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Title: A COMPARATIVE STUDY OF PRESERVATIVE TREATMENT OF SELECTED WOODS FROM GHANA AND THE UNITED STATES

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Abstract approved

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The response of three hardwoods from Ghana and a hardwood and three softwoods from the United States to liquid and gas-phase impregnation was investigated. Impregnation with liquids included a sink-float test in a water-glycerine solution and pressure treatment with a copper sulphate solution and creosote under identical treating conditions. Flow of gases through wood was measured with an air permeability test and by the movement of chloropicrin vapour, an agricultural fumigant, through the samples. The effect of physical and anatomical characteristics of each species on its treatment was investigated.

Penetration and retention of treating solutions in wood samples immediately after the time of removal from the treating cylinder followed nearly identical trends for the copper sulphate and creosote.

That is, a particular species of wood would have large penetration and retention of both preservative solutions compared to other species of wood, although the values for each preservative solution differed. The sapwood and heartwood of Sugar Maple (Acer saccharum Marsh) from the United States gave highest penetration and retention among the hardwoods. Among the woods from Ghana, highest retention and penetration were in the sapwood and heartwood of Subaha (Mitragyna stipulosa [De Candole] O. Kuntze). Low penetration and retention were found in Dahoma (Piptadeniastrum africanum [Hook f.] Brenan), and very low retention and penetration were present in Kaku (Lophira alata [Banks] Gaertner). Of the softwoods, the heartwood of redwood (Sequoia sempevirens [D. Don] Endl.) retained the greatest amount of preservative and was also the best penetrated sample. Sapwood of Ponderosa pine (Pinus ponderosa Laws) was penetrated better with preservatives and retained more preservatives than sapwood and heartwood of Douglas-fir (Pseudotsuga menziesii [Mirb] Franco) but the heartwood of Ponderosa pine was the least penetrated sample and retained the smallest amount of preservative. Retentions in samples treated with copper sulphate solution were higher than retentions in creosote treated samples. Loss of preservative solvent by evaporation or bleeding of preservative solution from treated samples 7 days after treatment was directly related to the amount of preservative retained in the sample immediately after withdrawal from the treating cylinder.

Retention of preservative solutions in the heartwood of hardwood species was directly related to the distribution of vessels but indirectly related to the diameter of the vessel lumen. Gum was the most important inclusion which influenced penetration and retention in the hardwood species. Retention among the softwood species was directly related to the diameter of the tracheid lumen.

The release rate of chloropicrin vapour from a vial attached to the treated specimen and the subsequent time taken by the vapour to diffuse through the length of the specimen were the two treating variables measured in vapour-phase treatment. These two variables were interdependent, and their values followed almost the same pattern as the air permeability measurements in hardwoods and softwoods.

Longitudinal permeability (liquid and air flow) was the only physical property of the species which was related to their preservative treatment. The extent of the relationship between values for air permeability and values for retention, penetration and vapour release was tested by applying linear regression analyses. The results showed that air permeability correlated better with the release of chloropicrin vapour than it did with preservative retention or penetration. Air permeability was a better indicator of the treatability of softwoods from the United States than the hardwoods from Ghana.

A Comparative Study of Preservative Treatment of Selected Woods From Ghana and the United States

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A COMPARATIVE STUDY OF PRESERVATIVE TREATMENT OF SELECTED WOODS FROM GHANA AND THE UNITED STATES

INTRODUCTION

Timber is a versatile construction material that is used under a wide variety of conditions, some of which provide an environment favorable for wood-destroying organisms. Wood from various species of trees can differ in their natural resistance to these organisms. Although a few species of wood are quite resistant to attack by decay fungi, insects and marine borers, most woods are not durable and must be protected with a preservative treatment.

One of the most important ways of providing protection consists of impregnating wood under pressure with liquid preservatives. Development of modern pressure impregnation processes began in the first half of the 19th Century in Europe. Since then, other pressure processes have been introduced in this continent and other technically developed countries. In the developing countries, on the other hand, wood preservation in general and pressure impregnation in particular have received less attention. In most of these countries, screening tests are in progress to find which of their numerous relatively unknown species of wood can respond well to pressure treatment.

The effectiveness of pressure processes depend on the ability to force liquid preservatives into wood to specified depths and retentions. High pressures must be applied to force the preservative through the capillary structure of the wood, because of the relatively high viscosities of the preservative used and surface tension effect. Air bubbles and foreign particles in the preservative solution can reduce penetration. The heartwood of some species are almost impermeable to liquids and absorb practically no preservative even when high pressures are applied for many hours. On the other hand, some woods are very permeable and easily treated.

Gases and vapours move through wood more easily than liquid because of the low viscocity of gases and vapours, and the absence of liquid-vapour interfaces that must be overcome during penetration. Further, molecules of a vapour can diffuse in wood under a vapour concentration gradient and a hydrostatic pressure may not be necessary.

Recent research has shown that fumigants like chloropicrin[R] (trichloronitromethane), Vapam[R] (sodium methyl dithiocarbamate), and Vorlex[R] (methyl isothiocyanate in C-3 hydrocarbons) stopped internal decay in poles of Douglas-fir (*Pseudotsuga menziesii*) and protected them against reinfestation (20, 25). Further tests of these fumigants have shown that chloropicrin was the most toxic to

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[R] Chloropicrin, Vapam and Vorlex are registered trade names.

decay fungi in Douglas-fir (26, 47). However, very little is known about how effective chloropicrin vapour is in diffusing in other wood species, especially the less known tropical species.

OBJECTIVES

The objectives of this study were to determine:

1. The penetration and retention of an oil-type preservative (creosote) and a water-borne preservative (copper sulphate) in selected hardwoods and softwoods from Ghana and the United States.
2. The rate of movement of chloropicrin vapours in these woods.
3. The effect of physical and anatomical characteristics of these woods on the penetration, retention and movement of these preservatives in the wood.

LITERATURE SURVEY

When a preservative is put into wood by either a pressure or non-pressure process, the preservative flows along specific paths in the wood and comes to be located in either the cell wall or lumen or both. For longitudinal flow through softwoods, the bulk of the preservative penetrates the wood by passing from one tracheid lumen to another through bordered pit-pairs. Sometimes preservatives pass through longitudinal resin canals and in parenchyma cells when present. In hardwoods, longitudinal flow is primarily through the perforated ends of the vessels, unless they are blocked by tyloses or extractives. Treatability of wood to liquid preservative may be defined in terms of distribution and the amount of preservative required to protect wood for a reasonable period of time under service conditions. Successful preservative treatment of wood is dependent upon the physical and anatomical properties of wood.

Effect of Physical Properties of Wood on Preservative Treatment

Permeability

Permeability is the property of a porous material which characterizes the ease with which a fluid flows through the material as a result of a pressure gradient. It may be defined as the fluid conductivity of the porous material (17). Permeability of wood to gases and liquids is a physical property of wood that greatly influences its processing by pulping, its impregnation with preservative chemicals, or its drying for use as lumber.

Timbers have been classified as very permeable, intermediate, resistant and very resistant depending on the ease with which they can be impregnated with preservatives (37, 43). Maclean (34) has classified many American species with respect to their heartwood penetrability. Chudnoff (15) and Graham (25) have related the liquid-permeability properties of small wood specimens to their preservative treatment of matched timbers. Other researchers have used the relationship between steady state air permeability properties and liquid permeabilities to predict the preservative treatment of timbers (14, 37, 58), and a few others have used non-steady state of air flow properties (18, 49). In most cases, this has been successful for certain classes of wood similar in structure such as softwoods but poor correlation has been found in certain hardwoods like sugar maple (*Acer saccharum* Marsh) and red oak (*Quercus rubra* L) (52).

Liquid Permeability

The steady-state flow of liquids through a porous media is generally beleived to obey Darcy's law of viscous flow which states that the permeability is equal to the flux divided by the gradient.

It is expressed by the following equation: (52)

$$K = \frac{QL}{A\ \Delta P} \qquad \text{where}$$

K = Permeability in $\frac{cm^3}{cm\ atm\ sec}$

Q = Rate of liquid in cm^3/sec.

L = Specimen length in cm.

A = Area in cm^2.

ΔP = Pressure drop across the specimen in atmospheres = $P_2 - P_1$ where P_2 = Upstream pressure, P_1 = Downstream pressure.

In determining the permeability of wood to liquids, the following conditions must be satisfied for application of this law:

1. The liquid must be incompressible.
2. The porous material must be homogenous.
3. Flow must be viscous and not turbulent.
4. Flow rate should be constant with time.
5. Flow rate must be proportional to the pressure drop across the specimen.
6. Permeability must be independent of the length of specimen.

Unfortunately, wood does not satisfy all these conditions.

The flow of liquids through wood has been studied for many years and attempts to satisfy all the conditions of Darcy's Law have not been accomplished. Many investigators have encountered a decreasing rate of flow with time and various theories have been advanced to account for this phenomenon (10, 52). Deviation from Darcy's Law as a function of specimen length has been reported by Comstock (18), Bramhall (10), and Siau (52). Bramhall (10) and Siau (52) found that the law was generally obeyed for changes in length for specimens with longitudinal permeabilities above 1 Darcy, with an increasing disagreement as specimen permeabilities decreased below this value. Kelso et al. (30) found that air blockage was largely responsible for decreasing flow rate. Erickson et al. (23) attributed the decrease in flow rate to particulate matter in water which was explained by the presence of hydrophobic surfaces which functioned as nuclei for the release of dissolved gases. Using a special filtration technique to eliminate air blockage and particulate matter, Kelso et al. (30) obtained a constant rate of flow through wood and a direct proportionality of flow rate to pressure. Comstock (18) obtained similar results for sapwood of Eastern hemlock. However, these conditions cannot be met in commercial treating practices.

Air Permeability

When Darcy's Law is applied to gaseous flow in wood, it must be modified to account for the gas compressibility factor which is due to the expansion of the air as it proceeds through the specimens. It is expressed by this equation (52):

$$Kg = \frac{AL\eta P}{A \Delta P \bar{P}} \qquad \text{where}$$

Kg = Specific permeability, cm^2.

P = Pressure at which flow rate, Q is measured, atm.

η = Viscosity of air (= $1.81 \times 10^{-4} \frac{\text{dyne sec}}{cm^2}$ at 20°C).

$\bar{P}$ = Average pressure in specimen (= $\frac{P_1 + P_2}{2}$) , atm.

where P_1 = Downstream end pressure

P_2 = Upstream end pressure

Other symbols are as stated for liquid flow.

Gas flow through wood is mainly viscous, but molecular slip flow may occur in addition to viscous flow with the fraction of slip flow increasing when the pit radius is less than 0.1 μm (52). Resch and Ecklund (44) concluded from measurements of nitrogen and oxygen through redwood (Sequoia sempervirens D. Don) that molecular slip flow at normal atmospheric pressures could be neglected and that flow of gases could, for practical purposes, be considered to obey Darcy's Law. An experimental advantage in the measurement of gaseous flow through wood is the fact that the problems associated with deaeration of liquids and filtering out of particulates are eliminated.

Specific Gravity

When a wood is dry, its specific gravity indicates the approximate amount of air space available to hold liquid. The larger the volume of these air spaces in dry wood, the lower the specific gravity and generally the greater the diffusion, retention and penetration of fluids will be. However, various inclusions in cell lumens and pits may hinder penetration to fluid flow so that it is not always possible to estimate preservative treatment of a wood species by its specific gravity. For example, Maclean (34) found wood with high specific gravity from Douglas-fir and Longleaf pine (*Pinus palustris* Mill) more permeable than wood with a much lower specific gravity from Western red cedar (*Thuja plicata* Donn). The same author (34), however, found lower specific gravity species of basswood (*Tilia americana* L.) and Ponderosa pine (*Pinus ponderosa* Laws) more permeable than denser yellow birch (*Betula alleghaniensis* Britton) and Western larch (*Larix occidentalis* Nutt.).

Within some species, notably softwoods, specific gravity of wood correlates with permeability. Comstock (18) found a good correlation between specific gravity and longitudinal permeability in heartwood of Eastern hemlock (*Tsuga heterophylla* (Raf) Sarg).

However, Miller (37) and Zoltan (60) did not find any correlation between specific gravity and permeability of Douglas-fir.

Choong (10, 13) found a decrease in the longitudinal and transverse diffusion coefficients with increasing specific gravity. This is explained by a greater amount of wood substance through which bound water diffusion must take place and less air space (also called void volume), available for vapour movement.

Porosity

Porosity is the fractional void volume of a wood. A fairly good approximation of porosity of a wood sample can be calculated using the equation:

$$P = 1 - G\,(0.667 + 0.01M) \times 100$$

where

P = Porosity (%).

G = Specific Gravity at moisture content, M.

M = Moisture Content (%).

As specific gravity increases, porosity decreases; therefore, the relationship between the porosity and treatability of a species is inversely influenced by the same factors as specific gravity.

Effect of Anatomical Properties on Preservative Treatment of Wood

Sapwood and Heartwood

The wood in a mature tree stem can usually be divided into sapwood and heartwood zones. The sapwood is the outer portion of this stem and is physiologically active, conducting a sap. The heartwood is a central core of wood in the stem and is inactive.

The transition of sapwood into heartwood is accompanied by the synthesis and deposition of extractives and formation of inclusions like tyloses in some hardwoods and tylosoids in a few softwoods. The build-up of extraneous matter is evidenced in many species by a darkening of the heartwood zone. Because these inclusions are reported to block fluid penetration in wood (32, 29, 52), heartwood of wood species in general respond poorer to fluid flow than the corresponding sapwood. The following discussion is limited to major cells and types of inclusions which have marked influence on fluid flow through wood.

Earlywood (Springwood) and Latewood (Summerwood)

In some temperate species, the wood produced in a growth ring may clearly be differentiated into open earlywood and dense latewood (29, 39). The earlywood produced in these woods at the beginning of the growing season is less dense and more porous than latewood produced during the latter part of the growing season. In softwoods, earlywood tracheids usually have large lumens and thin cell walls, but latewood tracheids have small lumens and very thick cell walls. In hardwoods, the vessels of earlywood have larger diameters than latewood vessels in species where earlywood and latewood zones can be recognized.

Latewood in softwoods usually responds better to preservative penetration than earlywood because the rigid nature of the bordered pit membrane can often resist aspiration (52, 39). Teesdale (56) has observed that creosote retention in latewood of Loblolly pine (*Pinus taeda* L.) was 80% more than in earlywood. However, Fleischer (24) has observed better treatment in earlywood of Douglas-fir.

Vessels

Vessels, also known as pores, are short cells with perforated ends and are arranged longitudinally to form tubes of indeterminate length which function as sap conducting channels in a living hardwood tree. They account for 5-60% of the volume of the wood (39) and are the longitudinal flow path of least resistance in hardwoods (29).

On the cross section, pores appear mostly oval in shape and may be solitary or multiple with lumen diameters ranging from 20 to 300 μm (39, 52). The range of distribution averages 15 per mm^2 (39).

When the lumens of vessels are free from inclusions, they are regarded as the most significant anatomical feature affecting initial penetration of hardwood. However, tyloses and gums may occur in the lumen of the heartwood vessels and can hinder fluid penetration.

