 25.—*Effect of high retentions of a CCA-type preservative on the mechanical properties of southern pine (Wood et al. 1980)*

Strength value	Retention (pounds/cu ft)[1]			
	0	1.0	1.2	2.5
Modulus of rupture (psi)	16,350	16,450	16,350	15,500
Modulus of elasticity (million psi)	2.21	2.18	2.06	2.08
Fiber stress at proportional limit (psi)	8,775	8,215	8,580	8,450
Work to proportional limit (in-lb/cu in)	1.98	1.75	2.04	1.96
Work to maximum load (in-lb/cu in)	14.4	15.2	14.6	10.7
Toughness (in-lb)	236	223	219	165
Compressive strength parallel-to-grain (psi)	3,355	3,485	3,530	4,500

[1]Each value is the average of 32 measurements.

with CCA to a retention of 2.5 pcf had significantly lower values of toughness and work to maximum load than untreated control specimens. Although not significant statistically, there was a trend toward lower bending strength among specimens treated to this retention. Wood's data (table 25) showed no effect on strength properties at retention values lower than 2.5 pcf. This is consistent with Kelso's[4] data showing no deleterious effects of CCA retentions less than 1 pcf on strength of wood.

How reduced shock resistance revealed by impact studies of small specimens translates to full-size structural members is unknown. Marine piling is the only item for which retentions of CCA-type preservatives in excess of 2.0 pcf are employed. Definitive data on the effect of such treatments on piling are not available, but it is generally conceded within the industry that piling treated with CCA tend to break during driving more frequently than those treated with creosote. Likewise, data are much too limited to permit more than speculation on how the strength properties of load-bearing hardwood members, such as railroad ties, are affected by preservative salts. Even if it is assumed that these chemicals would have a more serious effect on hardwoods than softwoods, it is unlikely that the effect would have practical significance because of the relatively low retentions used.

Strength reductions associated with treatments with oil-type or oil-borne preservatives are attributed to conditioning and not to the preservatives themselves. For example, it has been shown that the crushing strength of 3-foot piling sections cut from kiln-dried southern pine stock and treated with creosote was essentially the same as that for untreated, matched controls (Thompson 1969b). Reductions in this strength property occurred only among specimens that were steam conditioned preparatory to treatment. Similarly, the data shown in table 24 for oak and gum crossties show essentially no effect of the creosote per se on strength properties.

Published data also indicate that preservatives interfere with bonding of treated wood (Selbo 1959a; Blew and Olson 1950). Reductions in both shear strength and wood failure (i.e., increased glueline failure) have been reported for treated compared to untreated laminated wood. These reductions are attributed to changes in the surface properties of wood brought about by the preservative chemicals.

The effect of preservative salts on gluing properties and bond quality of sweetgum was evaluated by Thompson (1962). One-eighth-inch veneer pieces treated to a gradient series of retentions with each of four waterborne perservatives were bonded to form three-ply samples using three different adhesives (table 26). Retentions of 3.0 pcf greatly reduced both shear strength and wood failure for all combinations of adhesives and preservatives. Retentions of sodium pentachlorophenate between 0.37 and 1.50 pcf had little deleterious effect on bond quality for any of the adhesives. The effect of lower retentions of the three inorganic salt formulations varied among adhesives, with phenol formaldehyde resin showing the poorest results. Among preservatives, acid copper chromate most seriously reduced bond quality. With the exception of specimens treated with sodium pentachlorophenate, most of the average wood failure values (table 26) were much too low to meet applicable standards.

Similar results were obtained by Bergin (1962) who studied the gluability of birch veneer treated with fire-retardant chemicals to retentions of 6.2 to 9.5 pcf of anhydrous chemical. None of the 11 adhesives employed in the study produced exterior-quality bonds when the veneer was treated with a fire retardant composed of zinc chloride, ammonium sulfate, and boric acid. Serious interference with gluing was also recorded for fire retardants composed of ammonium phosphate and ammonium sulfate, but a special resorcinol adhesive met specifications for exterior-quality bonds in plywood treated with that formulation.

