

UTILIZATION OF THE SOUTHERN PINES

PETER KOCH

Agriculture Handbook No. 420

In two volumes:

- I The Raw Material
- II Processing

U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE
Southern Forest Experiment Station

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The Author

Peter Koch is one of America's most eminent scientists in wood technology.

After gaining early experience in the design and manufacture of heavy-duty planers and matchers, he spent a year studying the effects of chip formation on cutterhead horsepower and quality of surfaces generated in peripheral milling. His Ph.D. thesis, accepted by the University of Washington in 1954, contained high-speed photos of chips forming under the action of knives and was basic to later work on the chipping headrig.

After 2 years of teaching and research at Michigan State University and 5 years of managing a New England lumber company, he wrote the book *Wood Machining Processes*.

For the past 9 years, he has been in charge of the Southern Forest Experiment Station's timber utilization laboratory at Pineville, in central Louisiana. Here, in 1963, he cooperated with two manufacturers of wood-working machines to construct three experimental versions of chipping headrigs. These headrigs square a log by converting the round sides into pulp chips without creating slabs or wasting material as sawdust. They are now in wide industrial use throughout North America and comprise one of the major wood-machining advances of the 20th century.

During 1964, when manufacture of southern pine plywood was in early stages of development, he provided data that were instrumental in the formulation of gluing practices for the industry. Next, he invented a system of gluing up single-species wooden beams by placing the most limber laminae in the center and the stiffest in the outer, most highly stressed regions. Beams thus assembled are stronger, stiffer, and more uniform than those made by conventional methods.

For these three developments Koch was awarded, in 1968, the Superior Service medal of the U.S. Department of Agriculture. He has received patents on the method of beam construction and on a system of making straight studs from southern pine veneer cores and boltwood. Patent application has been made on a process for drying southern pine studs in 24 hours under restraints that prevent warping.

Acknowledgments

In preparing a work of this scope, characterizing an important and variable resource in relation to its industrial use, an author receives essential assistance and services of many kinds. Especially significant contributions were made by the researchers who wrote the papers referred to in footnotes of many of the chapters. Most of these were prepared for the symposium "Utilization of the southern pines," presented by the Southern Forest Experiment Station and the Forest Products Research Society at Alexandria, La., November 6-8, 1968. Cooperating were the Louisiana Forestry Association, Southern Pine Association (now the Southern Forest Products Association), American Plywood Association, American Pulpwood Association, and American Wood Preservers' Association.

Special acknowledgment is due the more than 100 scientists who meticulously studied and criticized various chapters and sections.

I also wish to express my great appreciation for aid from within the Department of Agriculture. Indispensable knowledge and guidance were provided by the Forest Service's Division of Forest Products and Engineering Research and by the Forest Products Laboratory at Madison, Wis. The New Orleans office of the Southern Forest Experiment Station supplied unfailing support and counsel, including the most essential editorial and library services.

To members of the Forest Products Utilization Research Project at the Alexandria Forestry Center, Pineville, La., I owe particularly personal thanks. The scientists accelerated their research to fill many gaps in information, the technicians assisted them in ways that often went beyond the call of duty, and the administrative personnel efficiently handled infinite details of correspondence and text.

Since the book is a digest of research observations specific to the properties and utilization of the southern pines, a substantial effort was made to abstract, or to make reference to, all major work published prior to 1971. Some findings published or in process during 1971 were also included. Inevitably some worthwhile work has been overlooked; for such omissions, I apologize.

Peter Koch
Pineville, La.
January 1972

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Part I—BACKGROUND

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2	THE RESOURCE
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1

Introduction

The southern pines comprise the primary softwood timber species in the United States. Further, their relative importance is increasing. It is estimated that by the year 2000, 51 percent of the softwood used in this country will come from the South (USDA Forest Service 1965, p. 112).

These pines occupy about 20 percent of the 509 million acres of commercial forest land in the United States (USDA Forest Service 1965, pp. 76, 80, 146). In the opinion of many foresters, the bulk of the southern pine lands are capable of growing in excess of a cord of wood per acre annually.

The southern pineries furnish the raw material for about 15 percent of the softwood plywood manufactured in the United States (Anderson 1968; Hair and Ulrich 1969, p. 25), 23 percent of the particleboard (Suchsland 1968; Dougherty 1968), 25 percent of the softwood lumber (Hair and Ulrich 1969, pp. 15, 16), 36 percent of the fiberboard¹, almost 40 percent of the market dissolving pulp (Durso 1969), 41 percent of the groundwood pulp (Trevelyan 1969), a major share of the kraft pulp (Kleppe 1970), over 75 percent of the poles (Christopher 1969), and nearly 100 percent of the turpentine and rosin (King et al. 1962).

Some of the commodities are also important in international markets. In 1968 the kraft mills of the South produced approximately 25 percent of the total pulps and 45 percent of the kraft pulps required in the world; the southern pines provided wood for about 77 percent of this pulp (Christopher and Nelson 1963; Slatin 1967; Kleppe 1970). They additionally supply about one-half of the world's naval stores and three-fourths of the crude tall oil produced outside the Sino-Soviet bloc (King et al. 1962).

In the South—not including the mid-Atlantic or Central States of Delaware, Maryland, West Virginia, and Kentucky—the timber-based industry in 1958 employed about 1 million people and added over \$6

¹ Turner, H. D. Fiberboard, hardboard, and moulded fiber from southern pine wood—processes and products. Presentation at a symposium, "Utilization of the Southern Pines", Alexandria, La., November 6-8, 1968.

billion to the gross national product (Hair 1963, pp. 80 and 82). Economic importance of the industry is increasing. In 1969 it was estimated that through production and distribution of wood products the 12 Southern States contributed \$4 billion to the economy of the North, while adding \$10 billion to the economy of the South (Southern Forest Resource Analysis Committee 1969, p. 48).

There are good reasons why the southern pines are preeminent as a source of raw material for industry.

First, substantial volumes of timber are available now and the resource is rapidly renewable. The trees can be grown economically on a short rotation in pure stands over a broad range of sites throughout the South. Technologies for regenerating and managing the stands are highly developed.

Second, geography favors the growth, utilization, and marketing of the species. Mechanized harvesting and year-round woods operations are made possible by the mild climate and generally flat to rolling terrain. Most of the resource is within 2 or 3 miles of existing all-weather roads. Labor and land costs are competitive with those of other regions. Water is abundant. Nowhere is the growing region distant from primary markets.

Third, the wood itself has an unusual combination of desirable properties. Its strength is outstanding. It is a prime material for structural plywood. Its light color and the strength of its fiber adapt it for pulping by both chemical and mechanical processes. The self-pruning attribute of the major species permits clear lumber for millwork to be produced in quantity. Further, the form of the trees favors their broad acceptance for poles and piling. The permeability of the wood facilitates drying and preservative treatment.

The southern pines, then, are an important national resource. To further the efficient use of this resource is the ultimate purpose of this book.