Tyloses are sac-like membranes which enter the heartwood vessels from adjacent parenchyma cells through pit pairs. Chattaway (12) reports that when the diameter of the pit is greater than 10 μm, the increased activity of ray parenchyma cells during heartwood formation is sufficient to extrude balloon-like membranes into adjoining vessels causing tyloses.

When the pit membrane is less than 10 μm, the activity of the ray parenchyma does not rupture the pit membrane. Instead, gummy exudations are forced through the membrane into the neighboring vessels, where they come in contact with air and solidify to form a gum (12).

Tracheids

Tracheids in softwoods are long, imperforated, narrow cells, tapered at both ends along the radial surfaces where they are in contact with other tracheids. Their length averages 3.5 mm and the lumen diameter is about 25 μm (39). On the cross-section, they appear square or rectangular in shape. Krahmer (31) and Meyer (36) have observed that lumens of more treatable Douglas-fir were larger than lumens of less treatable Douglas-fir.

Tracheids are longitudinally arranged and make up from 90 to 95% of the softwood volume (39). They are the initial and main path of fluid penetration in wood. As many as 50-300 bordered pits occur in adjacent tracheid walls of a single earlywood tracheid with decreasing number in latewood tracheids (52),

A bordered pit is "a pit with an overhanging margin, in which the cavity becomes abruptly constricted during the thickening of the secondary wall" (39). The importance of tracheids in fluid penetration is dependent on the condition of the membrane of the bordered pit pairs. When the pit is aspirated, that is, when the torus is displaced against one or the other pit borders, the aperture is blocked and fluid flow through it may be hindered depending on the perfectness of the seal (21, 22, 32).

Fibers

Fibers are elongated cells with closed ends and usually with thick walls and small lumens. The word "fiber" as used here is restricted to hardwoods only. Fibers are longitudinally arranged with a length ranging from about 0.5 to 2.0 mm (39, 29). A small bordered or simple pit with no apparent openings in the membrane occurs in the cell walls. Fibers make up from 10-50% of the wood volume (39) and because of their small lumen diameter, about 5 μm (39), they are not of great importance for fluid flow (29, 52).

Resin Canals (Ducts)

Resin canals are narrow intercellular canals of indeterminate length which form an intercommunicating system for vertical and radial passages in certain softwoods and hardwoods. They make up to 2% of the wood volume when present (39, 52). The effectiveness of the canals in aiding fluid permeation in wood is dependent upon their size, number, distribution and continuity, which in turn is influenced by hardened resin or extraneous materials and tylosoids often found in them (29). Tylosoids are formed from proliferations of unlignified epithelial cells into the lumens of the resin canal, as the epithelial cells pass from sapwood into heartwood (39). It is known in pine sapwood that, when the peithelial cells and tracheids surrounding the canal are permeable, the open resin duct facilitates conduction of fluid (29).

Longitudinal Wood Parenchyma

Longitudinal parenchyma are vertical strands of elongated cells which are involved in axial distribution of food in living trees.

They occur in most hardwoods and a few softwoods. Like all parenchyma cells, communication between two adjoining cells is provided by simple pit pairs in their common walls.

In softwoods, the parenchyma cells are best developed in Redwood where they are diffuse in distribution. In Douglas-fir, Ponderosa pine and other woods containing resin canals, however, they occur around the resin canal where they are called epithelial cells. In hardwoods, they may form definite sheaths around vessels or make up various patterns on the cross section of wood. In tropical hardwoods, they comprise an appreciable volume of the wood, about 30-60% (29, 39); but only 1-18% in temperate hardwoods (39, 52).

The longitudinal parenchyma cells are usually filled with stored food material which may hinder fluid movement through their lumens (8, 39). However, epithelial cells of some softwoods and longitudinal parenchyma cells of some tropical species, have been reported to aid penetration (8, 59). In the tropical species, longitudinal parenchyma are reported to be more permeable than fibers when both are free from inclusions (59).

Ray Parenchyma

Rays are transversely arranged parenchyma cells which serve as storage and radial conduction of plant food materials in a living tree. A simple pit pair occurs between two ray cells.

Ray parenchyma cells occur in both softwoods and hardwoods. In softwoods they are mainly uniseriate and make up from 3 to 12% of the wood volume (39, 52). In hardwoods, many rays are multiseriate and their volume may range from 15 to 22% (39, 52).

Rays are reported to be of little assistance for treating wood. Because of the dried protoplasm and other inclusions found in them, they may even obstruct fluid flow. Softwood rays, despite their low volume, are said to be more permeable than rays of hardwoods (8, 59). Côte states that the effect of rays on overall fluid conduction is much more variable in hardwoods than in softwoods.

Microscopic Examination of Pressure Treated Wood

Wood has been treated with preservatives for many decades but very few attempts have been made to examine treated wood microscopically. Most attempts have concentrated on the microscopic examination of wood pressure treated with water-borne preservatives (11, 59). Wardrop and Davies (59) observed microscopically thin sections cut from wood of *Pinus radiata* (D. Don) and *Eucalyptus regnans* (F. V. M.) treated with copper sulphate. They established that in both sapwood and heartwood of *Pinus* species, penetration proceeded from tracheid via the bordered pits and spread laterally through the rays with ray parenchyma appearing more penetrated than ray tracheids. In sapwood of *Eucalyptus* species, they found that penetration took place through the vessels to adjacent fibers and rays and then diffused through the cell wall with the middle lamella being the most effective.

Teesdale (56) examined microscopically wood pressure treated with creosote and concluded that resin canals were important in penetration of fluids into conifers. He also reported that tracheids and vessels were the most important cells for fluid penetration in softwoods and hardwoods, respectively. Booshard (9) found that rays in Scotch pine (Pinus sylvetris L.) were the main distribution path for creosote contained in the rays and other cells. Sargent (45) concluded that ray parenchyma and ray tracheids were important for penetration especially in sapwood of softwoods. Liese (33) reported from his work on hardwoods that pit membranes in vessels have no openings and cannot transmit oil. He believed that if the vessel lumen, which is the main preservative flow path was blocked at any point, it would remain unimpregnated throughout. Côte (22) on the other hand, found that pits of basswood were permeable to permeating preservative oil solutions even though no visible openings were found in the pits. Behr et al. (8) concluded from their microscopic study of hardwoods pressure treated with creosote that longitudinal parenchyma cells were unimportant in holding preservative oils except in sycamore (Platanus occidentalis L.). They observed that oily preservatives could completely fill the cell lumens or they might be present as droplets or isolated plugs separated by air bubbles. Tyloses, perforation plates and pit chambers aided in holding oily preservatives in the wood. Behr *et al.* (8) also noted that rays in softwoods were more important for transport and storage of oily preservatives than the rays in hardwoods.

Types of Wood Preservatives

Wood preservatives are chemicals which, when applied to wood, protect it from attack by organisms like fungi, insects or marine borers by making the wood toxic or repellent to these organisms. To be suitable for general commercial use, a wood preservative should be toxic to wood destroyers, exhibit permanency in the wood medium; be able to penetrate or diffuse in the wood, be safe to handle and use and be plentiful and economical (28, 29). For treatments of wood for special purposes, preservatives should be clean, colorless, odorless, paintable, non-swelling, fire resistant and moisture repelling, as well as providing a clean, paintable wood surface.

Many chemical compounds of moderate cost have been suggested as a wood preservative but only very few have earned the recognition of the American Wood Preservers' Association (AWPA) and are applied as liquids in the wood preserving industries (28).

Wood preservatives may be classified in many ways according to their chemical and physical properties (29, 28). In this review, preservatives are classified into three main groups: (a) water-borne, (b) oil-type, and (c) vapour-phase preservatives.

Water-borne Preservatives

According to AWPA, water-borne preservatives are limited to preservatives designed to form compounds of low water solubility as the water evaporates from the treated wood. Preservatives of this type contain compounds of two or more of the following elements: zinc, chromium, copper, fluorides, and arsenic (28, 29). Other metals and anions like mercury, nickel, borate, cyanide, not recognized by AWPA, are used in other countries (28).

The compounds are held in solution by means of a solubilizing reagent like ammonia, acetic acid or chromic acid which is unstable in contact with wood. In a treated wood, the solubilizing reagent may either evaporate leaving the compound in wood or the preservative solution undergoes complex reaction with extractives in wood to form a complex compound in wood which is toxic to wood destroying organisms (28, 29).

For example in ACA (ammoniacal copper arsenite) the compound is copper arsenite formed from cuprous oxide (CuO) and arsenic trioxide (AS_2O_3) dissolved in excess of a solubilizing agent ammonia (29). In treated wood the solubilizing volatile agent, ammonia, evaporates and the two metallic oxides undergo a complex reaction to form an insoluble complex compound--tetraminocupric arsenite which is toxic to decay organisms. Other water-borne preservatives recognized by AWPA are acid copper chromate (ACC), chromated copper arsenate (CCA) and chromated zinc chloride (CZC). Many other salts of weakly basic metals, such as zinc chloride and copper sulphate, which can hydrolyse to some degree so as to become partially fixed in wood, are used less extensively in some countries (29).

Water-borne preservatives penetrate wood well and are free from fire, explosion and health hazards. They, however, swell wood, are liable to weathering and mechanical wear and when in contact with water some may cause leaching problems. Wood treated with water-borne preservatives is especially suitable for use in buildings because of its cleanliness, freedom from odour, lack of preservative fire hazard and low increase in weight after drying. However, some standard water-borne preservatives of low water solubility have proved superior when used in contact with water (39).

Oil-Type Preservatives

Oil type preservative may be divided into two main groups: (1) Creosote and creosote solutions and (2) Oil-borne preservatives.

The first group include by-product preservative oils obtained in coal distillation, e.g., creosote, creosote-coal tar solutions and creosote dissolved in heavy oil solvent derived from petroleum refining such as creosote petroleum solutions (28, 29). The standard oil-borne preservatives include pentachlorophenol, copper-naphthenate or copper-8-quinolinolate dissolved in heavy oil, light oil or liquified petroleum gas. Pentachlorophenol dissolved in either heavy oil or liquified petroleum gas is the most important of the group.

Hartford (28) has recognized two basic mechanisms which take place in wood treated with oil-type preservatives. For non-volatile oil type preservatives, there are loses of volatile fractions of the preservative and movement of the liquid preservative downward and outward into the ground under the net influence of gravity. For preservatives dissolved in volatile liquids, like pentachlorophenol in light oils, the solid preservative is deposited in wood, and undergoes chemical bonding reactions with the wood.

Oil-type preservatives do not swell wood and may be used in wet places. However, some like creosote and creosote-solutions, may present paintability, cleanliness and odour problems and their use may be restricted.

Vapour-Phase Chemicals

Vapour-phase preservatives are volatile, low viscosity chemicals with the ability to release toxic vapours from their liquids to control decay in wood. Vapour-phase chemicals which have been used for preservative purposes include agricultural fumigants like chloropicrin (trichloronitromethane), vapam (soidum N-methyldithiocarbamate) and Vorlex (methyl isothiocyanate dissolved in chlorinated C3 hydrocarbons) (20, 26, 27, 47).

Because vapours have lower viscosities than liquids, vapours from these chemicals may flow easily through the wood's capillary structure. Since, there are no liquid-vapour interfaces to overcome, the vapours can diffuse through the pit membrane pores with ease. However, because of their high volatility, large retentions in wood are not possible or difficult to obtain and treated wood may be short lived (47). Nevertheless, some have remained effective for 6 years when used to control decay in poles (26, 47).

Wood-Preserving Processes

Most wood-preserving processes may be classified as either non-pressure or pressure processes. A non-pressure process is carried on without any pressure, but in a pressure process wood is treated with a preservative under considerable pressure. In technologically advanced countries, wood is treated mainly by a pressure process, but in less industrialized countries non-pressure processes may still play an important role. Non-pressure processes are simple and inexpensive, but they give less satisfactory results than pressure processes, which are expensive. Treating conditions for pressure processes can be controlled so that penetration and retention can be varied to meet the requirements of service. Because there are many pressure and non-pressure processes, this review is limited to the processes similar to the one adopted for treatment in this study.

Pressure Impregnation

Many pressure processes have been developed over the years but the most successful and widely used pressure processes which are used to meet varying requirements are: (1) the full cell and (2) the empty cell processes.

The Full Cell Process. In this process, the aim is to obtain maximum retention and penetration in wood. The main stages involved are as follows:

A preliminary vacuum period of at least 23 inches of mercury is drawn on the charge and maintained for 15-60 minutes during which the cylinder is filled with preservative. A pressure period of above 120-200 psi during which additional oil is forced into the cylinder and this pressure is maintained until the desired absorption or virtual refusal is attained. A short final vacuum period is then applied to dry the surface of the wood (29). The full cell process is usually used with water-borne preservatives but it has been used with oil-type preservatives (2, 29).

The Empty Cell Process. In the empty cell processes some of the preservative forced into the wood under pressure is recovered. There are two main processes used to achieve this objective. In the Lowry Empty Cell process, preservative solution is introduced into the wood in the cylinder at atmospheric pressure. The Rueping Empty Cell process on the other hand employs a preliminary pressure period of about 50-80 psi during which wood cells are filled with compressed air (29). The Empty Cell process is specified by the AWPA in preference to full cell method for impregnating wood with oil-type preservatives in all cases where the absorption required is not greater than can be obtained by empty-cell treatment (2, 29).

Effect of the Preservative Properties on Retention and Penetration

The effectiveness of pressure treated wood depends largely on the amount of preservative retained in wood and the depth to which the preservative penetrates the wood. Net retention is used to measure a pressure treated wood. Net retention is determined by dividing the difference between the measured weight of the sample after treatment and its calculated weight before treatment by the volume of wood in a charge. In the United States, retention by assay is used for most treated products. Assay retention specifies the depth of penetration required and the minimum amount of preservative in the outer wood as determined by analysis of borings from treated samples (29).

The anatomical and physical properties of wood which affect fluid flow also affect penetration and retention of preservatives in wood. The physical properties of the preservative solution which may influence penetration and retention include:

1. Viscosity: Maclean (34) has revealed that a reduction in viscosities of creosote and water-borne preservatives increased retention and depth of penetration of these preservatives in wood. He obtained 0.625 - 0.9 cm penetration increase for creosote when the viscosity was reduced from 8-4 centipoise and observed 1.13 - 3 cm increase for a reduction of zinc chloride viscosity from 0.8 to 0.4 centipoise. Siau (50) observed small increases in retention for some almost refractory woods.

2. Particulate matter: The amount of particulate matter in the preservative greatly influences retention especially in oil-borne preservatives. Maclean (34) has indicated that various organic compounds in creosote and particulate matter which become available in aged creosote tended to inhibit the penetration of this preservative in wood.

3. Liquid type: Nicholas (38) obtained higher retention in wood treated with oil-type preservative than wood treated with water-borne preservative, when the two preservatives were used under identical impregnation conditions. This finding is supported by the work of Choong et al. (13). The reason for low retention of water-borne preservative is that this preservative forms hydrogen bonds with cellulose material in wood which results in fractional drag between the cellulose material and the water-borne preservative (38, 13). Maclean (34) and Miller (37), on the other hand have obtained higher retention and penetration in wood treated with water-borne preservatives than wood treated with creosote. They attributed the reason to the low viscosity of water-borne preservative and its ability to penetrate the cell wall.