Table 26.—*Effect of preservative retention of 0.37 pcf on wood failure in sweetgum veneer specimens bonded with three adhesives and tested both wet and dry. (Adapted from Thompson 1962.)*

Preservative	Adhesives					
	Resorcinol-phenol		Phenol		Melamine	
	Wet	Dry	Wet	Dry	Wet	Dry
	percent wood failure					
Sodium pentachlorophenate (PCP)	90	89	58	92	100	100
Acid copper chromate (ACC)	15	3	72	28	4	5
Ammoniacal copper arsenate (ACA)	85	22	48	56	31	12
Chromated copper arsenate (CCA)	48	40	3	35	42	48
Controls	94	90	88	89	100	100

Block-shear values of red oak treated with a range of preservatives before bonding were reported by Selbo (1959b) to be lower after each exposure period (3 to 36 months) than matched controls. Reductions in shear values attributed to the preservatives ranged from about 4 to 16 percent.

Reconstituted and Composite Wood Products. —The increased use of reconstituted board products, with or without veneer overlays,as paneling products in home, hospital, and school construction and in applications where insect or decay hazards exist has prompted several studies of fire-retardant and preservative treatments of these products (Anonymous 1978; Surdyk 1975). Treatments are usually applied to the wood particles prior to application of adhesive and forming, because concurrent application of the preservative or fire-retardant with the resin adversely affects adhesive properties (Johnson 1964). Huber (1958), however, successfully treated both hardboard and particleboard by adding sodium pentachlorophenate to the adhesive in amounts equivalent to 0.65 percent of dry wood weight, without adversely affecting MOR or dimensional properties of the boards produced.

Brenden (1974) reported reduced peak heat release from building materials commercially treated with fire retardant salts: three-fourths-inch Douglas-fir plywood from 611 to 132 Btu/min/ft^2, and a gypsum wallboard-Douglas-fir stud assembly from 206 to 105 Btu/min/ft^2.

Flame-spread ratings ranging from good to excellent have been achieved with particleboard by spraying a volume of solution equivalent to 3 to 5 pcf on the furnish and redrying subsequent to boardmaking (Gilbert 1962). Arsenault (1964), however, found that two commercial fire-retardants added to aspen furnish prior to pressing into flakeboard seriously interfered with bonding. Sharp reductions in internal bond and bending strength were induced by all retentions between 2 to 8 pcf. Reductions in these strength properties occurred only in the case of urea-bonded boards treated with zinc borate; a formulation composed of dicyandiamide and ortho-phosphoric acid appeared to increase MOR.

Efforts to impart fire resistivity to hardboard by a bromination process have been unsuccessful because of the adverse effect of the treatment on board strength and water adsorption properties (Jurazs and Paszner 1978). Use of bromination to impart decay resistance to hardboard has been reported by Hong et al. (1978).

Reduction in hardboard flame spread of up to 60 percent were achieved by Myers and Holmes (1975) by treating the fiber furnish with a series of fire retardants in amounts equal to 10 percent of dry fiber weight (table 27). Ten of the formulations tested reduced MOR by 20 percent or less, while three reduced this property by 40 to 50 percent.

In later work Myers and Holmes (1977) tested 4- by 8-foot panels of a hardboard following treatment of the fiber furnish with disodium octaborate tetrahydrate-boric acid (DOT-BA) or dicyandiamide-phosphoric acid-formaldehyde (DPF). An application rate of 20 percent based on dry fiber weight was used. Both treatments gave average flame-spread values that met criteria for Class B material—75 or under. Smoke development with the DOT-BA treatment was quite low—17 in the 25-foot tunnel test, compared to 399 for untreated controls. This treatment reduced internal bond strength (IB) by 30 percent but had no effect on or increased other strength properties.

While it is the usual procedure either to add fire-retardant chemicals to particleboard or fiberboard furnish prior to consolidation or to employ post-treatment in a pressure retort, Shen and Fung (1972) used a hot-pressing technique to accomplish this goal. Fire retardant chemicals (ammonium dihydrogen orthophosphate or liquid ammonium polyphosphate) were added to the surface of panels and forced into the surface by pressing the treated panels for a short period of time using temperatures and pressures of about 500°F and 250 psi, respectively. Surface loadings of up to 50 g/ft^2 were achieved in this manner. Flame spread was reduced from over 100 for untreated panels to less than 30 at loadings of 40 to 50 g/ft^2.