The presentation encompasses two major objectives: characterization of the southern pine tree as raw material, and description of the processes by which it is converted to use. Information is mainly from three sources: literature on southern pine dating back to near the turn of the century; research within the last 8 years designed to fill obvious gaps in the literature; and reviews by authorities in their fields, of information specific to other species but extendable to southern pines.

The current dramatic expansion of the plywood, particleboard, and fiber industries of the South has brought a new generation of men into the region, many of whom have no prior experience with southern pine.

The book is addressed primarily to the oncoming generation of researchers and industrial managers in the southern pine industry. Foremen, superintendents, quality control personnel, wood procurement men, forest managers, extension workers, professors and students of wood technology should all find the handbook of value. The text is not a treatise

on techniques, such as saw filing, but rather is a presentation of facts which characterize the resource as raw material, and the factors controlling conversion processes.

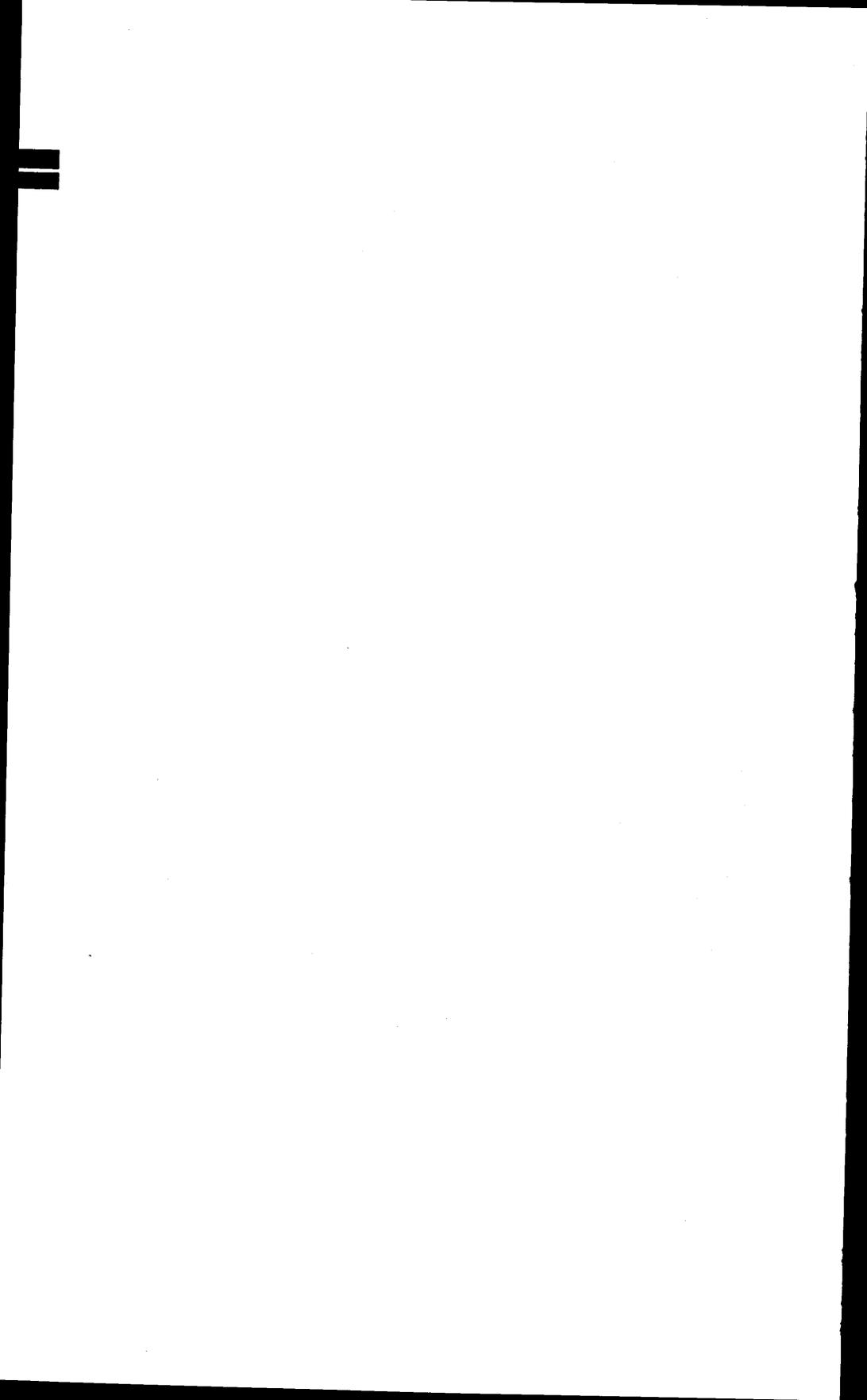
It will become evident to the reader that not all subjects are treated in equal depth. For example, an effort has been made to present the anatomy and ultrastructure of southern pine wood in some detail. By contrast, the chapter devoted to pulping processes is short; the technology of the pulp and paper industry is highly developed, and it is not possible to comprehensively digest this technology within the covers of a single book.

Some readers will perhaps question the pertinence of certain text content—the information on root systems of young trees and the life history of bark beetles, for example. Such data are included because the associated utilization problems are not yet solved; attainment of ultimate solutions will likely be accelerated through study of what now appears to be peripheral information.

Doubtless, many users of the handbook will desire additional information about particular phases of utilization. Hopefully, the references cited will assist those who wish to probe to greater depth.

LITERATURE CITED

- Anderson, W. C.
1968. Meeting competition for southern pine timber. *Forest Prod. J.* 18(8): 6-9.
- Christopher, J. F.
1969. Pole supply outlook. *Forest Farmer* 28(4): 6-7, 17.
- Christopher, J. F., and Nelson, M. E.
1963. Southern pulpwood production, 1962. USDA Forest Serv. Resource Bull. SO-1. 24 pp. Southern Forest Exp. Sta., New Orleans, La.
- Dougherty, R. E.
1968. Particle-board industry forges ahead toward new production record. *South. Lumberman* 217(2704): 145.
- Durso, D. F.
1969. Dissolving pulp from southern pine wood. *Forest Prod. J.* 19(8): 49-56.
- Hair, D.
1963. The economic importance of timber in the United States. USDA Misc. Pub. 941, 91 pp.
- Hair, D., and Ulrich, A. H.
1969. The demand and price situation for forest products, 1968-1969. USDA Misc. Pub. 1086, 74 pp.
- King, D. B., Wagner, H. B., and Goldsborough, G. H.
1962. The outlook for naval stores. 89 pp. USDA.
- Kleppe, P. J.
1970. The process of, and products from, kraft pulping of southern pine. *Forest Prod. J.* 20(5): 50-59.
- Slatin, B.
1967. The paper industry in the south: New directions in new mills. *Southern Pulp and Pap. Manufacturer* 30(10): 32-34, 36, 38, 40.
Southern Forest Resource Analysis Committee.
1969. The South's third forest . . . how it can meet future demands. 111 pp. New Orleans: South. Forest Resource Council.
- Suchsland, O.
1968. Particle-board from southern pine. *South. Lumberman* 217(2704): 139-144.
- Trevelyan, B. J.
1969. Mechanical pulping of southern pine wood. *Forest Prod. J.* 19(1): 29-38.
- USDA Forest Service.
1965. Timber trends in the United States. USDA Forest Resource Rep. 17, 235 pp.