Vapour-Phase Diffusion

In treating wood by this method, holes are bored in the wood, filled with preservative and the holes are then plugged with suitable stoppers (29). The vapours of the preservative then diffuse through the wood to control decay.

Diffusion involves the spontaneous movement of a fluid from a zone of high concentration to another of low concentration. This spontaneous movement of vapour in wood with a moisture content below fiber saturation point may occur in two ways: (1) by vapour diffusion through the void or capillary structure of wood which involves relative free movement through cell lumens with little interaction between vapour molecules and lumen surface, or (2) by sorbed diffusion through the cell wall which is hindered diffusion resulting from greater interaction between the vapour molecules and wood (54, 55).

Partridge (40) used fumigants of volatile chemicals on decayed oak blocks to control the oak wilt fungus. Other workers placed soil fumigants in holes in wood and were able to kill decay fungi as well as provide residual protection against reinfestation (20, 26). Graham et al. (27) found that 0.3 ml of chloropicrin placed in a hole at midlength of side coated 2.5 by 2.5 by 10 cm long Douglas-fir heartwood blocks infested at both ends with Poria carbonica Overh. was sufficient to destroy the fungus. Cooper (20) placed liquid chloropicrin in a hole drilled into the center of a 2.4 meter long Douglas-fir pole that had active decay present. He found that chloropicrin moved in vapour form through the pole at varying concentrations to control decay. Scheffer and Graham (47) concluded from their bioassay study that chloropicrin vapour moved more readily downward than upward, showing the influence of gravitational force. They also found that the lethal concentration of chloropicrin vapour was still present in the assay and treatment holes of chloropicrin treated sections 14 months after treatment.

EXPERIMENTAL APPROACH

For the comparative study of preservative treatment of selected woods from Ghana and the United States, the procedure outlined in the following steps was used:

1. Characterization of the following physical properties of the species:

   (a) Specific Gravity

   (b) Porosity

   (c) Longitudinal Permeability (liquid and air flow)

2. Investigation of the response of the species to the following preservative treatments:

   (a) Pressure impregnation with copper sulphate solution and creosote.

   (b) Vapour-phase treatment with chloropicrin.

3. Estimation of how well the physical properties can be used as indicators of preservative treatments.

4. Light microscopic examination of:

   (a) Untreated heartwood samples to study their anatomical structure.

   (b) Impregnated sapwood samples to find the distribution of copper sulphate solution and creosote in the wood.

SAMPLE COLLECTION

Four hardwoods and three softwoods (Table 1) were used in this study. The woods from Ghana, all from the tropical rain forest region, were selected for their differences in permeability and potential commercial use. Planks 5 by 5 by 30 cm long, cut at least one meter above the buttress zone, were air seasoned for about four months and flown here for this study. All hardwoods were diffuse porous. The woods from the United States were selected to obtain a fairly wide range in permeabilities. The Pacific Coast Douglas-fir specimens were from a freshly cut tree. The specimens of the remaining woods from the United States were obtained from a wood collection at the School of Forestry and had been in the collection for many years.

Sapwood and heartwood specimens were obtained for each species except redwood which was all heartwood. Differentiation between sapwood and heartwood was based on color differences, heartwood being darker, and proximity to the bark if present. All specimens were stored in a standard room at 26 ^{o}C in which wood attained an equilibrium moisture content of 12 percent. Three specimens of sapwood and heartwood of each species except redwood were used for each test.

Table 1. Wood Species Selected for Treatability Study.

Scientific Name of Species	Local Name	Family	Origin
	HARDWOODS		
Mitragyna stipulosa (De Candole)). Kuntze	Subaha	Rubiaceae	Ghana
Piptadeniastrum africanum (Hook f) Brenan	Dahoma	Leguminosae	Ghana
Lophira alata (Banks) Gaertner	Kaku	Ochnaceae	Ghana
Acer saccharum Marsh	Sugar Maple	Aceraceae	United States
	SOFTWOODS		
Sequoia sempevirens (D. Don) Endl.	Redwood	Taxodiaceae	United States
Pseudotsuga menziesii (Mirb) Franco	Douglas-fir	Pinaceae	United States
Pinus ponderosa Laws	Ponderosa pine	Pinaceae	United States

SAMPLE PREPARATION

The dowels used for longitudinal permeability measurements, prepared with an electric plug cutter, were 1.25 cm in diameter and 5 cm along the grain. A low cutting speed was used to obtain smooth surfaces. The dowels were lightly sanded and the longitudinal surface was coated with two layers of epoxy[1/] resin at 24-hour intervals. The coated dowels were cut to a length of 3 cm for air-flow measurements and 1.25 cm for the sink-float (liquid flow) tests.

The samples for specific gravity determination were end-matched with samples for permeability measurements and were 2.5 cm cubes, carefully sawn to provide smooth surfaces.

Specimens for longitudinal treatability tests measured 2.5 by 2.5 by 10 cm along the grain and were end-matched with specimens for permeability and specific gravity measurements. Half of the specimens for pressure impregnation were coated on the 4 side surfaces twice with epoxy resin at 24-hour intervals. Half of the specimens for vapour-phase treatment were coated twice with a fiber glass[2/] resin. At one end of the vapour-phase specimens a

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[1/] Duro Plastic Quick Set Epoxe, Woodhill Chemical Corp., Cleveland, Ohio 44128.

[2/] Fiber glass resin, Stock No. FR-3, Woodhill Chemical Corp., Cleveland, Ohio 44128.

hole 1.6 cm in diameter and 1.2 cm deep was drilled. Another hole of equal depth but 1.4 cm in diameter was drilled at the other end of the specimens. All specimens were returned to the standard room until used. A preliminary study indicated that epoxy resin and fiber glass resin each provided a satisfactory sealant.

EXPERIMENTAL PROCEDURES

Specific Gravity

Specific gravity of each specimen was determined using the formula:

$$\text{Specific Gravity} = \frac{\text{Oven dry weight of wood sample}}{\text{weight of water displaced by wood sample at 12\% M.C.}}$$

Weight of displaced water was obtained after the specimen had attained equilibrium in the standard room. The specimens were then oven dried at 105°C to constant weight. A Mettler top loading balance accurate to 0.001 gram was used for all weighings.

Porosity

Porosity, a measure of the fractional void volume of the species, was obtained from the specific gravity of the species using the equation on page 11.

Longitudinal Permeability

Sink-Float Test

The main purpose of the sink-float test was to determine the permeability of the species, based on the ease with which a liquid moves into the voids of wood, causing a specimen to sink or float in that liquid.

Since the specific gravity of Kaku was higher than that of water, I used a 75% glycerine-water solution in which all wood specimens floated. The physical properties of this solution at 21°C were:

Density: 1.21 gm/cc

Viscosity: 2.11 centipoise

When the normal procedure as stated by Graham (25) was adopted for this solution, some specimens which had been rated permeable with water were rated intermediate, and those of intermediate permeability were rated refractory. After preliminary experiments, the following procedure was found to give results comparable to water:

The dowels to be used in the sink-float test were oven-dried, submerged in the glycerine-water solution in a dessicator which was then aspirated at a vacuum to 45 cm of mercury for 10 minutes (Figure 1). The dessicator was vented to the atmosphere and specimens that sank 2 minutes after venting were rated permeable (P). The specimens were submerged and aspirated for an additional 30 minutes. Specimens that sank 2 minutes after venting were rated intermediate (I) in permeability, while those that floated were rated refractory (R).

Figure 1. Apparatus for sink-float test.

Air Permeability

The experimental apparatus (Figure 2) for air flow through wood specimens under constant pressure gradient, consisted of a large reservoir with an adjustable pressure regulator (not shown), specimen holder (H), a flow measuring device (B, F, T) and a system of pressure tubes (PT) with 0.6 cm internal diameter and 0.5 cm wall thickness.

The specimen holder (Figure 3) was constructed of 2.5 cm thick plexi glass. The coated specimen (S) was sealed between two cells of the plexi glass by applying a pressure with four brass bolts (BB). A circular hole 1.05 cm in diameter, drilled in each half-cell provided a flow area of 0.866 cm^2.

The measuring device for high air flows consisted of two sets of Gilmont flowmeters (Figure 2, F) in series, capable of measuring a flow rate from 100 to 2000 ml per minute. To measure a lower air flow rate I used a buret (T), calibrated from zero to 50 ml to which a rubber bulb (B), was attached at its lower end which served as a soap reservoir. By carefully pressing the bulb, a bubble of soap solution was released which flowed through the buret. The rate of bubble flow along the length of buret was timed using a stop watch accurate to one-tenth of a second.

To measure air-flow rate, a specimen was first sealed between

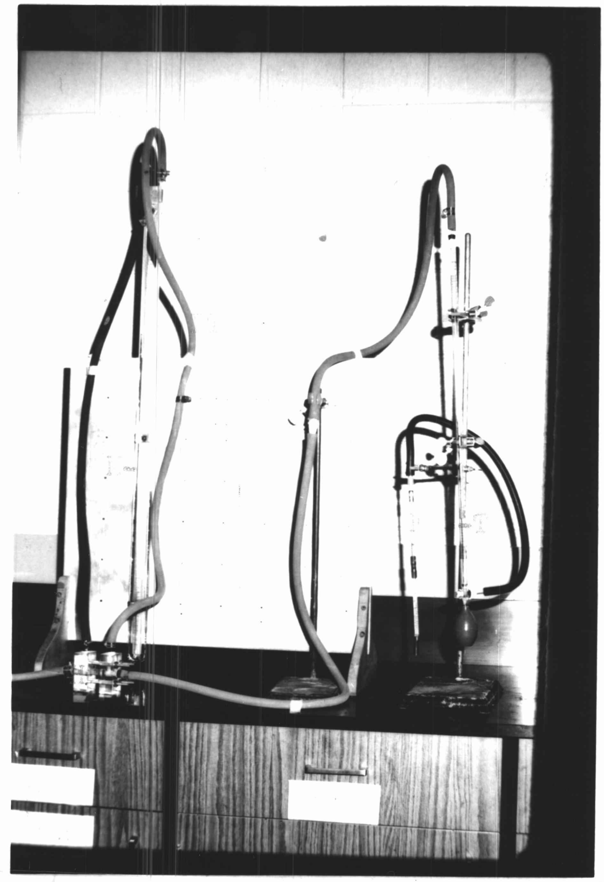


Figure 2. Apparatus for measuring the rate of longitudinal air flow through the wood samples.

<u>Legends</u>

B = Rubber bulb
F = Gilmont flowmeter
H = Specimen holder
M = Mercury mannometer
PT = Pressure tube
T = Buret

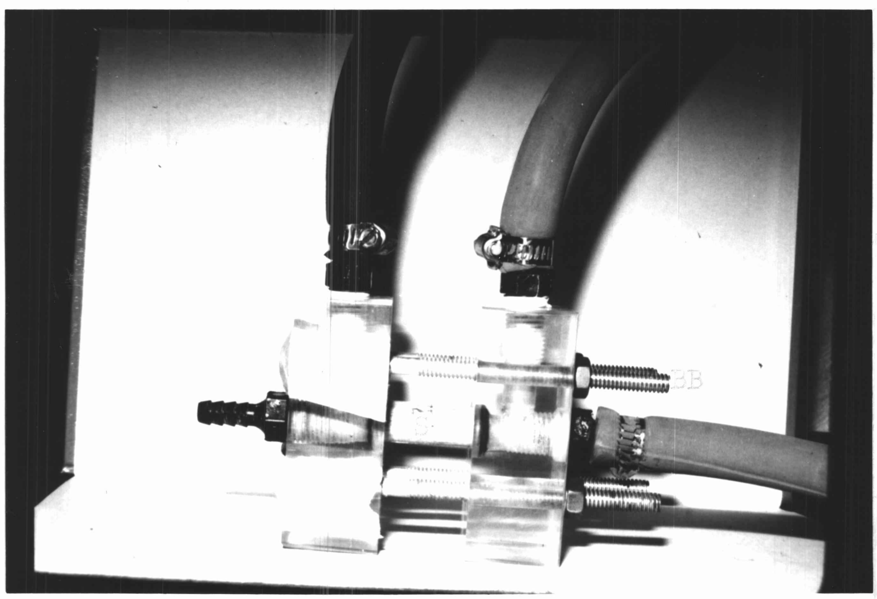


Figure 3. Specimen holder for the air flow apparatus.

<u>Legends</u>

BB = Brass bolt
S = Wood specimen

the two half-cells. A vacuum was created in the reservoir with a vacuum pump. The vacuum regulator was adjusted to release a constant desired differential pressure (about 600 mm Hg) as indicated by the upper and lower levels of mercury mannometer (Figure 2, M). The rate of air flow was then measured with the appropriate flow device. Three measurements were made for each specimen. Air flow was measured at a pressure of 160 mm Hg with a mean pressure of 510 mm Hg at room temperature. Longitudinal air permeability was then determined for each species using the integrated form of Darcy's law adapted for gas flow shown on Page 9.

To make air permeability measurements comparable to other results (50, 51, 52), the value obtained was multiplied by 56×10^8 which converted air permeability from cm^2 units to

$$\frac{cm^3}{\text{atm cm sec}}$$

and 1.3×10^3 which converted pressure measured in mm Hg to dynes/cm^2 (52).

Preservative Treatment

The copper sulphate and creosote preservatives (Table 2) were selected for pressure impregnation because they are widely used commercially to protect wood. Chloropicrin (trichloronitromethane), an agricultural fumigant, was used for vapour-phase treatment because of its promising use to control internal decay in Douglas-fir poles (26, 27, 47).

Table 2. Description and Physical Properties of Preservatives Used for Treatment. *

Name of Preservative	Concentration by weight %	Solvent	Density gm/cc	Viscosity Cp.
Copper Sulphate	10	Water	1.13	1.10
Creosote	20	Toluene	1.12	1.50
Chloropicrin	99	None	1.65	--

*The preservatives were obtained from the following firms:
Copper sulphate: J. H. Baxter & Co., Eugene, Oregon.
Creosote: L. D. McFarland & Company, Eugene, Oregon.
Chloropicrin: Morton Chemical Company, Chicago, Illinois.

Pressure Impregnation

Specimens were treated in a pressure treating cylinder (Figure 4). Coated specimens and uncoated controls were divided equally into two groups. Each group was placed in a plastic container measuring 60 by 40 by 20 cm deep, alternating the coated among the uncoated specimens.

The copper sulphate or creosote solution was poured into the container until the preservative was about 2.5 cm above the specimens which were weighted down to prevent them from floating. The container was inserted into the cylinder and the door was bolted shut.