Strength and dimensional properties of phenolic-bonded particleboard prepared from ACA-treated flakes of 22 Ghanaian hardwood species were evaluated by Hall and Gertjejansen (1978). The effect of preservative retentions of 0, 0.2, 0.4, and 0.6 pcf on MOR, MOE, and IB (internal bond) for two resin levels and both the vacuum-pressure-soak-dry and accelerated-aging tests are summarized in figure 14. Percent thickness swelling is shown in figure 15 as a function of preservative retention, resin content, and type of test. This figure shows mechanical properties expressed as percentages of respective test values for control specimens—specimens which were not subjected to the vacuum-pressure-soak-dry or accelerated aging test, but which were in other respects treated like the remaining specimens.

All panels manufactured from flakes treated with preservative had lower MOR's and IB's than corresponding controls. MOR was reduced by preservative treatment by an amount equivalent to 5 percent for each 0.2-pcf increase in preservative retention. The effect of preservative treatment on IB was magnified by the weathering tests to an extent greater than that for the other strength properties. MOE was the strength property least affected by the preservative.

Thickness swelling was influenced more by resin content (either 5 or 8 percent) and method of test than by preservative retention. Treated boards had substantially higher thickness swelling than untreated

Table 27.—*Strength properties and fire performance of fire-retardant treated hardboards (Myers and Holmes 1975)*

Board treatment[3]	Bending properties[1] MOE	Bending properties[1] MOR	Internal bond[1]	Fire performance: 8-foot tunnel furnace Flame-spread index	8-foot tunnel furnace Fuel-contributed index	8-foot tunnel furnace Smoke density index	2-foot tunnel furnace[2] Flame-spread index
	thousand psi	*psi*	*psi*				
Untreated (control)	694	6,120	439	119	128	302	111
	702	6,110	336	122	124	289	112
	752	6,490	299	119	151	375	122
Average	716	6,240	358	120	134	322	115
Untreated (¼-inch thick) (control)[2]	676	6,000	289	96	140	474	113
10-percent fire retardant treatment							
Water-soluble salts							
Disodium octaborate tetrahydrate	748	5,640	398	103	63	143	42
Disodium octaborate tetrahydrate-boric acid 94:1	772	5,910	369	97	66	82	42
Monoammonium phosphate[4]	680	4,600	307	92	50	708	75
Monoammonium phosphate (¼-inch thick)	...	....	...	83	46	594	86
Ammonium sulfate	725	4,760	349	90	86	254	62
Monoammonium phosphate-ammonium sulfate (1:1)	677	4,260	293	90	52	428	69
Diammonium phosphate	691	4,970	277	62	37	732	69
Diammonium phosphate-ammonium sulfate (1:1)	682	4,590	273	95	56	276	70
Borax	840	5,950	432	79	53	159	44
Borax-monoammonium phosphate (2:1)	634	5,000	385	83	72	141	62
Borax-boric acid (1:1)	739	6,040	257	83	55	221	50
AWPA Type C	659	4,190	248	109	88	89	71
AWPA Type D	624	3,040	233	93	76	176	74
Liquid ammonium polyphosphates[5]							
11-37-0	620	4,360	242	59	43	958	64
11-37-0 and ammonium sulfate (1:1)	684	4,220	264	93	60	568	61
12-44-0	586	3,730	178	48	23	954	61
Curing-type-organic phosphates							
THPC[6]	652	4,830	295	121	140	395	108
THPOH[7]	758	4,250	316	127	134	397	109
Dicyandiamide-phosphoric acid	822	5,430	281	79	45	641	64
Dicyandiamide-phosphoric acid-formaldehyde (pre-reacted)	797	5,630	265	83	53	485	67
MDP[8]	791	6,050	356	109	108	164	85
MDP[9]	627	3,700	232	79	69	694	81
Guanylurea phosphate	727	5,240	276	93	59	571	73
20-percent fire-retardant treatment							
Disodium octaborate tetrahydrate-boric acid (4:1)	796	6,610	349	69	22	281	44
12-44-0 liquid ammonium polyphosphate	634	4,090	274	7	1	986	...
Dicyandiamide-phosphoric acid-formaldehyde (pre-reacted)	725	5,100	260	21	4	909	46