2

The resource

For purposes of this text the southern pines are defined as those species whose major range is in the United States south of of the Mason-Dixon line (lat. 39°43' N.) and east of the Great Plains. Some of the species range considerably northward of this region, but all have at least 50 percent of their standing volume in the South. There are 10 species, all hard pines—diploxylon members of the genus *Pinus*, family Pinaceae, and order Coniferales. In addition, at least one species has two varieties and some species appear to contain races.

<u>Species or species and variety</u>	<u>Common name</u>
<i>Pinus palustris</i> Mill.	Longleaf pine
<i>P. elliotii</i> Engelm. var. <i>elliotii</i>	Slash pine
<i>P. elliotii</i> var. <i>densa</i> Little and Dorman	South Florida slash pine
<i>P. taeda</i> L.	Loblolly pine
<i>P. echinata</i> Mill.	Shortleaf pine
<i>P. glabra</i> Walt.	Spruce pine
<i>P. virginiana</i> Mill.	Virginia pine
<i>P. clausa</i> (Chapm.) Vasey	Sand pine
<i>P. rigida</i> Mill.	Pitch pine
<i>P. serotina</i> Michx.	Pond pine
<i>P. pungens</i> Lamb.	Table Mountain pine

All together, the southern pines occur on more than 100 million acres of commercial forest land, either in pure stands or as a sizable component of the species mixture.

According to the Forest Survey of the USDA Forest Service, the standing inventory of southern pine totals 64 billion cu. ft. (table 2-1). This is the net volume (from stump to a minimum 4.0-inch top diameter outside bark of the central stem) in growing stock trees 5.0 inches and larger in diameter at breast height. Included in the growing stock estimate is 227 billion bd. ft. (International 1/4-inch rule) in the saw log portion of pines at least 9.0 inches in d.b.h. (table 2-2).

The four principal southern pines—loblolly, shortleaf, longleaf, and slash—make up 90 percent of the total inventory. Of the 6 billion cu. ft. in the minor species, about half is Virginia pine. Pond, pitch, spruce,

TABLE 2-1.—*Volume of southern pine growing stock on commercial forest land by state and species (Sternitzke and Nelson 1970)*

State	Date of survey	All species	Loblolly pine	Short-leaf pine	Long-leaf pine	Slash pine	Viginia pine	Pond pine	Pitch pine	Spruce pine	Table-Mountain pine	Sand pine
<i>Million cubic feet</i>												
Alabama	1963	7,556.2	3,776.6	1,725.9	1,150.5	553.3	197.0	4.2		148.7		
Arkansas	1959	5,215.9	2,162.6	3,053.3								
Connecticut	1953	1.4							1.4			
Delaware	1957	230.3	178.4	3.1			48.8					
Florida	1959	3,243.0	354.1	6.6	1,260.9	1,417.2		92.2		30.7		81.3
Georgia	1961	9,109.5	3,549.1	1,585.4	1,169.0	2,402.2	159.5	179.9	29.1	33.2	2.1	
Illinois	1962	10.9		10.9								
Indiana	1967	31.9		11.0			20.9					
Kentucky	1963	436.9		208.7			186.0		42.2			
Louisiana	1964	5,456.1	3,759.7	1,035.3	374.0	198.7				88.4		
Maine	1959	27.8							27.8			

Maryland.....	1964	604.1	350.1	17.5	-----	-----	227.6	-----	8.9	-----	-----	-----
Massachusetts.....	1953	47.0	-----	-----	-----	-----	-----	-----	47.0	-----	-----	-----
Mississippi.....	1967	6,384.9	3,301.9	1,784.1	678.7	487.5	-----	-----	-----	132.7	-----	-----
Missouri.....	1959	276.8	-----	276.8	-----	-----	-----	-----	-----	-----	-----	-----
New Hampshire.....	1960	21.4	-----	-----	-----	-----	-----	-----	21.4	-----	-----	-----
New Jersey.....	1956	215.8	-----	14.1	-----	-----	54.9	-----	146.8	-----	-----	-----
New York.....	1950	57.8	-----	-----	-----	-----	-----	-----	57.8	-----	-----	-----
North Carolina.....	1964	7,313.5	4,091.5	1,380.9	344.1	-----	558.3	808.8	112.4	-----	17.5	-----
Ohio.....	1967	76.4	-----	19.4	-----	-----	51.1	-----	5.9	-----	-----	-----
Oklahoma.....	1966	749.6	58.7	690.9	-----	-----	-----	-----	-----	-----	.6	-----
Pennsylvania.....	1965	168.0	-----	.5	-----	-----	47.2	-----	119.7	-----	-----	-----
Rhode Island.....	1953	2.8	-----	-----	-----	-----	-----	-----	2.8	-----	-----	-----
South Carolina.....	1968	5,583.6	3,367.8	786.9	654.2	214.4	128.1	394.3	5.5	30.0	2.4	-----
Tennessee.....	1961	917.6	37.7	458.2	-----	-----	349.9	-----	63.4	-----	8.4	-----
Texas.....	1965	6,364.2	3,925.6	2,206.0	193.1	39.5	-----	-----	-----	-----	-----	-----
Virginia.....	1966	3,941.5	1,788.1	755.3	-----	-----	1,135.6	11.5	203.2	-----	47.8	-----
West Virginia.....	1961	312.0	-----	62.8	-----	-----	126.6	-----	81.1	-----	41.5	-----
All States.....		64,356.9	30,701.9	16,093.6	5,824.5	5,312.8	3,291.5	1,490.9	976.4	463.7	120.3	81.3

TABLE 2-2.—Volume of southern pine sawtimber on commercial forest land by state and species¹

State	Date of survey	All species	Loblolly pine	Shortleaf pine	Longleaf pine	Slash pine	Virginia pine	Pond pine	Pitch pine	Spruce pine	Table-Mountain pine	Sand pine
<i>Million board feet</i>												
Alabama	1963	27,847.1	14,954.2	5,247.9	4,369.2	2,161.1	421.9	17.6		675.2		
Arkansas	1959	23,320.2	10,686.0	12,634.2								
Connecticut	1953	.5							0.5			
Delaware	1957	593.1	459.4	8.0			125.7					
Florida	1959	10,273.7	1,388.2	21.0	3,960.4	4,432.2		268.0		119.8		84.1
Georgia	1961	26,345.2	10,707.6	3,745.2	3,717.5	7,124.6	255.7	578.5	100.0	107.7	8.4	
Illinois	1962	5.7		5.7								
Indiana	1967	58.6		10.0			48.6					
Kentucky	1963	1,427.1		698.1			594.2		134.8			
Louisiana	1964	25,020.8	17,923.8	4,392.1	1,659.7	611.1				434.1		
Maine	1959	41.9							41.9			