The Lowry empty-cell process was used. Preliminary

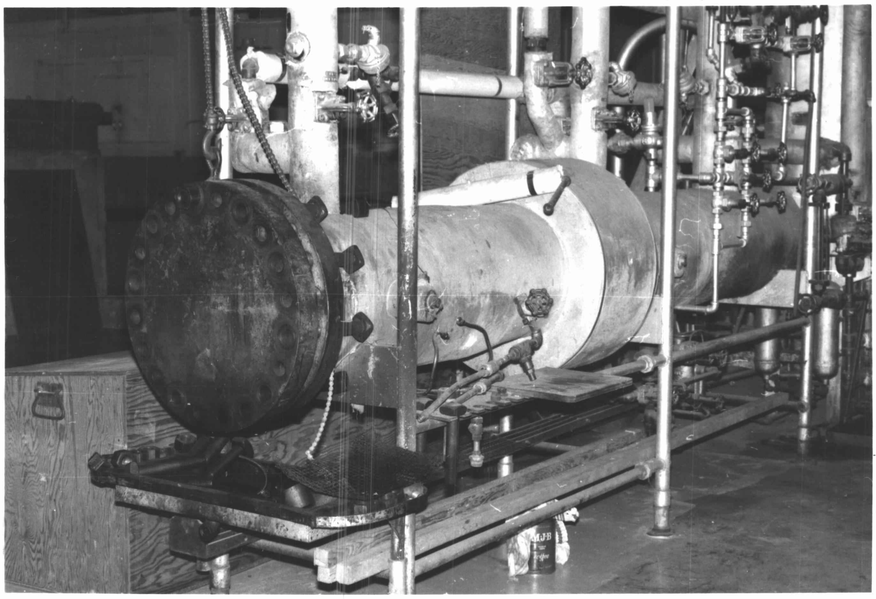


Figure 4. Pressure treating cylinder used for pressure impregnation.

treatments were made to determine the conditions that provided a wide variation in treatment among the samples. The following treating schedule was found to be favorable:

Pressure: 100 Psi

Pressure period: 30 minutes

Temperature: 26°C

After impregnation, excess surface accumulation of preservative was blotted from the treated specimens and the specimens were then weighed to determine net retention as explained on Page 26. Specimens were reweighed on the seventh day just before splitting.

The treated specimens were split longitudinally into two halves along a radial axis to expose a radial-longitudinal surface. The copper sulphate treated specimens were sprayed with a reagent[1/] soon after splitting to impart a blue discernible color to the treated wood.

The depth of longitudinal preservative penetration in each specimen was rated visually by comparing the specimens with standard ratings of Miller (37) (Figure 5).

[1/] Reagent consisted of 0.5 gm Chrome Azurol S concentrate and 5.0 gm of Sodium Acetate dissolved in 80 ml of distilled water and diluted to 100 ml.

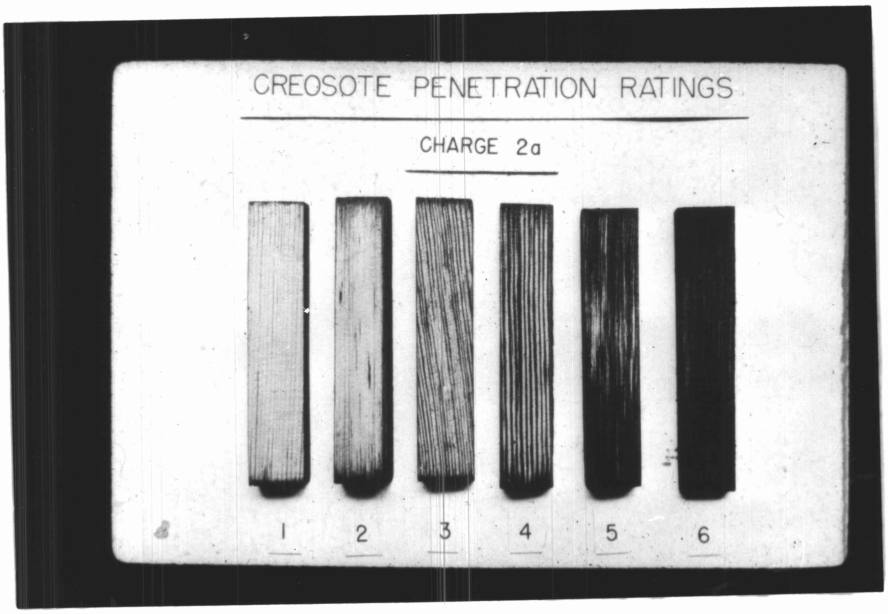


Figure 5. Standard creosote treated specimens of Miller (37) used to determine penetration ratings of treated samples.

Vapour-Phase Diffusion

Two vials of different sizes were used for each specimen (Figure 6, Table 3). The larger vial (upper vial) had a molded screw cap (Figure 6, A) and contained Poria monticola (Murr) fungus, growing on 1.5 cc of 3% potato dextrose agar slant (Figure 6, B). P. monticola was innoculated on the slant by asceptically planting a three millimeter disc of actively growing mycelium. This fungus was selected for the test because it is very sensitive to chloropicrin and is a major wood decayer.

Table 3. Description of Vials Used for Vapour-phase Treatment.*

	Upper Vial	Lower Vial
Total Height Including Neck	4.5	3.5
Height Excluding Neck	3.6	2.8
External Diameter Excluding Neck	1.5	1.2
Internal Diameter of Neck	0.9	0.5
Thickness of Side-Wall	0.1	0.1
Total Internal Volume	4.0	2.0

*All measurements are given in centimeters.

A hole 0.6 cm in diameter was drilled in the center of the cap (Figure 6, A). A white thread sealant was tightly wound around the sides of the cap (Figure 6, C). The cap was inserted into the 1.6

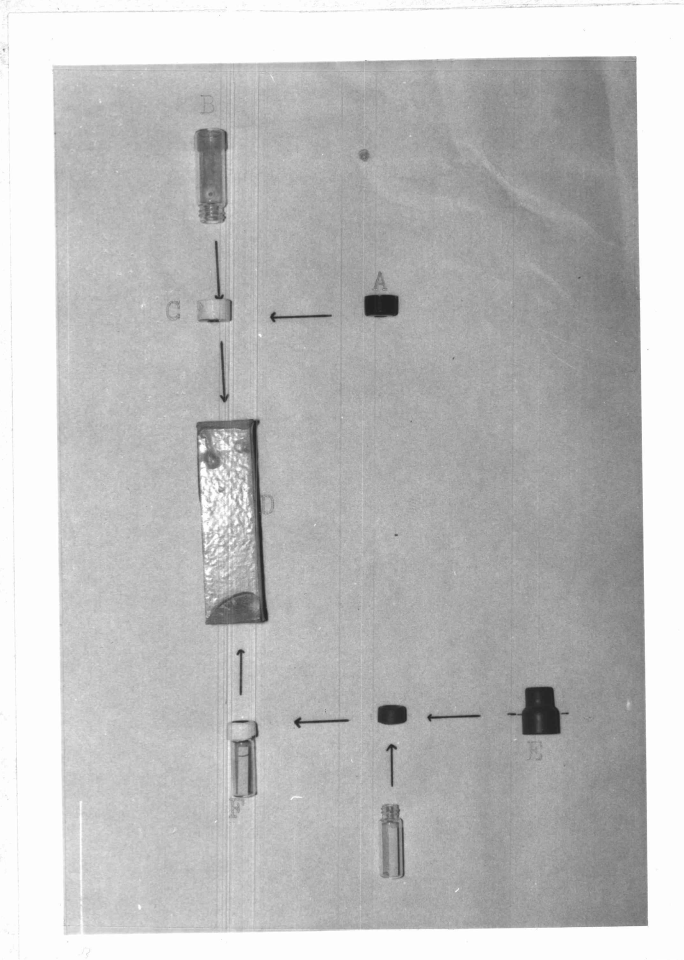


Figure 6. Procedure adopted for vapour-phase diffusion treatment.

<u>Legends</u>

A = Cap of larger vial with a hole in the centre.
B = Upper larger vial.
C = Cap with thread sealant wound around the sides.
D = 10-cm wood specimen.
E = Silicone cap.
F = Smaller lower vial with inserted silicone cap.

cm diameter hole at one end of the specimen. The larger vial was then screwed into the cap (Figure 7).

The small portion of a silicone cap (Figure 6, E) was cut from its larger portion with a pair of scissors. This was inserted around the neck of the smaller vial and a ribbon sealant wound around it (Figure 6, F). Using a syringe with a hypodermic needle, 1.75 ml of liquid chloropicrin at 21^{o}C was carefully transferred into this vial. The vial with chloropicrin was inserted in the 1.4 cm diameter hole at the other end of the specimen (Figure 7). All specimens and their control were then arranged for treatment in standard room as shown in Figure 8.

To time the rate of vapour movement in the specimen, the larger upper vial with fungus was changed after every 24 hours for one week. To prevent possible loss of chloropicrin vapour from the vial during change, the vial was held up and quickly capped. About half an hour later, a 3 ml disc of the P. monticola was removed from the vial and planted in a petri-dish containing 10 ml of 3% potato-dextrose agar. Both cultures in vials and in petri dishes were incubated for six weeks in an incubator at 21^{o}C and observed for any growth of fungus.

After diffusion rates for various species had been determined, a study was made to find the rate of vapour release at the following conditions:

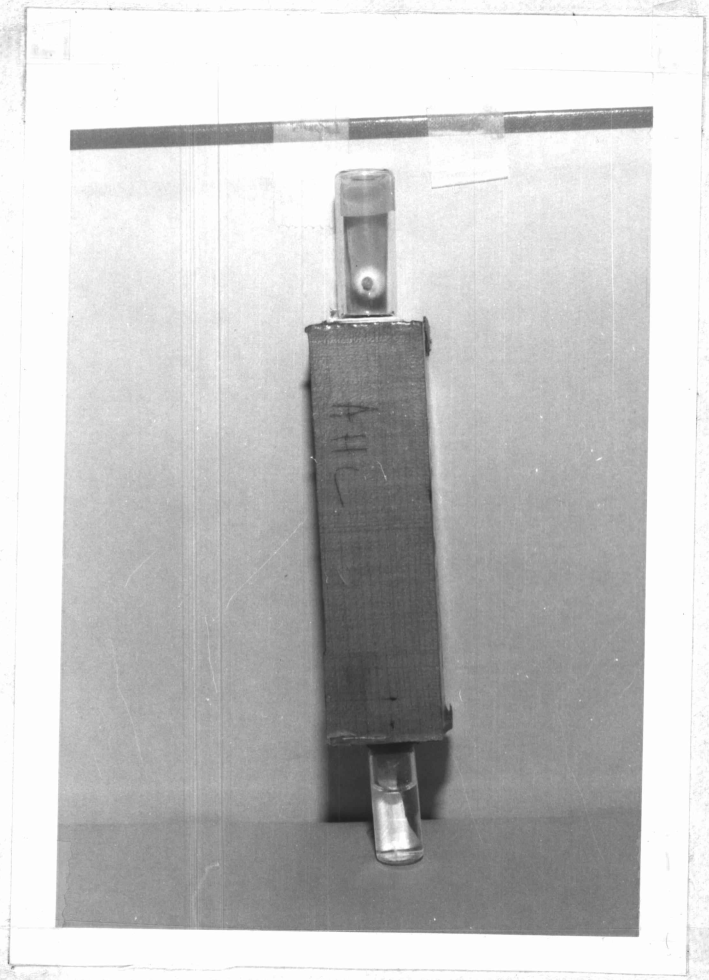


Figure 7. A specimen arranged for vapour-phase diffusion treatment. Bottom vial contained *Poria monticola* Murr. fungus growing on Potato-dextrose agar.

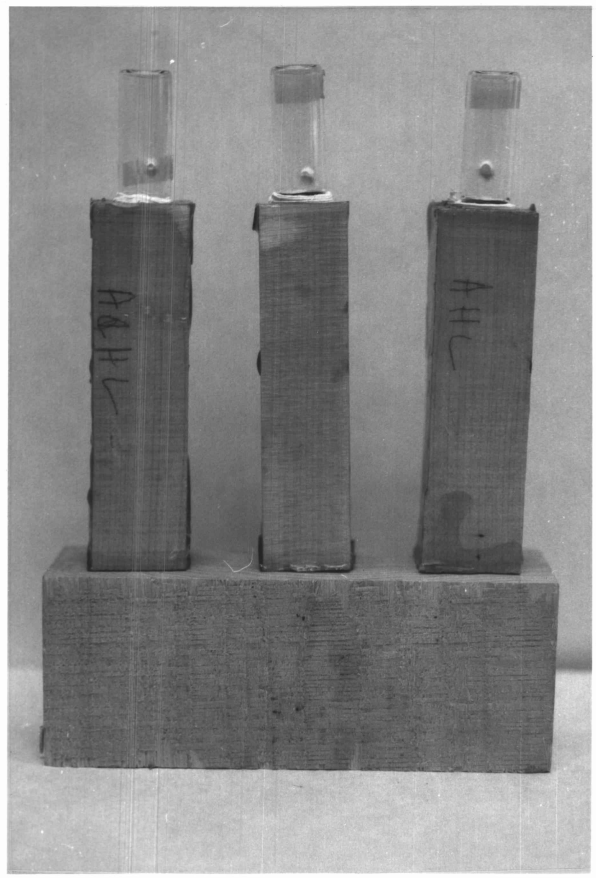


Figure 8. Specimens undergoing vapour-phase diffusion treatment in a standard room. Lower vials containing chloropicrin are suspended in holes drilled in the wooden block. Vial attached to middle specimen contained no chloropicrin.

Storage Room	Temperature	Relative Humidity
Standard	$26^{o}C$	65%
Hot dry	$32^{o}C$	35%
Hot wet	$32^{o}C$	85%

The hot dry and hot wet rooms simulate the climatic conditions in the tropics.

The level of the liquid chloropicrin in the lower vial was recorded at two-day intervals for 12 days at each test condition in the sequence shown above. To find the maximum possible release at these conditions, three similar vials containing the same amount of liquid chloropicrin were exposed to each testing room and the liquid level similarly recorded.

Microtechnique

Temporary slides from preservative impregnated specimens and permanent slides from untreated heartwood specimens were prepared for the anatomical study.

To locate preservatives in an impregnated specimen, heavily treated areas of sapwood from each species except redwood were used. For redwood the heartwood sample was heavily treated and used for these observations. For the location of copper sulphate preservatives a 2 cm cube was cut from the specimen of each species. A blotting paper was dipped into the coloring reagent and applied carefully to the cross section. The surface was allowed to dry, a transparent scotch tape was applied to the surface, and sections measuring 30-40 microns were cut with a sliding microtome. Mountings were made by taping the section to the lower side of a cover glass and cementing this assembly to the glass slide.

For creosote treated specimens, a 1 cm cube cut from each specimen was placed in a 75% glycerin-water solution for four weeks. The solution softened the wood but it did not displace creosote from it. Each cube was sectioned on a sliding microtome and sections were mounted in glycerol solution.

To find the general distribution of cell types and inclusions in each species, permanent slides, stained and unstained, were prepared from end-matched samples of treated heartwood by the conventional method (46).

RESULTS AND DISCUSSION

The microscopic observation will be presented and discussed first because the anatomical information will be used to explain results of the physical properties and preservatives treatment.

Microscopic Observation

Size and Number of Vessels or Tracheids

In hardwoods, the number of vessles in Subaha and Sugar maple were "very numerous". In Dahoma, vessels were "few" in number while those of Kaku were "very few" in number. The size and number of pores of Kaku, Subaha and Sugar maple compared favorably with the values obtained by others (3, 39). There were no data available to compare the anatomical characteristics of Dahoma. The size and distribution of tracheids in softwoods (Table 4, Figures 13-15) were also in agreement with other findings (39).