[1]Adjusted to 60 lb/cu ft density.
[2]Values are averages of two tests.
[3]Specimens ⅛-inch thick unless indicated otherwise.
[4]Values for 8-foot tunnel furnace are averages of two tests; values for 2-foot tunnel furnace are averages of four tests.
[5]Products bearing code numbers listed were formulated as commercial fertilizers; the numbers refer to percent assay of nitrogen, phosphate, and potash, respectively.
[6]THPC means tetrakis (hydroxymethyl) phosphonium chloride.
[7]THPOH means tetrakis (hydroxymethyl) phosphonium hydroxide.
[8]MDP means melamine dicyanidiamide phosphoric acid.
[9]Contained 15 percent fire-retardant chemical and no phenolic resin.

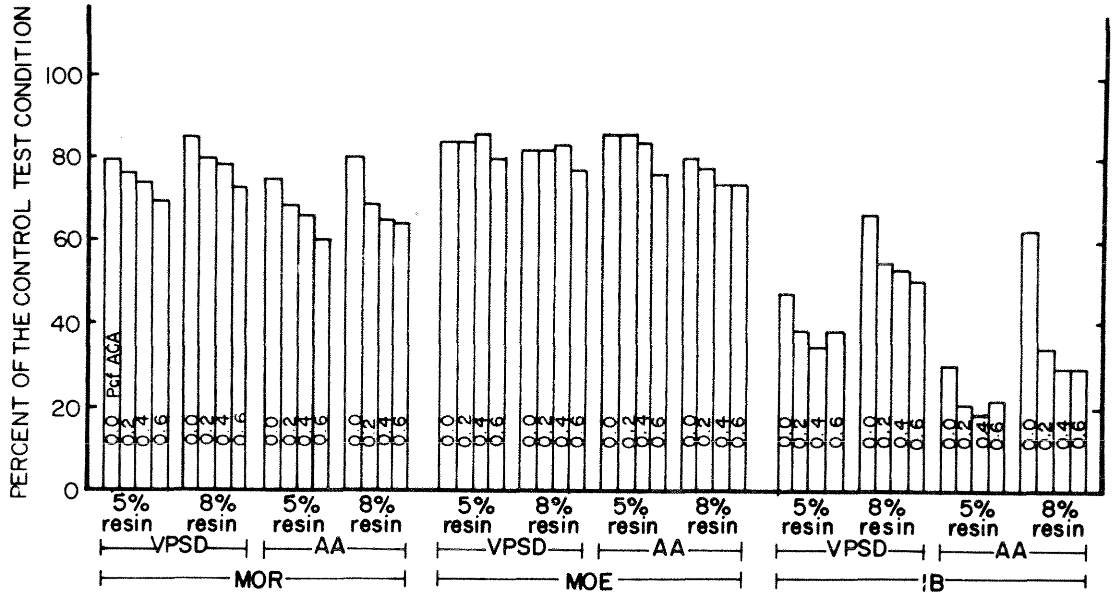

Figure 14.—*Average modulus of rupture, modulus of elasticity and internal bond values following exposure to vacuum-pressure-soak-dry (VPSD) and accelerated aging (AA) conditions, as percents of their control condition values. Samples were from ACA-treated phenolic-bonded particleboard manufactured from flakes of Ghanaian hardwood species. (Drawing after Hall and Gertjejansen 1978).*

Table 28.—*Condition of particleboard stakes from mixed Ghanaian hardwoods after 1 year's exposure in the Caribbean National Forest of Puerto Rico*[1]