Maryland.....	1964	1,469.9	901.5	45.1	-----	-----	503.6	-----	19.7	-----	-----	-----
Massachusetts...	1953	36.0	-----	-----	-----	-----	-----	-----	36.0	-----	-----	-----
Mississippi.....	1967	24,628.8	13,747.2	5,897.3	2,691.4	1,673.6	-----	-----	-----	619.3	-----	-----
Missouri.....	1959	702.0	-----	702.0	-----	-----	-----	-----	-----	-----	-----	-----
New Hampshire..	1960	25.3	-----	-----	-----	-----	-----	-----	25.3	-----	-----	-----
New Jersey.....	1956	363.5	-----	23.8	-----	-----	92.8	-----	246.9	-----	-----	-----
New York.....	1950	95.0	-----	-----	-----	-----	-----	-----	95.0	-----	-----	-----
North Carolina..	1964	23,491.5	15,561.2	3,309.1	919.6	-----	977.0	2,361.1	309.6	-----	53.9	-----
Ohio.....	1967	211.3	-----	21.8	-----	-----	167.7	-----	21.8	-----	-----	-----
Oklahoma.....	1966	2,498.1	274.1	2,224.0	-----	-----	-----	-----	-----	-----	-----	-----
Pennsylvania....	1965	334.9	-----	1.2	-----	-----	54.4	-----	277.9	-----	1.4	-----
Rhode Island....	1953	2.6	-----	-----	-----	-----	-----	-----	2.6	-----	-----	-----
South Carolina..	1968	17,686.1	11,543.1	1,810.6	2,285.2	400.9	244.7	1,288.3	12.6	92.9	7.8	-----
Tennessee.....	1961	2,765.7	45.7	1,440.3	-----	-----	1,008.7	-----	244.7	-----	26.3	-----
Texas.....	1965	25,868.0	16,818.4	8,144.0	864.8	40.8	-----	-----	-----	-----	-----	-----
Virginia.....	1966	10,592.9	6,234.9	1,729.0	-----	-----	1,818.4	46.8	630.9	-----	132.9	-----
West Virginia...	1961	841.0	-----	120.0	-----	-----	366.3	-----	234.6	-----	120.1	-----
All states.....		226,546.5	121,245.3	52,230.4	20,467.8	16,444.3	6,679.7	4,560.3	2,434.8	2,049.0	350.8	84.1

¹ Nelson, T. C. Southern pine resources. Keynote address at a symposium "Utilization of the southern pines," Alexandria, La. November 6-8, 1968.

Table-Mountain, and sand pines make up the rest. Although some of the minor species have economic significance with reference to a given locality or wood-using establishment, none are regionally important. Ranges and relative concentrations of each species are depicted on maps in chapter 3.

The southern pine resource is generally considered to have been at low ebb in the early 1930's, when most of the old growth had been harvested and many of the second-growth stands had been high-graded for sawtimber or cut for pulpwood (Mann 1969). Though some efforts at regeneration had been started in the 1920's, they were largely stifled by the Great Depression. At the end of World War II, however, the situation began to improve. By then there had developed a broad awareness that the forests could be restored to their former productivity, forest industry seemed ready to expand, and large landowners had accumulated capital to invest in development of lands. From 1947 to 1967 about 14 million acres were planted and seeded to pines (Southern Forest Resource Analysis Committee 1969, p. 85); and existing stands on additional millions of acres were improved by a variety of managerial techniques.

Increased growth brought about by better management, in conjunction with a fairly stable cut, built up the South's growing stock and hence considerably increased annual growth. Further improvements can be anticipated. In 1965, the annual growth potential of the southern pines was estimated at 5.5 billion cu. ft. for 1980, but only 4.8 billion cu. ft. for 2000 due to a reduced land base (USDA Forest Service 1965, p. 126).

Demand is expected to rise—proportionately more in the South than elsewhere in the Nation. By the year 2000, it is estimated that demand for southern pine will be about 8.8 billion cu. ft. (Southern Resource Analysis Committee 1969); this is approximately triple the 1962 harvest.

The difference between the projected growth potential in the year 2000 (4.8 billion cu. ft.) and the projected demand (8.8 billion cu. ft.) is one of the primary reasons why this book was written. Management practices will doubtless be improved so that growth potential will ultimately surpass that projected in 1965; it is evident, however, that an increased fraction of each tree must be utilized in the future if the gap between demand and growth is to be closed.

LITERATURE CITED

- Mann, W. F.
1969. Techniques and progress in regenerating southern pines. *Forest Prod. J.* 19(8): 10-16.
- Southern Forest Resource Analysis Committee.
1969. The South's third forest . . . how it can meet future demands. 111 pp. New Orleans: South. Forest Resource Council.
- Sternitzke, H. S., and Nelson, T. C.
1970. The southern pines of the United States. *Econ. Bot.* 24: 142-150.
- USDA Forest Service.
1965. Silvics of forest trees of the United States. *USDA Agr. Handbook* 271, 762 pp.

3

Species

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3

Species

3-1 DESCRIPTION AND RANGE

Growth characteristics, range, and volume of the species strongly influence utilization, and brief descriptions therefore seem appropriate. Except for Table-Mountain and spruce pines, the descriptions that follow are condensed from *Silvics of Forest Trees of the United States*, a work that should be consulted if fuller information is desired (USDA Forest Service 1965).

The ranges and relative concentrations of each species are mapped. The cubic volumes indicated on the maps are from studies by the Forest Survey of the USDA Forest Service (Sternitzke and Nelson 1970). The lines depicting natural limits are from Critchfield and Little (1966). In a few instances, timber volumes have been recorded beyond the mapped natural limits of a given species. Some of this volume accrues from naturally occurring trees, some from plantations.

The descriptions are in alphabetical order by common names of the species.

LOBLOLLY PINE (*Pinus taeda* L.)

Because of its wide range, its occurrence in pure stands, and its abundance, loblolly pine is the principal commercial pine species in the Southeastern United States. It accounts for nearly half of the total southern pine inventory. Except in Florida, where slash pine prevails, it is the dominant pine species in each of the Atlantic and Gulf Coastal States south of New Jersey. It does not occur in the Mississippi River bottoms, and is scarce on the deep, coarse sands of the Lower Gulf Coastal Plain and the sandhills of North and South Carolina (fig. 3-1). It grows at sea level and reaches elevations above 2,000 feet in northern Alabama and Georgia. Rainfall in the loblolly pine range averages 40 to 60 inches. Temperature ranges from -10° to over 100° F.

The trees grow best on soil with poor surface drainage, a deep surface layer, and a firm subsoil. Height growth begins about March 1 in the Gulf States and about 6 weeks later near the North Carolina-Virginia border. Growth is usually 80 percent complete by July 1 in all parts of the range.