Cell Inclusions in Heartwood

Typical major cell inclusions characterized the hardwoods (Table 5, Figures 9-12). Gum in the lumen of the vessels was most abundant. This amorphous extraneous material partly or completely occupied the lumen of some vessels in all hardwoods. In

Table 4. Distribution and Size of Lumens in Vessels and Tracheids in Heartwood.

Local Name of Species	Diameter of Lumen* mm. Vessel	Tracheid	Distribution** No/mm^2
Subaha	0.092		44
Dahoma	0.22		5
Kaku	0.24		2
Sugar maple	0.09		46
Redwood		0.040	610
Douglas-fir		0.035	620
Ponderosa pine		0.034	600

*Based on the average of tangential and radial measurements of 10 randomly selected microscopic fields of each three specimens. In ring-porous species, 5 fields each were selected from early and latewood of a specimen.

**Based on the average of 10 randomly selected microscopic fields of each of three specimens.

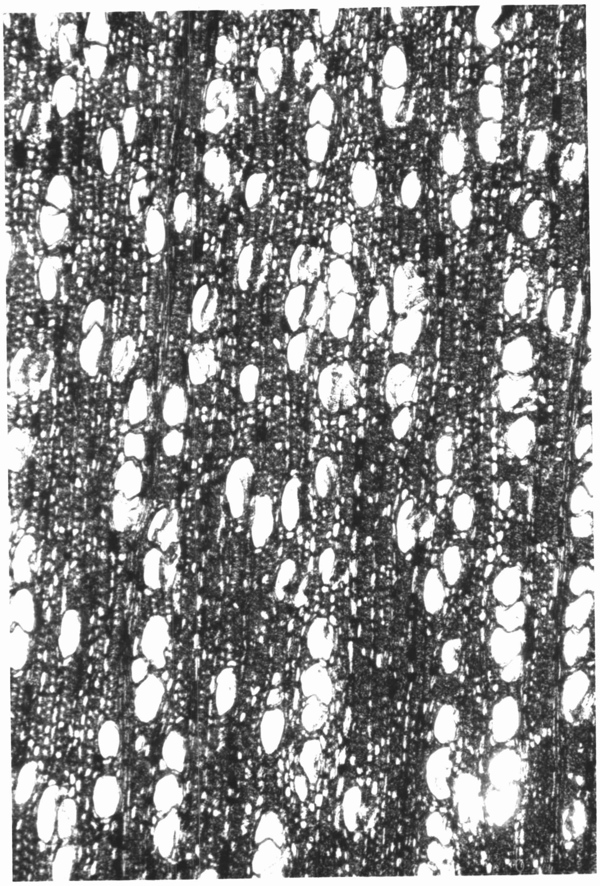


Figure 9. Distribution of cell types and inclusions in Subaha (Mitragyna stipulosa [De Candole] O. Kuntze). Magnification 50X.

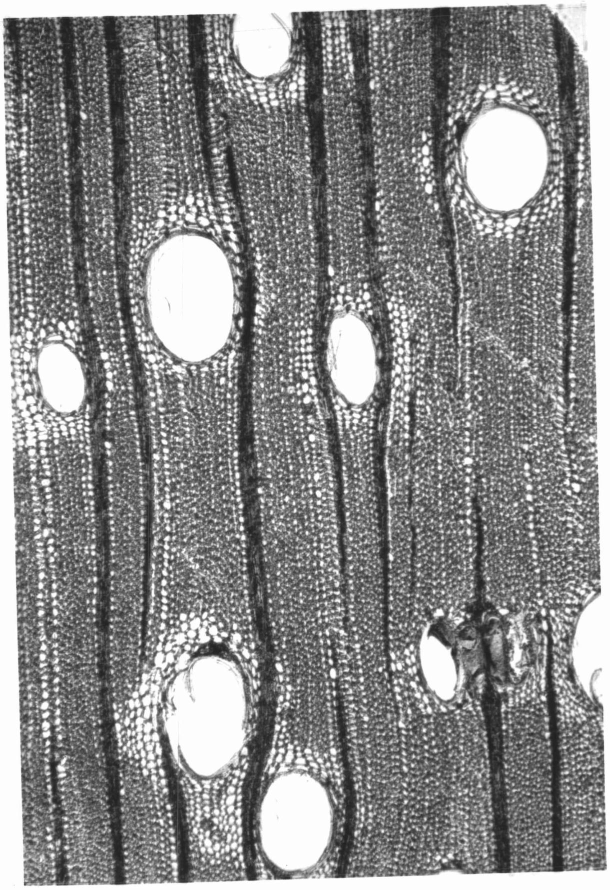


Figure 10. Distribution of cell types and inclusions in Dahoma (Piptadeniastrum africanum [Hook f.] Brenan.). Magnification 50X.

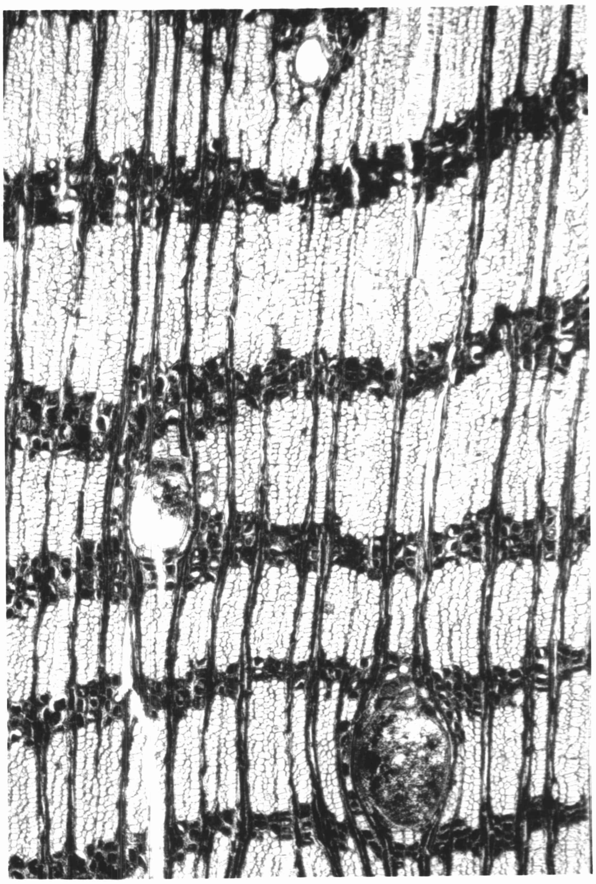


Figure 11a. Distribution of cell types and inclusions in Kaku (Lophira alata [Banks] Gaertner). Magnification 50X.

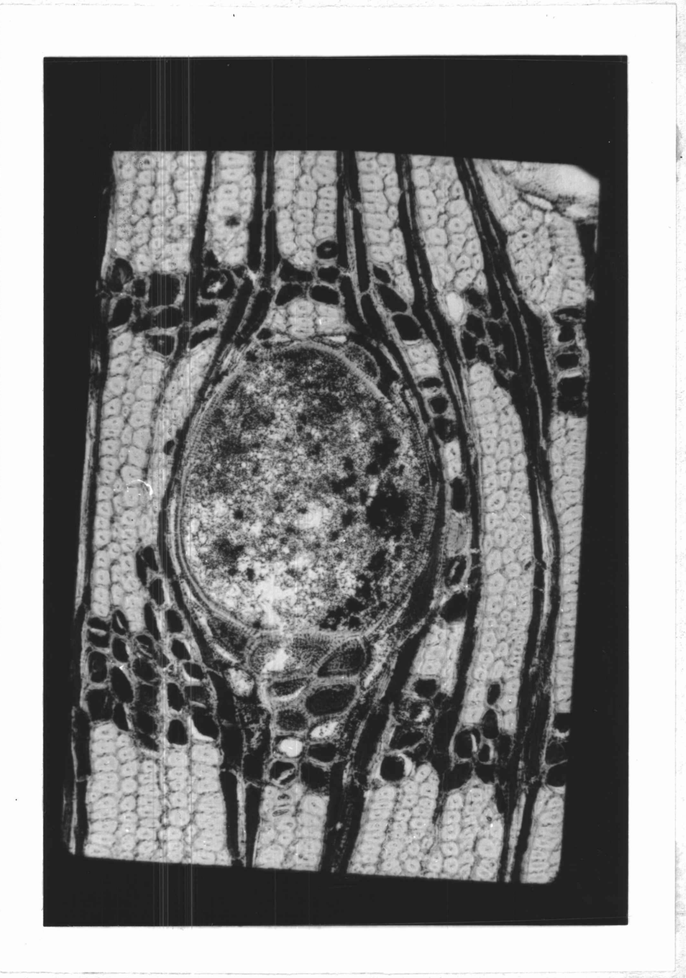


Figure 11b. A completely gum-occluded vessel of Kaku. Magnification 150X.

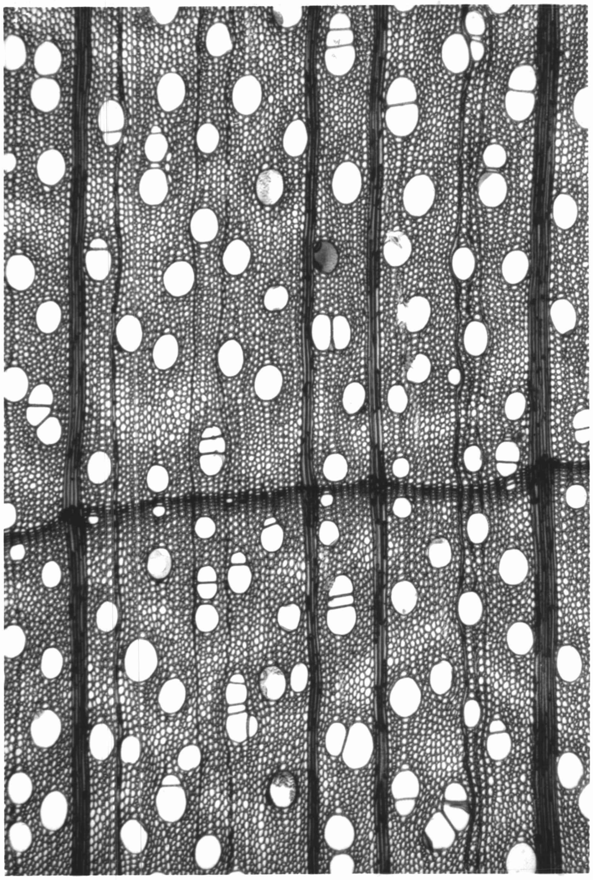


Figure 12. Distribution of cell types and inclusions in Sugar Maple (Acer saccharum Marsh). Magnification 50X.

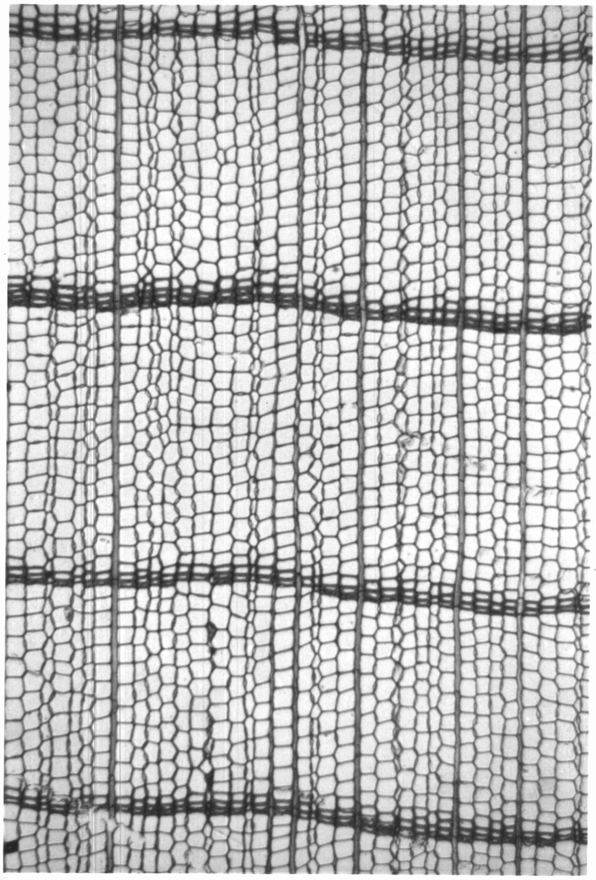


Figure 13. Distribution of cell types and inclusions in Redwood (Sequoia sempervirens D. Don). Magnification 50X.

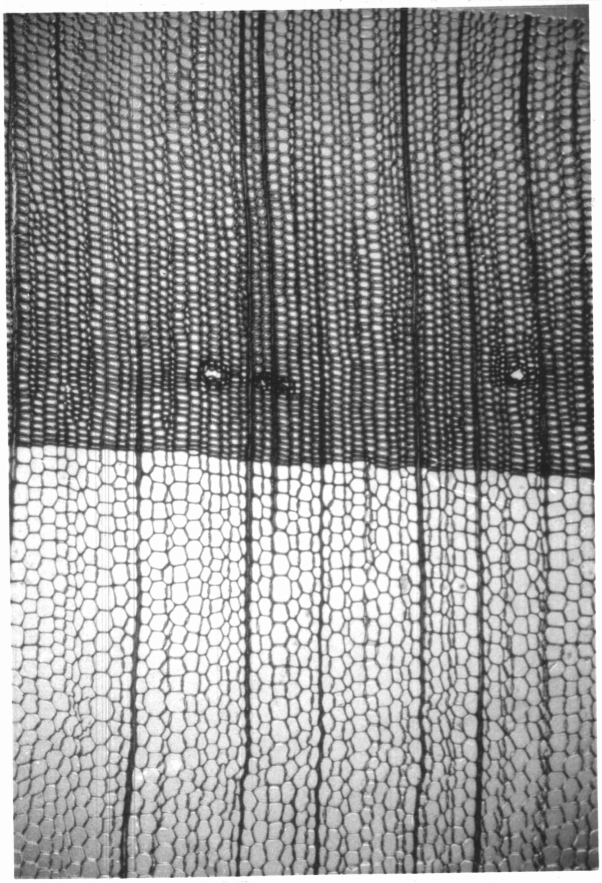


Figure 14. Distribution of cell types and inclusions in Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco.) Magnification 50X.