Retention of ammoniacal copper arsenate	5 percent phenolic resin		8 percent phenolic resin	
	Decay	Termite	Decay	Termite
pounds/cu ft	*ratings*[2]			
0	49	86	87	91
0	46	89	77	92
.2	86	96	92	100
.2	91	100	90	98
.4	97	100	100	100
.4	100	99	100	99
.6	100	100	100	100
.6	100	100	100	100

[1]Laundrie, J. F., G. C. Myers, and L. R. Gjovik. 1980. Evaluation of particleboards and hardboards from mixed Ghanaian hardwoods after a one-year exposure in the Caribbean National Forest of Puerto Rico. U.S. For. Prod. Lab., U.S. Dep. Agric. For. Serv., Madison, Wis. Interoffice Rep. prepared by the Univ. Minnesota. 20 p.

[2]Ratings based on a perfect score of 100.

boards; but within the former, there was a trend toward a direct relationship between swelling and retention. A similar trend was evident for irreversible thickness swelling and irreversible linear expansion.

The condition of 3¼- by 18-inch stakes cut from these phenolic-bonded particle board panels and exposed for one year in a test plot in Puerto Rico is shown in table 28. All treated stakes, including those containing the lowest retention of preservative, sustained little or no decay and termite damage following exposure. Controls suffered substantial decay damage, but those bonded with 8 percent resin had much less damage than those bonded with 5 percent resin. Results with fiberboard specimens treated and exposed in the same manner as that for the particleboard specimens were very similar.

Internal bond losses of specimens after field exposure were reported by the authors to parallel those induced by the vacuum-pressure-soak-dry test. Reductions in internal bond attributable to exposure averaged 62 and 45 percent for 5 and 8 percent resin levels, respectively. The magnitude of the reductions appeared to be related to preservative retention only in the case of specimens containing 8 percent resin.

Beal[7] studied the efficacy against termites of insecticides applied at several concentrations in the glue of plywood, particleboard, and hardboard by exposing them in southern Mississippi and in the Panama Canal Zone. Chlordane at 0.05, 0.10, and 0.20 percent, and heptachlor at 0.02, 0.05, and 0.10 percent protected all three materials from subterranean termites over 4 years. The higher levels also prevented damage by drywood termites in laboratory tests.

[7]Beal, R.H. 1980. Final office report summary FS-SO-7.303. Southern Forest Experiment Station, U.S. Dep. Agric. For. Serv., Gulfport, Mississippi.

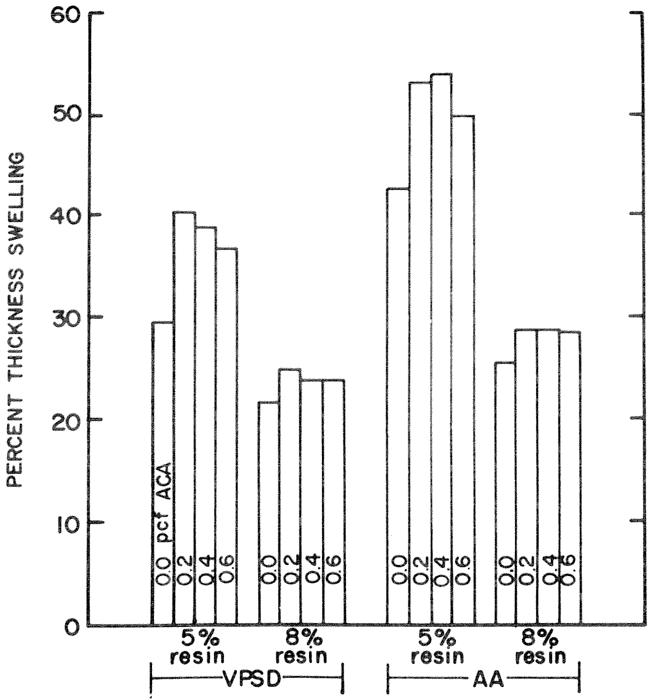

Figure 15.—*Average percent thickness swelling values for test samples similar to those in figure 14. (Drawing after Hall and Gertjejanson 1978.)*

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This report reviews pertinent information on treatment of 56 American hardwood species with more than a dozen preservatives by pressure and non-pressure methods.