Vigorous seedlings make several surges of height growth, normally three, during the growing season; the first is the longest and the last is

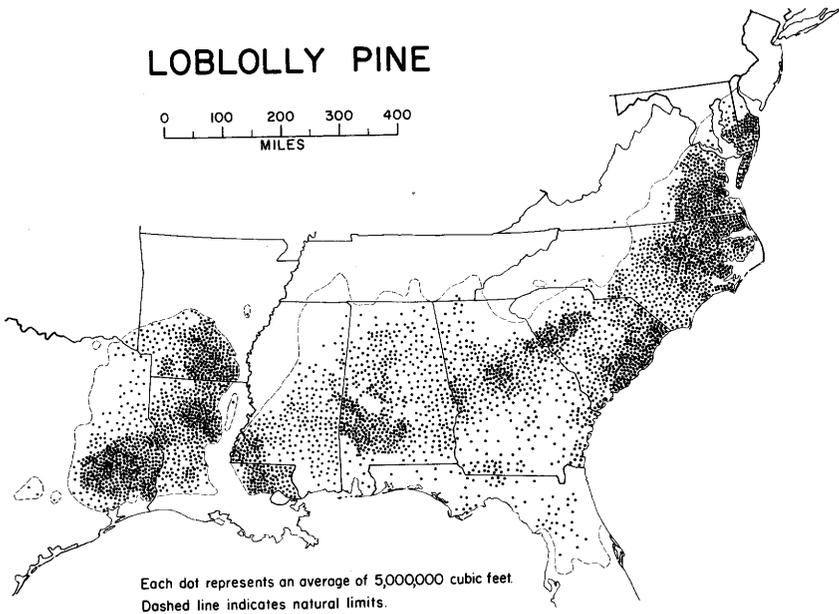


Figure 3-1.—The range and volume of loblolly pine. (Drawing after Sternitzke and Nelson 1970.)

usually very short. When 1- to 3-year-old seedlings are decapitated or injured, they sprout readily from buds formed in the axils of primary needles. Older trees do not sprout.

Loblolly stocks from different geographic sources, when planted together in one locality, differ significantly in survival, growth, and susceptibility to southern fusiform rust (Wakely 1944; Wakely and Bercaw 1965). In one large study, loblolly pines from 15 geographic seed sources, grown in 13 widely separated areas from Maryland to Texas, displayed well-defined patterns of variations after the first 10 years. In practically all plantings trees of western origin survived best. In all but the coldest locations trees from coastal areas grew fastest. Trees from western sources and from the one source farthest to the northwest were consistently least infected with fusiform rust (Wells and Wakeley 1966).

Individual trees may attain diameters of 50 to 60 inches and heights of 150 feet at advanced ages. Sizes attained by average dominants in well-stocked, unmanaged natural stands are shown in table 3-1. Trees in managed stands would be considerably larger in d.b.h. at the same ages. Loblolly pine prunes itself readily before branches develop heartwood (fig. 3-2).

In a sample of the entire range of the species a maximum mean annual growth rate was indicated to be 1,300 bd. ft. per acre (International $\frac{1}{8}$ -inch rule) in trees 6.6 inches d.b.h. and larger at 45 years, the age of culmination of mean annual increments for stands of 120-foot site index.

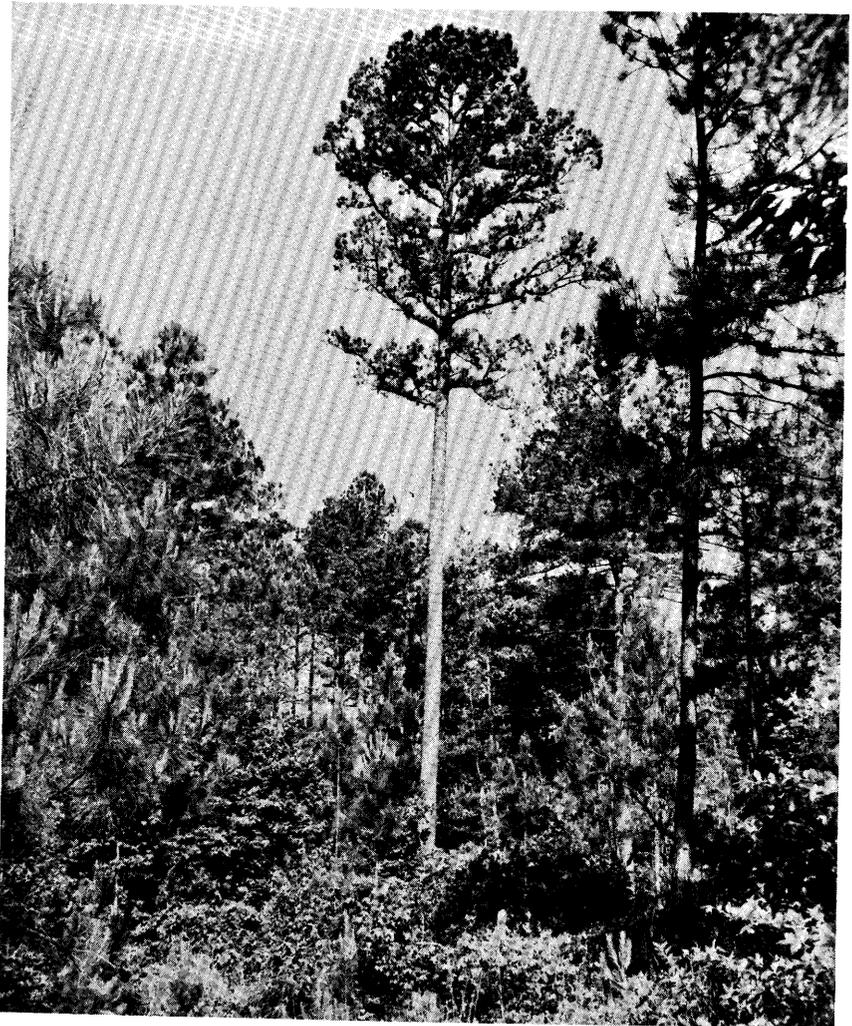


Figure 3-2.—A 24-inch loblolly pine with three clear logs.

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TABLE 3-1.—Average size of loblolly pine dominants in well-stocked, unmanaged natural stands

Age (years)	Site index 60 feet		Site index 90 feet		Site index 120 feet	
	D.b.h.	Height	D.b.h.	Height	D.b.h.	Height
	<i>Inches</i>	<i>Feet</i>	<i>Inches</i>	<i>Feet</i>	<i>Inches</i>	<i>Feet</i>
20	4.6	32	6.9	48	8.5	64
30	6.6	45	9.6	67	11.9	89
40	8.1	54	11.7	81	14.6	108
50	9.4	60	13.6	90	16.8	120
60	10.4	64	15.0	96	18.6	128

(Site index, as used here, refers to the expectable height of dominant trees at age 50 years.) On 60-foot sites the maximum rate was 318 bd. ft. per acre per year. Data from permanent sample plots in the Atlantic Coast States indicated a possible current annual growth rate of 1,500 to 2,000 bd. ft. per acre (International $\frac{1}{4}$ -inch rule) in trees 9.6 inches d.b.h. and larger on the very best sites at age 55. Yields at 60 years in trees 6.6 inches d.b.h. and larger range from 19,000 bd. ft. per acre (International $\frac{1}{8}$ -inch rule) in well-stocked stands on 60-foot sites to 73,000 bd. ft. per acre on 120-foot sites.