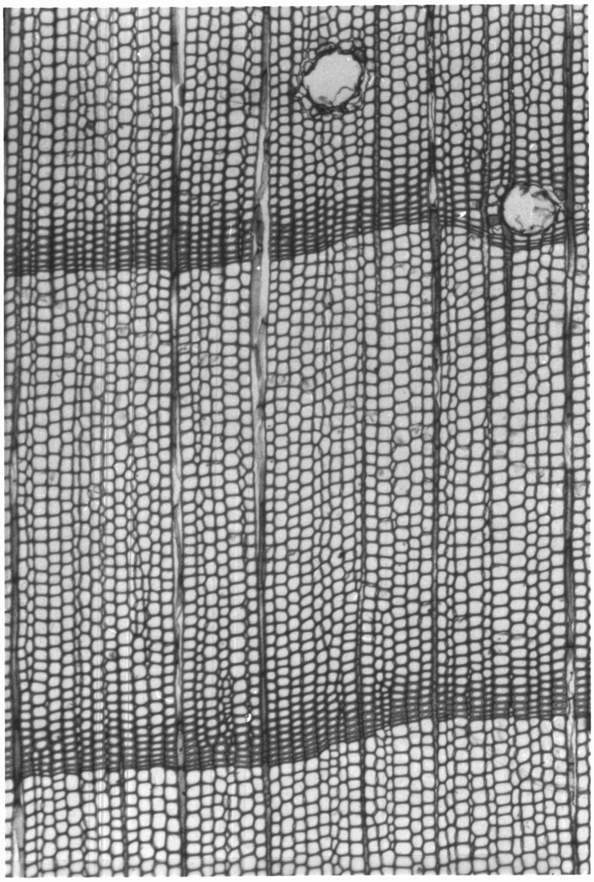


Figure 15. Distribution of cell types and inclusions in Ponderosa pine (Pinus ponderosa Laws). Magnification 50X.

Table 5. Occurrence of Cell Inclusions in Heartwood of the Species.*

Local Name of Species	Tyloses in Vessel	Gum in Vessel	Tylosoid in Resin Canal	Longitudinal Parenchyma	Ray Cell
Subaha	25-49	1- 9	-	10- 24	50- 74
Dahoma	25-49	25-49	-	10- 24	75-100
Kaku	1- 9	50-74	-	75-100	75-100
Sugar Maple	-	1- 9	-	1- 9	50- 74
Redwood	-	-	-	-	50- 74
Douglas-fir	-	-	1-9	25- 49	50- 74
Ponderosa Pine	-	-	1-9	25- 49	50- 74

*Each pair of numbers represents a percentage range of the type of cell found to contain inclusion or inclusion type based on 10 randomly selected microscopic fields of each specimen.

Kaku (Figures 11a, 11b), the very visible yellowish gum deposits invariably completely blocked the lumen in 2 out of 3 vessels. Such a distinct characteristic is of taxonomic importance (1).

Tyloses, occurred in all hardwood species except Sugar Maple. Some of the tyloses was torn loose during preparation of permanent slides, leaving only traces in the finished sections (Figures 9, 10). Brownish-colored extractives were found in the lumens of most multiseriate rays and longitudinal (axial) parenchyma cells of all hardwoods.

In softwoods, tylosoids and unidentified cell inclusions characterized the species (Table 5, Figures 13-15). Tylosoids, proliferations of unlignified epithelial cells into resin canals, occurred in very few resin canals in Douglas-fir and Ponderosa pine (Figures 14, 15). Like the hardwoods, most uniseriate ray and epithelial cells contained extractives in their lumens (Figures 13-15).

Preservative Distribution in Sapwood

In general, vessels of hardwoods and tracheids of softwoods were the most frequent cells that contained preservatives (Table 6).

In hardwoods, most vessels, when free from inclusions, contained preservatives. In Kaku, where most vessel lumens were occluded with gum, fiber lumens were equally important for penetration and rentention of preservatives. The importance of fibers as paths for preservative treatment in species with less-occluded vessels

Table 6. The Distribution of Preservatives in Major Cells of Pressure Impregnated Sapwood Samples.*

Preservative and Species	Vessel	Fiber	Longitudinal Parenchyma	Ray Cell	Cell Wall
Copper Sulphate					
Subaha	75-100	25-49	25-49	10-24	50-74
Dahoma	50- 74	25-49	25-49	10-24	25-49
Kaku	25- 49	25-49	1- 9	1- 9	25-49
Sugar Maple	75-100	25-49	25-49	10-24	50-74
Creosote					
Subaha	75-100	25-49	25-49	10-24	Nil
Dahoma	50- 74	25-49	25-49	10-24	Nil
Kaku	25- 49	25-49	1- 9	1- 9	Nil
Sugar Maple	75-100	25-49	25-49	10-24	Nil

	Tracheid	Resin Canal	Epithelial Cell	Ray Cell	Cell Wall
Copper Sulphate					
Redwood**	75-100	-	-	25-49	50-74
Douglas-fir	50- 74	10-24	10-24	25-49	50-74
Ponderosa pine	50- 74	25-49	25-49	25-49	50-74
Creosote					
Redwood**	75-100	-	-	25-49	Nil
Douglas-fir	50- 74	10-24	10-24	25-49	Nil
Ponderosa pine	50- 74	10-24	10-24	25-49	Nil

*See footnote Table 5.

**Redwood showed completely penetrated heartwood.

was small. Few parenchyma cells surrounding an impregnated hardwood vessel contained preservatives in spite of the brownish inclusions found in them. When vessels were completely occluded, neither the vessels nor occlusion-free parenchyma cells contained preservatives. This probably suggests that preservatives first entered occlusion-free vessels and then passed through the half-bordered pit pairs into ray and longitudinal parenchyma cells.

Tracheids by virtue of their large occlusion-free lumen and frequency of occurrence, were the most predominant cell type containing preservatives in softwoods. In Douglas-fir and Ponderosa pine, only a few resin canals contained preservatives. No resin canals are present in Redwood. Very few epithelial cells surrounding impregnated resin canals of Douglas-fir and Ponderosa pine and few ray cells adjacent to impregnated tracheid or resin canal contained preservatives.

In both hardwoods and softwoods, the cell inclusions did not always hinder penetration of preservative. In Subaha and Dahoma, preservatives were found in vessel lumens where tyloses and gum did not occlude them completely. Likewise, preservatives were found in partly tylosoid occluded resin canals of Douglas-fir and Ponderosa pine.

Comparing the two preservatives, copper sulphate solution was found in cell lumens as well as in the cell wall, but creosote occurred only in the lumens, which showed that copper sulphate have slightly swollen the specimens during impregnation. Behr et al. (8) did not find creosote in the cell wall of longitudinally impregnated specimens of various domestic species.

Physical Properties

Specific Gravity and Porosity

In hardwoods from Ghana the specific gravity of Kaku (Table 7) was highest due to very few vessels, very thick walled fibers and many cell inclusions. This was followed by Dahoma with few vessels and less thick-walled fibers. Subaha, with very numerous vessels, thin wall fibers, and few inclusions had the lowest specific gravity. Even though vessel distribution in Subaha and Sugar maple were the same, the specific gravity of maple was higher because of its comparatively thicker wall fibers and smaller lumen of the vessels and fibers. Values for softwood were typical of the wood species.

Within each species, specific gravity showed a variation between the sapwood and heartwood. Specific gravity of heartwood which normally contained more extractives was always slightly higher than that of sapwood. The specific gravity values for the woods from the United States fall within the range reported by others (39), while the values for Kaku and Subaha compare favorably

Table 7. Physical Properties of the Sapwood and Heartwood of the Species at 12% Moisture Content.

Name of Species and Type of wood	Species Gravity	Porosity %	Longitudinal Sink Float Test	Permeability Air Flow cm^3/cm atm sec.
Subaha				
Sapwood	0.58	54	P	111.2
Heartwood	0.60	53	P	51.8
Dahoma				
Sapwood	0.66	48	P	78.0
Heartwood	0.68	46	P	48.7
Kaku				
Sapwood	1.02	20	I	29.1
Heartwood	1.05	17	R	0.13
Sugar Maple				
Sapwood	0.64	50	P	107.8
Heartwood	0.66	48	P	33.1
Redwood				
Heartwood	0.38	70	I	7.7
Douglas-fir				
Sapwood	0.50	61	I	1.60
Heartwood	0.51	60	R	0.80
Ponderosa Pine				
Sapwood	0.38	70	I	2.25
Heartwood	0.40	69	R	0.080

with the work of others (1, 3).

Porosity decreased with increasing specific gravity, therefore species with low specific gravity gave the highest porosity values and were inversely influenced by the same factors affecting specific gravity.

Sink-Float Test and Air Permeability

Since the viscosity of the glycerin solution was 2.10 times more than that of water and had a specific gravity 1.24 times more than water, the magnitude of vacuum, the vacuum period and the sinkage time was increased slightly beyond the values reported by Graham (25), who used water instead of a glycerin solution.

The sapwood and heartwood of most of the heartwoods were rated permeable (Table 7) while the sapwood of most softwoods was of intermediate permeability and the heartwood refractory. Glycerin flow in softwoods was probably restricted by the small pits and pit aspiration.

The sapwood and heartwood of Subaha, Maple and Dahoma rated quite permeable and contained less gum inclusions than sapwood and heartwood of Kaku. The refractory nature of Kaku heartwood was due to the occlusion of the vessel lumen with yellowish gum deposits. Tyloses in Subaha and Dahoma did not affect permeability as much as the gum deposits in Kaku. Ponderosa pine and Douglas-fir heartwood rated refractory, and their sapwood and the heartwood of Redwood were all rated intermediate.

In either hardwoods or softwoods, sink-float test compared favorably with air flow measurements. Species rated permeable gave higher air permeability than others rated intermediate even though air flow measurements in equally rated specimens were quite variable. For example, all hardwood samples except sapwood and heartwood of Kaku, were rated permeable but the air permeability in Subaha sapwood was about 2 times that of Dahoma sapwood.

When air permeability measurements in hardwoods and softwoods were compared, it was found that the average for the heartwood of hardwoods was about 12 times more than the average for the heartwood of softwoods, and the sapwood of hardwoods was 43 times more permeable than the sapwoods of softwoods. The huge difference is due to the varying air flow channels in the two groups.

In softwoods, the maximum effective radii of the pit membrane openings, which are the limiting structures for air flow in unaspirated or partially aspirated pits of the sapwood, range from 0.01 to 4 μm (52). Their resistance to longitudinal air flow is very high and might be the cause of low air permeability. Permeability of heartwood is further reduced because of pit aspiration.

In hardwoods, the vessels with their perforated ends offer very low resistance to longitudinal air flow except in gum-occluded vessels like Kaku heartwood where the abundant inclusions were very important in influencing the permeability of the wood.

The lower permeability in softwoods may further be explained by the varying air flow types in wood structure. For the determination of longitudinal air permeability by Darcy law, air flow was considered to be viscous. This is usually the case in open vessels where diameters are more than one micrometer but in softwood, constricted flow through the pit openings less than a micrometer is turbulent. When the size of the opening is in the order of the free mean path of air, a molecular slip or Knudsen flow occurs (52). Because the frictional force which restricts turbulence flow is more than viscous flow, flow in most softwoods is less than in hardwoods if flow channels are devoid of cell inclusions.

Preservative Treatment

Pressure Impregnation

After impregnated specimens were removed from the treating cylinder, many of them exuded preservatives from the ends because of the trapped air in the wood. The amount of preservatives exuded from the ends of coated specimens was visually found to be more than from uncoated specimens. Creosoted specimens exuded more preservatives than specimens treated with copper sulphate solution.

There was no evidence of preservative exudation from the sides of coated specimens. A similar observation has been made by Behr et al. (8).

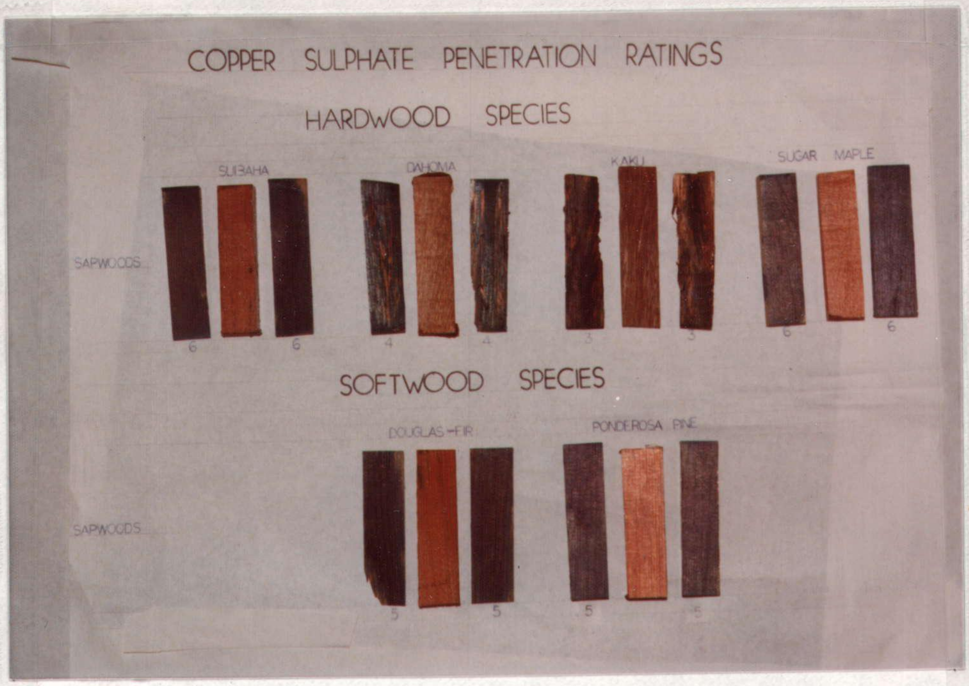
Penetration was uniform in all species except in copper sulphate and creosote treated specimens of the sapwood and heartwood of Dahoma and Kaku and copper sulphate treated heartwood of Ponderosa Pine and Douglas-fir where spotty treatment was found (Figures 16, 17). Since Kaku and Dahoma contained appreciable amounts of cell inclusions, spotty treatment might have been caused by the inability of the creosote to force its way out of the main passageways into adjoining cells. In Douglas-fir and Ponderosa pine spotted treatment was caused by the variations in treatability of the earlywood and latewood.

There was no significant difference in penetration and retention between the coated and uncoated samples.

Penetration and Retention

Penetration and retention among the species followed nearly identical trends for the copper sulphate and creosote preservatives.

In hardwoods, Sugar maple gave the highest penetration and retention for sapwood and heartwood (Table 8), followed by Subaha. Both species are similar in structure but Subaha contains more tyloses in the heartwood than Sugar maple. The fact that Subaha



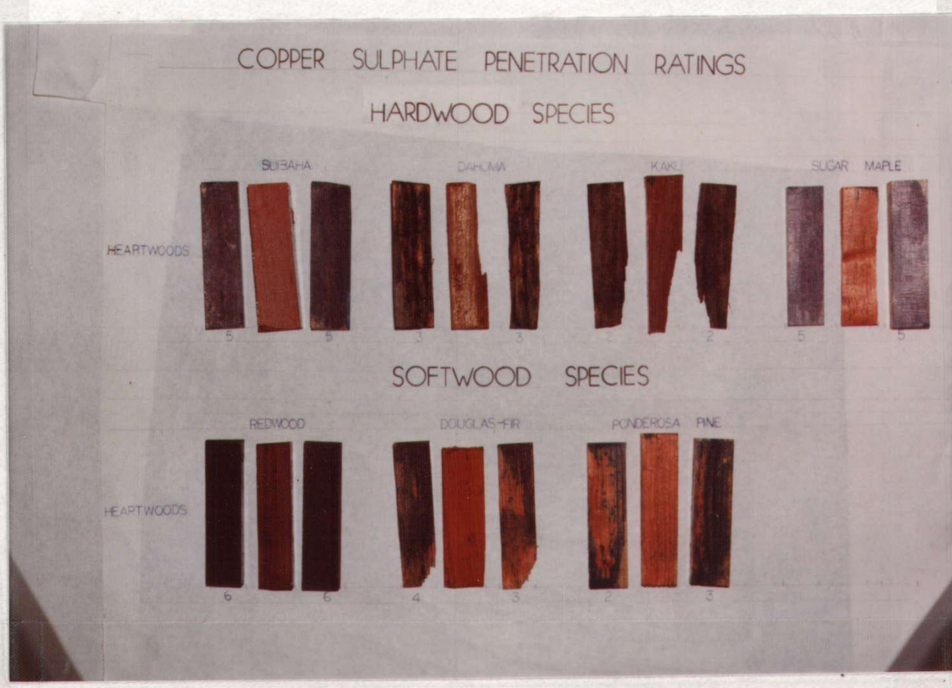


Figure 16. Specimens impregnated with copper sulphate under pressure. Penetration ratings are indicated by numbers below each treated specimen. Three specimens are shown for each species. The side coated specimens are at the right and uncoated specimens at the left of each of the 3 specimens of each species. The specimen in the middle of each group is untreated.