Mean annual growth per acre in trees 1.6 inches d.b.h. and larger ranges from 76 cu. ft. at 35 years (culmination of mean annual increment) on a 60-foot site to 204 cu. ft. on a 120-foot site. Yields at 60 years in well-stocked stands vary from 2,400 cu. ft. per acre on the poorest sites to nearly 12,000 cu. ft. on the best sites. Well-stocked stands range from 118.7 sq. ft. of basal area per acre for trees 4 inches in d.b.h. up to 175.4 sq. ft. for trees 16 inches d.b.h. In Arkansas, well-stocked stands tended toward a basal area of 155 sq. ft. per acre. (Basal area is defined as the summation of cross-sectional areas of stumps if trees are cut $4\frac{1}{2}$ feet from the ground.)

In southeastern Arkansas the average annual growth of uneven-aged stands on 85-foot sites ranged from 371 bd. ft. per acre for residual stands of 2,610 bd. ft. to 405 bd. ft. in stands of 5,225 bd. ft. (International $\frac{1}{4}$ -inch). In terms of cubic feet per acre per year, the growth was 68 cu. ft. for stands of 721 cu. ft. and 76 cu. ft. for stands of 1,260 cu. ft.

LONGLEAF PINE (*Pinus palustris* Mill.)

Longleaf is the third most abundant of the southern pines, ranking after loblolly and shortleaf. It is found from the southeastern part of Virginia to central Florida and west into southeastern Texas; about three-fifths of the inventory is in Alabama, Georgia, and Florida. The main belt seldom extends over 150 miles from the coast except in the Appalachian foothills of northern Alabama and Georgia (fig. 3-3). Although it is found at nearly 2,000 feet in northern Alabama, longleaf usually grows at low altitude.

Average annual temperature in the longleaf range is between 60° and 70° F. The winter average is over 45° F. and the summer average above 75° F. The frost-free period is about 200 days in the northern part of the range and 300 days in the southern part. Annual precipitation exceeds 50 inches in much of this range and nowhere falls below 40 inches.

Longleaf pine grows most often on soils that are low in organic matter, light-colored, sandy in the surface portion, medium to strongly acid, and well to excessively drained—the sandhills of the Carolinas, Georgia, and Florida are examples. Along the coast, however, longleaf is found on flatlands characterized by mottled subsoils or hardpans indicative of poor

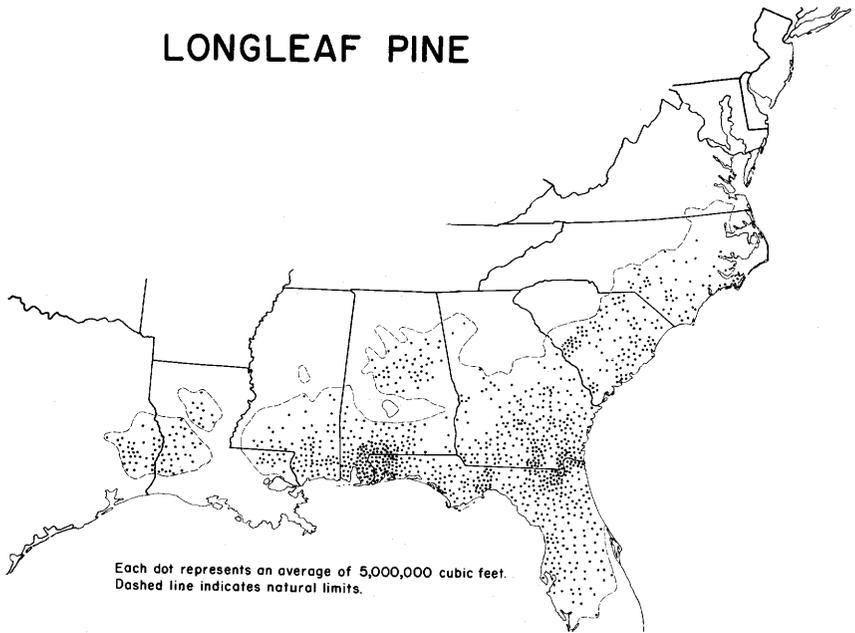


Figure 3-3.—The range and volume of longleaf pine. (Drawing after Sternitzke and Nelson 1970.)

internal drainage and aeration. These soils also are medium to acid in reaction and most are low in organic matter.

Seedlings remain in a "grass stage" for 3 years or longer, growing very little in height until they attain a groundline diameter approaching 1 inch. Then they most frequently elongate 4 to 6 inches in the first spurt, and subsequently grow from 1 to 3 feet per year. Height growth begins during late March in the Gulf States and about two weeks later in North Carolina. It is usually complete by July 1. In the Gulf States, diameter growth is usually about 90-percent complete by October 1. Longleaf pine does not reproduce naturally by sprouts. Cuttings can be rooted, but not easily.

Longleaf exhibits considerable geographic variation. Seedlings from western sources appear to be above average in drought-hardiness; their resistance to the brown-spot needle disease, however, is below average (Henry and Wells 1967). Stock from the central Gulf Coast (southern Mississippi, southern Alabama, and western Florida) has outgrown stock from more western and northern sources in plantings 150 miles north and 250 miles east or west of the central Gulf Coast source (Wells and Wakeley 1970).

While longleaf pine is one of the finest timber trees, it is not a large tree, nor does it produce large volumes per acre. The largest living longleaf is 41 inches in diameter and 113 feet high. The old-growth stands, averaging less than 15,000 bd. ft. per acre, were irregularly stocked with



520 909

Figure 3-4.—Typically straight longleaf stems in a 45-year-old stand of poletimber near Gulfport, Miss. Average d.b.h., 11 inches.

trees that were rarely over 31 inches in diameter. The tree is notable for straightness of bole (fig. 3-4), which makes it a desirable pole species.

Measurements in south Mississippi showed that well-stocked, second-growth longleaf forests can be managed to produce more wood in 80 years than the original stands did in two centuries. Though the stands were burned by wildfire at least twice after the seedling stage, growth has been excellent (table 3-2). Longleaf is exceptionally fire-resistant after it reaches a height of $\frac{1}{2}$ to 3 feet. In dense stands on good sites natural pruning begins at 10 years of age.

Longleaf pine is a source of naval stores. Stands managed for these products are thinned earlier and more heavily than those managed exclusively for timber. Working the trees for naval stores slows their growth.

PITCH PINE (*Pinus rigida* Mill.)