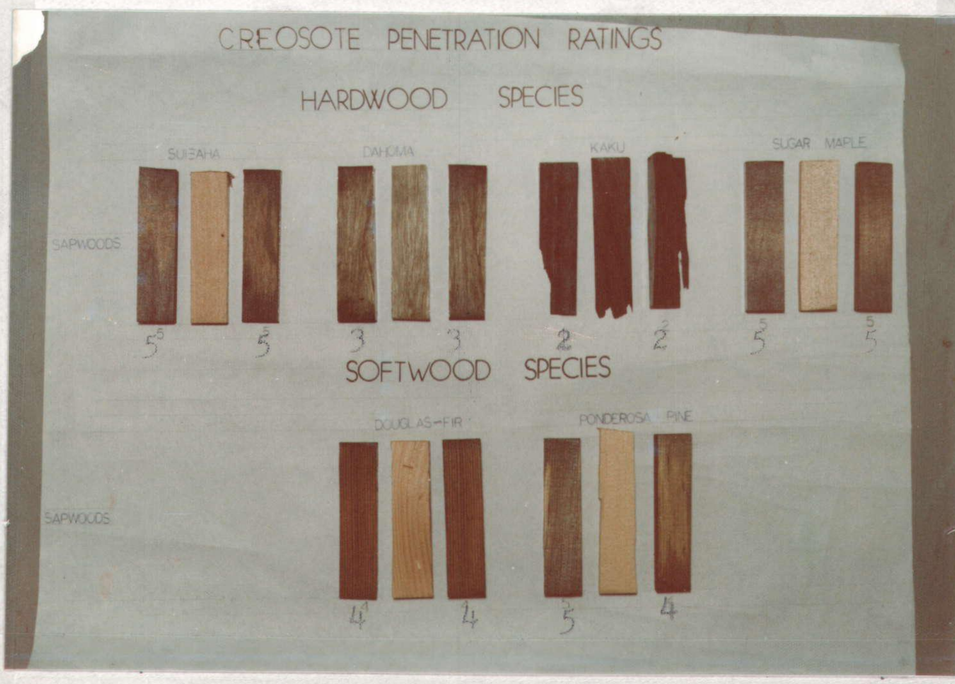


Figure 17. Specimens impregnated with creosote under pressure. Penetration ratings are indicated by numbers below each treated specimen. Three specimens are shown for each species. The side coated specimens are at the right and uncoated specimens at the left of each of the 3 specimens of each species. The specimen in the middle of each group is untreated.

Table 8. Preservative Retention and Penetration Ratings of Copper Sulphate and Creosote Treated Species.

	Copper Sulphate: Retention on withdrawal gm/cc	Copper Sulphate: Retention after 7 days gm/cc	Copper Sulphate: Penetration Ratings	Copper Sulphate: Loss of preservative solvent %	Creosote: Retention on withdrawal gm/cc	Creosote: Retention after 7 days gm/cc	Creosote: Penetration Ratings	Creosote: Loss of preservative solvent %
Subaha								
Sapwood	0.36	0.12	5.25	67	0.14	0.113	3.0	19
Heartwood	0.29	0.15	5.0	48	0.118	0.098	2.25	17
Dahoma								
Sapwood	0.16	0.085	3.5	47	0.085	0.077	2.0	9
Heartwood	0.146	0.078	3.5	47	0.065	0.062	1.3	5
Kaku								
Sapwood	0.145	0.103	3.0	29	0.082	0.076	1.75	10
Heartwood	0.059	0.157	2.25	3	0.034	0.035	1.25	6
Sugar Maple								
Sapwood	0.46	0.128	5.5	70	0.306	0.243	4.0	21
Heartwood	0.43	0.162	5.25	65	0.284	0.23	3.75	19

Table 8. Continued.

	Copper Sulphate: Retention on withdrawal gm/cc	Copper Sulphate: Retention after 7 days gm/cc	Penetration Ratings	Loss of preservative solvent %	Creosote: Retention on withdrawal gm/cc	Creosote: Retention after 7 days gm/cc	Penetration ratings	Loss of preservative solvent %
Redwood								
Heartwood	0.375	0.109	5.75	71	0.364	0.278	5.0	24
Douglas-fir								
Sapwood	0.305	0.123	4.25	60	0.265	0.19	3.0	19
Heartwood	0.22	0.087	3.25	60	0.131	0.119	2.0	9
Ponderosa Pine								
Sapwood	0.315	0.098	3.75	69	0.213	0.157	2.0	12
Heartwood	0.099	0.085	2.25	20	0.023	0.22	1.0	4

with the highest heartwood air permeability was less penetrated than Sugar maple, shows that the effect of tyloses in hindering fluid penetration is more effective in liquid than in air flow. Kaku, with its abundant gum inclusions and very few pores had the least penetration and retention. Penetration and retention in hardwood species were directly related to the vessel distribution but was indirectly related to vessel size and gum inclusion found in them (Tables 4, 5, 8).

For the softwood samples, the redwood heartwood, which has been classified by Maclean (34) as one of the less penetrable types of wood, was actually the best penetrated sample in this study. It was better penetrated than the sapwood of Ponderosa pine, which in turn was better penetrated than Douglas-fir sapwood and heartwood. The Ponderosa pine heartwood samples had the least penetration which is also contrary to the findings of Maclean (34). Specimens with high penetration also retained more preservatives than those with low penetration ratings. Penetration and retention in the softwood species were directly related to the diameter of the tracheid lumen (Table 4, 5, 8).

The specimens treated with copper sulphate solution showed higher penetration and retention than the creosoted specimens. The average of the total penetration ratings for all creosoted sapwood and heartwood specimens was only 61% of the average penetration of copper sulphate specimens. The average of the sapwood and heartwood retention for creosote was 63% of the average for copper sulphate treated specimens. The superior preservative treatment of specimens treated with copper sulphate is due to the ability of the water-borne preservative to penetrate the cell wall material, resulting in swelling. Other workers have found a higher retention and penetration in water-borne preservatives when this and oil-borne preservatives were used under identical impregnation conditions (29, 37).

A comparison of the physical properties of the species to their ability to be treated with copper sulphate or creosote preservatives showed that neither the porosity nor the specific gravity was related to retention and penetration (Tables 7, 8). The effect of porosity and specific gravity on preservative treatment was obscured by the variations in character and conditions of vessels, fibers, tracheids and resin ducts in the species. This is in agreement with findings of others (37, 60).

The results of the permeability tests, however, were directly related to immediate retention and penetration of the copper sulphate and creosote preservatives (Tables 7, 8). The sapwood and heartwood of Subaha, Dahoma and Sugar maple were all permeable to air flow and had higher penetration ratings and retentions than Kaku sapwood and heartwood, which were almost impermeable to air flow.

The sapwood of Kaku with an intermediate air permeability rating had better retention and penetration than Kaku heartwood which was rated refractory to air permeability. For softwoods, the heartwood of Redwood and sapwood of Douglas-fir and Ponderosa pine were all rated intermediate by the sink-float test. They were better treated than low air permeability heartwood of Douglas-fir and Ponderosa pine, both of which were rated refractory.

Loss of Preservatives

When the difference between the initial weight of samples immediately after treatment with creosote or copper sulphate and the weight on the 7th day was expressed as a percentage of the initial weight, it was found that weight loss was higher in samples with higher retentions than those with lower retentions (Table 8). For example, the percent loss of weight of sapwood sample of Sugar maple which retained the most copper sulphate preservative was 70%. The percent loss of weight of heartwood of Kaku treated with copper sulphate was 3%. In softwood samples treated with copper sulphate, the Redwood samples had very high retentions and lost 71%, while the refractory Ponderosa pine heartwood lost only 20%. The average percent loss in weight from heartwood of all species was 78% of the loss in sapwood for specimens impregnated with copper sulphate solution. For creosoted specimens, the average total loss from heartwood was 60% of the total loss from sapwood. Further, the total loss from all hardwoods was 75% of the total loss from softwoods. These results indicate that the loss in weight on the 7th day was directly proportional to the immediate retention of the treated specimens.

The loss in weight from the treated specimens within the 7-day period might be due to one or both of these processes:

(1) Evaporation of solvent from specimens treated with copper sulphate resulting in drying, and

(2) Bleeding of creosote preservative from the ends of treated specimens.

Evaporation is the emission of vapor molecules from a solution as a result of vapor pressure differences between the solution and the environment. Rate of evaporation is indirectly proportional to the viscosity of the evaporating solvent. Since creosote is 1.3 times more viscous than the copper sulphate solution, the loss of weight in copper sulphate treated specimens may have been from evaporation.

The tendency for treated specimens to exude oil preservative on the surface is referred to as bleeding. The amount of creosote injected into wood might be the main dependent factor for exudation since treated specimens with higher retentions bled more than others with lower retentions. This is in agreement with the findings of Maclean (34) and Mayfield (35).

At higher retentions, preservatives fill nearly all the voids in the treated layer at the surface of the specimen. When this layer is heated, there is insufficient room in these voids for preservatives to expand and this results in creosote exudation on the specimen surface.

Vapour-Phase Diffusion

The rate of longitudinal diffusion of chloropicrin, determined by the movement of vapour along the grain of the coated specimen to inhibit growth of actively growing fungi in the upper vial, varied from less than 2.4 cm per hour to 9.6 cm per hour (Table 9).

Differences in the rate of diffusion of chloropicrin vapour in the various species followed nearly the same pattern as the air permeability measurements. Other workers have observed a direct relationship between longitudinal air permeability and vapour diffusion (14, 20), indicating that these are probably influenced by the same anatomical characteristics.

The average rate of growth of fungus in control specimens, based on hyphal elongation, was about 2.5 mm per day.

The results after six weeks incubation (Figure 18) was identical for incubations in vials and petri dishes.

Table 9. Longitudinal Rate of Diffusion of Chloropicrin Vapour Through 10-cm Coated Specimens Compared to the Physical Properties of the Wood Species.

Local Name and Type of Species	Longitudinal Sink-float Test	Permeability Air Flow Measurement cm^3/cm atm sec	Porosity %	Rate of Diffusion cm/hour
Subaha				
Sapwood	P	111.2	54	≤ 2.4
Heartwood	P	51.8	53	2.5-4.8
Dahoma				
Sapwood	P	78.0	48	2.5-4.8
Heartwood	P	48.7	46	4.9-7.2
Kaku				
Sapwood	I	29.1	20	4.9-7.2
Heartwood	R	0.13	17	7.3-9.6
Sugar Maple				
Sapwood	P	107.8	50	≤ 2.4
Heartwood	P	33.1	48	2.5-4.8
Redwood				
Heartwood	I	7.7	70	≤ 2.4
Douglas-fir				
Sapwood	I	1.60	61	2.5-4.8
Heartwood	R	0.80	60	4.9-7.2
Ponderosa Pine				
Sapwood	I	2.25	70	≤ 2.4
Heartwood	R	0.08	69	7.3-9.6

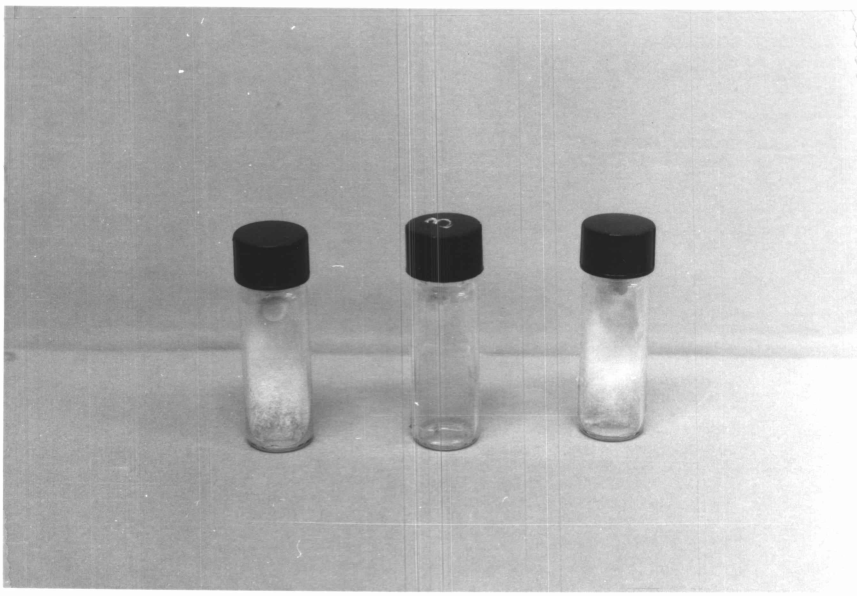


Figure 18. The results of incubation of <u>Poria</u> <u>monticola</u> fungus in a vial (middle) attached to a chloropicrin treated specimen and vials (left and right) attached to non-treated specimens after six-week incubation period.

Vapour Movement into Upper Vial

The movement of chloropicrin vapour to inhibit growth of fungus in upper vial may be divided into five phases:

(1) Release of vapour from the liquid chloropicrin in the lower vial.

(2) Free movement of vapour molecules in the direction of the vial opening to the lower end of the wood specimen.

(3) Diffusion of chloropicrin vapour lengthwise along the grain of the wood to the upper end of specimen.

(4) Free movement of vapour from the upper end of the specimen into the upper fungus vial.

(5) Absorption of vapours of chloropicrin by the fungal mycelium.

The vapour pressure of chloropicrin at 26^{o}C is about 2mm Hg. It is very volatile and easily releases vapours at this temperature. Initial release of vapours of chloropicrin must be the same in all vials attached to different species of wood since they were all exposed to the same test conditions. However, subsequent vapour release should be directly proportional to the vapour concentration gradient between the liquid surface and that just below the lower end of wood. Once release was accomplished, the vapour molecules moved unhindered to the lower end of the specimen where vapour concentration should vary depending on the diffusivity of the specimen.

At 12% moisture content, the diffusion of chloropicrin vapour through the softwood specimen should occur through the lumens and pits of tracheids, with greatest hindrance in pits. In hardwoods the vapour would move easily through vessel lumens unless the vessel was occluded with gum or tyloses. Once vapors had diffused to the upper end of the specimen, they again moved unhindered, but against gravity into the vial where they came in contact with the actively growing test fungus.