Pitch pine grows over a wide range from Ontario to northern Georgia and western South Carolina (fig. 3-5). More than half of the standing inventory, and more than two-thirds of the sawtimber, is south of the

TABLE 3-2.—*Size and yield per acre of second-growth longleaf pine in south Mississippi (USDA Forest Service 1965, p. 387)*

Age (years)	Trees 4 inches and over, d.b.h.					Volume in trees 9 inches and over in d.b.h.
	Trees per acre	Height ¹	D.b.h.	Basal area	Volume	
	<i>Number</i>	<i>Feet</i>	<i>Inches</i>	<i>Square feet</i>	<i>Rough cords</i>	<i>Board feet³</i>
13	133	25	4.2	13	1.2	
18	251	33	4.9	33	4.4	
23	346	44	5.7	61	11.7	
28	386	53	6.3	84	20.7	
37	383	68	7.4	116	38.6	8,470
42	² 347	73	8.8	² 118	² 43.8	² 11,990

¹ Heights of dominants and codominants.

² Includes material removed in thinnings at age 37 to 42 years.

³ International rule, $\frac{1}{4}$ -inch kerf.

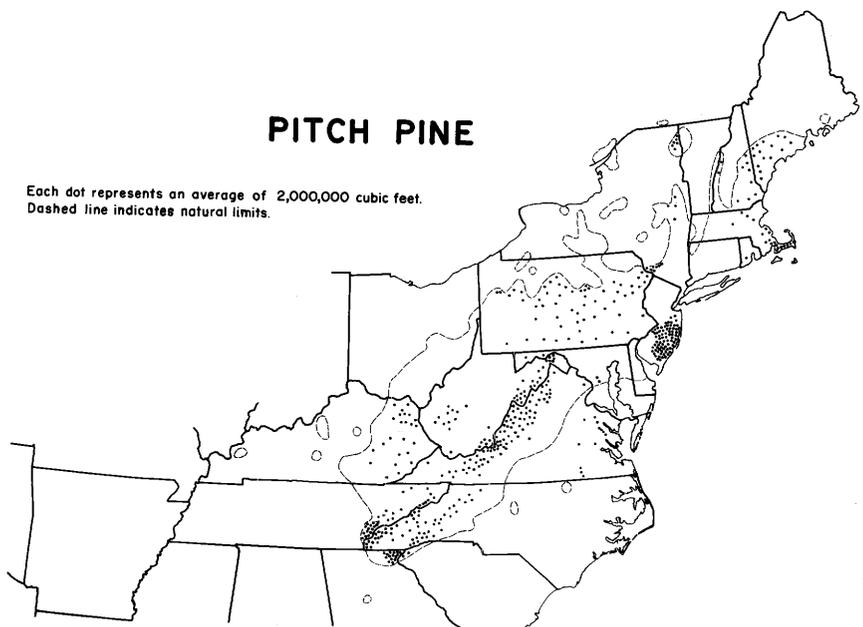


Figure 3-5.—The range and volume of pitch pine. (Drawing after Sternitzke and Nelson 1970.)

Mason-Dixon line. In the Northern States the most notable concentration is in the Pine Barrens of southern New Jersey. The climate in the range of pitch pine is humid. Average annual precipitation is usually between 37 and 56 inches, and is well distributed throughout the year. The frost-free season varies from 112 to 190 days and the temperatures range from winter lows of -40° F. in the North to summer highs of 100° in most sections.

Pitch pine is usually restricted to the less fertile acid soils—those of shallow depth, or of sandy or gravelly texture. It grows in a wide variety of moisture conditions from excessively drained sands and gravels to poorly drained swamps. In New England pitch pine is most common near sea level, but in the Great Smoky Mountains it is found at elevations between 1,400 and 4,500 feet. In hilly sections it often occupies the warmer and drier sites, i.e., those facing south or west.

Height growth begins about mid-April in the southern and 2 to 3 weeks later in the northern part of the range. By late June, height growth is about 80-percent complete in the middle range. While some trees bear cones that remain closed for many years (often until the heat of a fire opens them or until the trees are cut), others have cones that open soon after maturity.

Pitch pine is outstanding in its ability to survive injury. After defoliating fires, new needles may form from buds and cambium protected by the thick bark. A new terminal often develops when the old one is killed back as much as 3 feet. If the entire stem is killed, sprouts frequently start from dormant buds at the base. Both pitch and shortleaf pines have these buds along the bole to an age of 60 years or more, but only in pitch pine do the buds at the base retain the potential for growth to advanced ages.

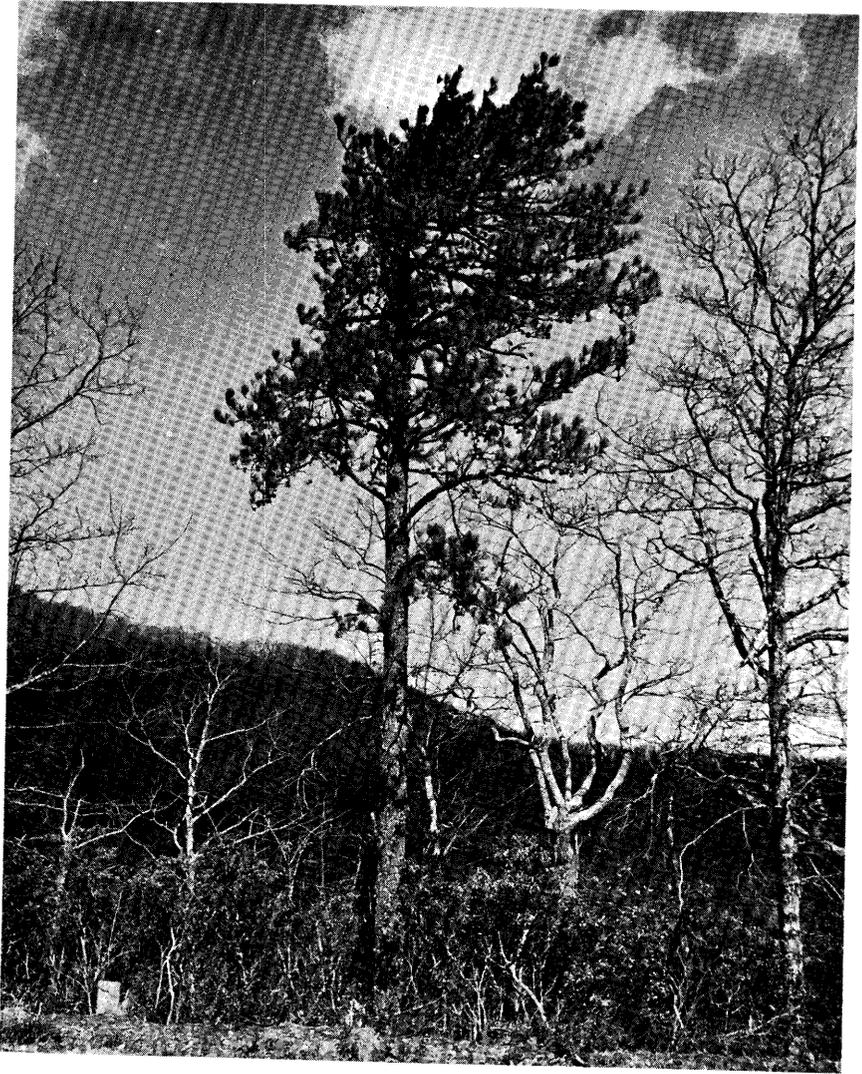
Pitch pine trees root deeply and are relatively windfirm.