The cell wall of the test fungus, P. monticola, Basidiomycete, consists of loosely knitted chitinic and cellulosic fibrils so that vapors readily passed through (16). After passing through the cell wall, the vapours might have come in contact with the cytoplasmic membrane, where molecules of the vapour probably became attached to the numerous bonding sites of the membrane. The passage of fumigant vapours from the membrane into the protoplasm was achieved probably by either diffusion or active transport (16). In the protoplasm, they might have been transported by protoplasmic streaming and then carried by mitochondria and ribosomes to other active sites of the organelles, resulting in killing of the fungus.

Release of Vapours of Chloropicrin
at Various Test Conditions

In both hardwoods and softwoods, the rate of vapour release from the liquid chloropicrin at the three test conditions (Table 10) was directly related to the vapour diffusion rates in the species (Table 9). In hardwoods, release at 3 conditions was highest in Subaha, followed by Sugar maple and then Dahoma, all of which had the fast diffusion rates. The heartwood of Kaku gave the smallest release and slowest diffusion rate. In softwoods, Redwood released the highest volume of chloropicrin which corresponded to its fast diffusion, while Ponderosa pine heartwood with smallest release also recorded the longest time for diffusion. This shows that vapour release from the vial and the diffusivity of the specimen attached to the vial are interdependent.

The rate of release was highest in all species in the hot wet room (Temp. 32°C, R.H. 85%) which was 1.24 times more than release in the hot dry room (Temp. 32°C, R.H. 34%) and 1.48 times more than that of standard room (Temp. 26°C, R.H. 64%). This was also true for the exposed chloropicrin vials.

The different temperatures in the test rooms influenced the release of chloropicrin vapours. At higher room temperature, the temperature of the liquid chloropicrin also increases, which results in a greater number of vapour molecules escaping from the liquid chloropicrin due to increase in kinectic energy of the chloropicrin molecules. The explanation for the faster release of chloropicrin in the hot wet room compared to the hot dry room

Table 10. Release of Chloropicrin Vapour From Vials at Test Conditions.

Local Name of Species	Standard Temp 26°C RH 64% cm^3/day	Hot Dry Temp 32°C RH 34% cm^3/day	Hot Wet Temp 32°C RH 64% cm^3/day
Subaha			
Sapwood	0.076	0.090	0.100
Heartwood	0.064	0.076	0.096
Dahoma			
Sapwood	0.070	0.081	0.098
Heartwood	0.062	0.070	0.092
Kaku			
Sapwood	0.059	0.065	0.073
Heartwood	0.052	0.055	0.062
Sugar Maple			
Sapwood	0.072	0.082	0.10
Heartwood	0.067	0.071	0.095
Redwood			
Heartwood	0.080	0.105	0.128
Douglas-fir			
Sapwood	0.068	0.098	0.123
Heartwood	0.064	0.088	0.110
Ponderosa Pine			
Sapwood	0.080	0.093	0.125
Heartwood	0.058	0.066	0.079
Exposed Chloropicrin in vial	0.213	0.278	0.335

could be that the water molecules in the hot wet room would transfer heat to the chloropicrin in the vial when the water condensed on the vial.

Linear Regression Analyses

To test for the correlation between

(1) Air Permeability and Immediate Retention (Retention1)

(2) Air Permeability and Penetration Rating, and

(3) Air Permeability and Release of Vapours of Chloropicrin,

linear regression analyses were applied.

Correlation between Log of Air Permeability (Kg) and Immediate Retention or Penetration

The results of the regression analyses (Tables 11, 12) show show a higher coefficient of determination (r^2) compared to the findings of Choong (14). The reason is that values reported in this study were pooled averages of three specimens for each type of species, whereas Choong's values were for individual specimens. Similar findings have been reported by Siau (50) for various temperate hardwoods and softwoods.

A higher coefficient of determination and statistical significance were obtained for softwoods than for woods from Ghana indicating that air permeability predicts preservative retention and penetration

Table 11. Linear Regression Analyses Log of Air Permeability (K_g) and Immediate Retention of Copper Sulphate and Creosote Treated Samples.***

Combination	Regression Equation	r^2	F	Observation	
<u>Samples Treated with Copper Sulphate Preservative</u>					
Ghana Sapwood & Heartwood	$0.069 \text{ Log } K_g + 0.102$	0.46	3.45	18	N. S.
U. S. Sapwood & Heartwood	$0.041 \text{ Log } K_g + 0.256$	0.98	161.3	15	**
Ghana Sapwood	$0.290 \text{ Log } K_g + 0.311$	0.56	1.3	9	N. S.
Ghana Heartwood	$0.061 \text{ Log } K_g + 0.114$	0.62	1.67	9	N. S.
U. S. Heartwood	$0.137 \text{ Log } K_g + 0.220$	0.98	48.2	9	**
<u>Samples Treated with Creosote Preservative</u>					
Ghana Sapwood & Heartwood	$0.026 \text{ Log } K_g + 0.053$	0.58	5.56	18	*
U. S. Sapwood & Heart	$0.175 \text{ Log } K_g + 0.195$	0.93	57.2	15	**
Ghana Sapwood	$0.079 \text{ Log } K_g + 0.088$	0.55	1.22	9	N. S.
Ghana Heartwood	$0.033 \text{ Log } K_g + 0.062$	0.64	1.75	9	N. S.
U. S. Heartwood	$0.170 \text{ Log } K_g + 0.343$	0.95	18.9	9	**

N. S. Not statistically significant

*Significant at 5% level of probability.

**Significant at 1% level of probability.

***Sugar maple is not included in the regression analyses.

Table 12. Linear Regression Analyses of Log of Air Permeability (K_g) and Penetration of Copper Sulphate and Creosote Treated Samples. ***

Combination	Regression Equation	r^2	F	Observation
<u>Samples Treated with Copper Sulphate Preservative</u>				
Ghana Sapwood & Heartwood	0.083 Log K_g + 3.75	0.50	3.98	18 N.S.
U.S. Sapwood & Heartwood	1.80 Log K_g + 3.86	0.90	35.8	15 **
Ghana Sapwood	3.26 Log K_g - 1.96	0.71	2.45	9 N.S.
Ghana Heartwood	0.096 Log K_g + 3.72	0.73	2.70	9 N.S.
U.S. Heartwood	1.77 Log K_g + 3.80	0.93	15.4	9
<u>Samples Treated with Creosote Preservative</u>				
Ghana Sapwood & Heartwood	0.39 Log K_g + 1.39	0.42	2.9	18 N.S.
U.S. Sapwood & Heartwood	2.11 Log K_g + 2.81	0.90	37.7	15 **
Ghana Sapwood	1.80 Log K_g - 1.35	0.69	2.21	9 N.S.
Ghana Heartwood	0.233 Log K_g + 1.36	0.39	0.064	9 N.S.
U.S. Heartwood	2.04 Log K_g + 4.74	0.91	10.1	9 *

N. S. Not Statistically Significant.

*Significant at 5% level of probability.

**Significant at 1% level of probability.

***Sugar maple is not included in the regression analyses.

better in softwoods than the tropical Ghana hardwood species used in this study. The reason may be due to the homogenous structure of softwoods compared to the heterogenous type in hardwoods.

The coefficient of determination and statistical parameter (F) for samples treated with creosote and copper sulphate were nearly of the same magnitude. This shows that air permeability of wood can be used to predict penetration and retention of the copper sulphate and creosote preservatives in wood.

Correlation between Air Permeability and Release of Chloropicrin Vapours.

The results of the linear regression analyses applied to air permeability and release of chloropicrin vapour for various species groupings showed a very high statistical significance (Table 13). This result compared to that of impregnated samples showed that longitudinal air permeability is a better indicator of vapour-phase chloropicrin treatment than retention and penetration in samples treated with copper sulphate and creosote under pressure.

Table 13. Linear Regression Analyses of Log of Air Permeability (K_g) and Release of Chloropicrin Vapour.***

Combination	Regression Equation	r^2	F	Observation
Ghana Sapwood & Heartwood	$0.040 \text{ Log } K_g + 0.008$	0.75	12	18 *
U.S. Sapwood & Heartwood	$0.0082 \text{ Log } K_g + 0.063$	0.97	106	15 **
Ghana Sapwood	$0.040 \text{ Log } K_g + 0.008$	1.0	6212	9 **
Ghana Heartwood	$0.0082 \text{ Log } K_g + 0.063$	0.98	41	9 **
U.S. Heartwood	$0.018 \text{ Log } K_g + 0.088$	1.0	5904	9 **

*Significant at 5% level of probability.

**Significant at 1% level of probability.

***Sugar maple is not included in the regression analyses.

SUMMARY AND CONCLUSIONS

Classification of Treated Wood Samples

On the basis of the wood species response to pressure impregnation with creosote and copper sulphate solutions as well as vapour phase treatment with chloropicrin, the species used in this study may be classified as follows:

Pressure Impregnation

Group 1 Treatable

Hardwood

Sugar Maple Sapwood, *Acer saccharum*

Subana Sapwood, *Mitragyna stipulosa*

Subaha heartwood, *Mitragyna stipulosa*

Sugar maple heartwood, *Acer saccharum*

Softwood

Redwood heartwood, *Sequoia sempevirens*

Ponderosa pine sapwood, *Pinus ponderosa*

Douglas-fir sapwood, *Pseudotsuga menziesii*

Group 2 Intermediately Treatable

Hardwood

Dahoma sapwood, *Piptadeniastrum africanum*

Dahoma heartwood, *Piptadeniastrum africanum*

Kaku sapwood, *Lophira alata*

Softwood

Douglas-fir heartwood, *Pseudotsuga menziesii*

Group 3 Refractory

Hardwood

Kaku heartwood, *Lophira alata*

Softwood

Ponderosa pine heartwood, *Pinus ponderosa*

Vapour-Phase Treatment

Group 1 Very Diffusible

Hardwood

Subaha sapwood, *Mitragyna stipulosa*

Sugar maple sapwood, *Acer saccharum*

Softwood

Redwood heartwood, _Sequoia sempervirens_

Ponderosa pine sapwood, _Pinus ponderosa_

Group 2 Diffusible

Hardwood

Subaha heartwood, _Mitragyna stipulosa_

Sugar maple heartwood, _Acer saccharum_

Dahoma sapwood, _Piptadeniastrum africanum_

Softwood

Douglas-fir sapwood, _Pseudotsuga menziesii_

Group 3 Moderately Diffusible

Hardwood

Dahoma heartwood, _Piptadeniastrum africanum_

Kaku sapwood, _Lophira alata_

Softwood

Douglas-fir heartwood, _Pseudotsuga menziesii_

Group 4 Least Diffusible

Hardwood

Kaku heartwood, *Lophira alata*

Softwood

Ponderosa pine heartwood, *Pinus ponderosa*

Physical Properties

1. Permeability to air and liquid within the species of hard woods and softwoods were the only physical properties of the wood which were directly related to retention and penetration of copper sulphate and creosote preservatives in the wood samples. Permeability to air and liquid were also directly related to the rate of diffusion of chloropicrin vapour through the woods.
2. As an indicator of treatment of wood either with liquids under pressure or with vapour-phase diffusion, permeability of the wood to air had higher correlation coefficient with vapour-phase diffusion treatment than with liquid treatment under pressure.
3. The softwoods from the United States, inspite of their

lower permeability to air had better retention and penetration than selected hardwoods from Ghana, which had higher air permeability measurements. Permeability of wood to air also correlated better with preservative retention and penetration of selected woods from the United States than those from Ghana.

4. The effect of specific gravity or porosity on the preservative treatment of the wood species was not proportionally related, because the two properties were obscured by the variations and conditions of vessels, tracheids and resin canals in the wood species.

Anatomical Properties

1. All major cell types found in the selected wood species contributed towards the total retention of preservatives in the species, but the vessels of hardwoods and tracheids of softwoods were the most significant cell types.
2. Among the selected hardwoods, the number of vessels per cm^2 in the transverse section was directly related to the response of the woods to retention of copper sulphate and creosote, as well as the rate that chloropicrin vapour diffused lengthwise through the wood species.

3. Among the selected softwoods, the diameter of lumen of tracheids was directly related to the retention of copper sulphate and creosote in the wood species, as well as the rate that chloropicrin vapour diffused through the softwoods.

4. The diameter of the lumen of vessels was indirectly related to the retention and rate of chloropicrin diffusion, because gum inclusions in the vessels was an important factor to hinderance of fluid flow through the vessels. The influence of tyloses in vessels and tylosoids in resin canals was less significant.

5. For the same schedule of pressure treatment, better retention and penetration were found in samples treated with copper sulphate solution than samples treated with creosote. The higher viscosity of creosote appeared to be the influencing factor.

6. The loss of creosote by bleeding from treated samples and the loss of solvent by evaporation from samples treated with copper sulphate solution were directly related to the initial retention of preservatives in the wood.

RECOMMENDATION

The results of the preservative treatment indicate that the three wood species from Ghana respond quite favorable to the two treatment methods, and treated species may be utilized commercially if certain treatment factors are recognized.

The high preservative retention in the sapwood and heartwood of Subaha (Mitragyna stipulosa (De candole) O. Kuntze) will favor the response of the species to commercial treatment. The fast vapour diffusion rate will also favor the distribution of lethal concentration of chloropicrin vapour, if the chemical is used to control internal decay in the species. However, the high permeability of this wood may cause enough preservative loss by bleeding within relatively short period and this may probably reduce the service life of the treated wood, especially when exposed to the tropical rain forest regions of Ghana. This problem can be avoided if certain remedial measures are taken. For example, the empty cell process used with high preservative temperatures may reduce creosote loss by bleeding. Impregnation conditions may also be controlled so that retention and penetration in species may not be high enough to cause major bleeding. Mayfield (92) has suggested 35 ways of reducing bleeding of woods treated with creosote. Leaching of copper sulphate solution from wood may be reduced by lowering the surface-area-to volume ratio or by adding a fixing agent to the preservative prior to impregnation.

The intermediate treatability species of Dahoma (Piptadeniastrum africanum (Hook f) Brenan) as well as its moderate diffusivity to chloropicrin vapours, may present little or no major problem when treated species are utilized on a commercial scale.

The refractory nature of Kaku heartwood (Lophira alata (Banks) Gaertner) to pressure impregnation may be a problem if high retentions are required in their commercial utilization. However, if additional mechanical preparation is implemented before impregnating, the hearwood of Kaku may obtain optimum treating results. For example many refractory species respond well to treatment by pressure impregnation when their sawn or round surfaces are mechanically incised before impregnation (29). Further, since the sapwood of Kaku is of intermediate treatability, the refractory inner core hardwood may be protected by the surrounding sapwood in round wood form where the two remain intact. Of particular importance is the natural durability of Kaku heartwood (3), so that low retentions may be sufficient to eradicate any biological hazards which may be able to stand the toxicity of the heartwood extractives.

In order to obtain a uniform distribution of vapours of chloropicrin in both longitudinal and transverse directions of timbers, several treating hole patterns suggested by Cooper (20) can be bored over the surface of wood.

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