Pitch pine reaches a maximum age of 200 years and a maximum height of 100 feet in Pennsylvania. In stands it is seldom more than 80 feet tall or 2 feet in diameter.

On the better sites in Pennsylvania, pitch pine maintains an average height growth of a foot or more annually until the trees are 50 to 60 years old. The rate then starts to decline, and the trees add little to their height after they are 90 to 100 years old. On the best sites, diameter growth is most rapid (1 inch in 5 years) at 20 years of age, falling to an inch in 8 years at 90 years.

Total cubic volume is at its maximum in Pennsylvania at 90 years; at this age fully stocked even-aged stands yield 15,000 to 25,000 bd. ft. per acre. Mean annual growth reaches its maximum at about 30 years—43 to 83 cu. ft., depending on the site.

In closed stands of seedling origin undamaged by fire, pitch pine self-prunes about as well as shortleaf pine, but in understocked stands its branches are larger and more persistent. In typical understocked, fire-damaged pitch pine stands, spreading tops and persistent lower branches



520 910
Figure 3-6.—Seventy-five-year-old pitch pine measuring 16.2 inches d.b.h. growing on Brasstown Bald Mountain near Blairsville in northern Georgia. Flattened tops, persistent branches, and rough-appearing stems are characteristic of trees commonly found in understocked stands. (Photo from Saucier and Clark 1970.)

(often sprouts from dormant buds) contribute to the rough appearance usually associated with the species (fig. 3-6).

Even without the stimulus of fire, pitch pines released by heavy cutting may develop branches along the bole. Pruning of living branches also may have the same effect. The species can be best maintained in stands by even-aged management.

POND PINE (*Pinus serotina* Michx.)

Pond pine ranges over the Coastal Plain, principally from Virginia to northern Florida. Some four-fifths of the entire inventory is in North and South Carolina (fig. 3-7). Over the range the frost-free season varies from 190 to 347 days. Rainfall averages 45 to 55 inches annually but exceeds 60 inches in western Florida. Nearly twice as much rain falls from June through August as in any other 3-month period.

The greatest concentration of pond pine is in North Carolina, where pure stands occur on upland bogs called pocosins. Further south, stands are frequently found in certain poorly drained depressions, i.e., "Carolina bays," "ridge bays," and wet flatwoods.

The cones are generally (but not always) serotinous. On the tree they open gradually over several years—usually in less than five. Fire or felling of the tree causes the serotinous cones to open.

Pond pine sprouts readily, even at advanced ages, and stands up to sapling size are reestablished by sprouting after light fires. As with pitch pine, stem sprouting is a primary reason for low quality in pond pine which has been burned frequently.

Height growth begins not later than March 1 in Florida and about a month later in North Carolina. Diameter growth is usually 80-percent complete by August 1 in all parts of the range.

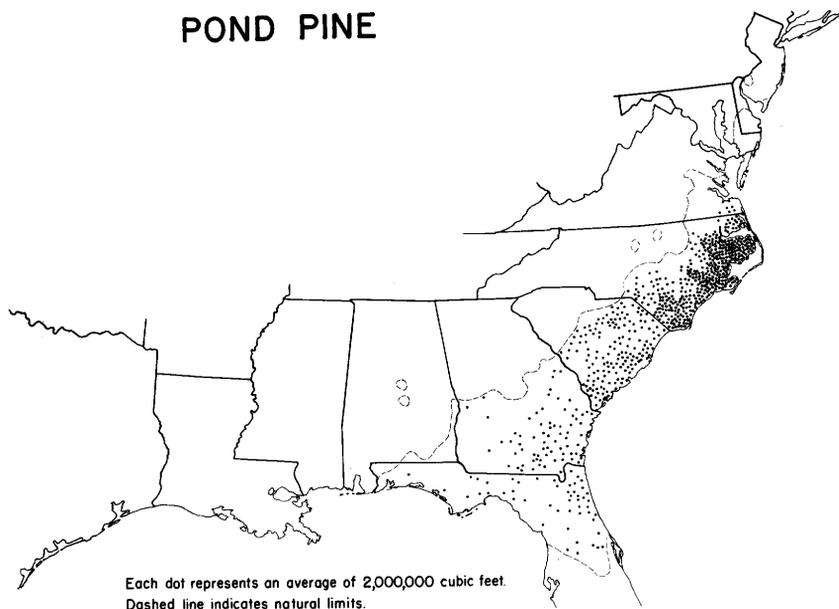
POND PINE

Figure 3-7.—The range and volume of pond pine. (Drawing after Sternitzke and Nelson 1970.)

Pond pine normally does not grow to large size on the heavily organic soil of pocosins, and its growth is retarded by frequent fires. Average sizes attained in a pocosin in North Carolina were as follows:

<u>Age</u>	<u>Height</u>	<u>D.b.h.</u>
<i>Years</i>	<i>Feet</i>	<i>Inches</i>
20	28	5.8
50	49	10.4
100	66	13.8

Pocosin stands seldom contain more than 5,000 bd. ft. per acre, and tree form and quality tend to be poor. Site quality in pocosins can often be increased by drainage, which also improves logging conditions. Stands of greater volume, good vigor, and good form develop on mineral soils of heavier texture and good internal drainage. Pond pine also grows faster in the southern part of its range (fig. 3-8).

Over the range of the species, yields of 55-year-old stands vary from 6 standard cords per acre on 40-foot sites to 45 cords on 90-foot sites.

SAND PINE (*Pinus clausa* (Chapm.) Vasey)

Sand pine is the least abundant of the southern pines (fig. 3-9). Except for Baldwin County, Ala., its natural range is entirely within Florida. The most extensive stand is on the Ocala National Forest in north-central Florida. Many of Florida's offshore islands support sparse stands.

Sand pine grows on light, sandy, fine-textured, well-drained soils that are infertile and slightly acid. The sand pine of western Florida grows on shallow littoral deposits. Elevations are less than 200 feet.

Two races, or varieties, of sand pine are recognized. The Ocala race of north-central Florida grows in dense, even-aged, pure stands which originated as a direct result of fire. It is characterized by serotinous cones that remain tightly closed for many years unless opened by fire. By contrast, the Choctawhatchee race¹ of west Florida frequently occurs in uneven-aged stands and often invades oak land. This stand difference probably occurs because most of the cones open readily.

Seedlings usually make two growth spurts each year; the first in March and April and the second in late summer, usually September. Height growth varies considerably but may be as much as 24 inches annually.

Although an occasional tree on better sites will grow to a diameter of 26 inches and a height of 75 feet, smaller sizes are more common. For this reason, and because the form is usually poor, most of the trees are cut for pulpwood for kraft mills (fig. 3-10).

Stands tend to break up after they reach 50 or 60 years of age. On

¹D. B. Ward (1963) proposes that this is a variety rather than a race. He calls it var. *immuginata*.

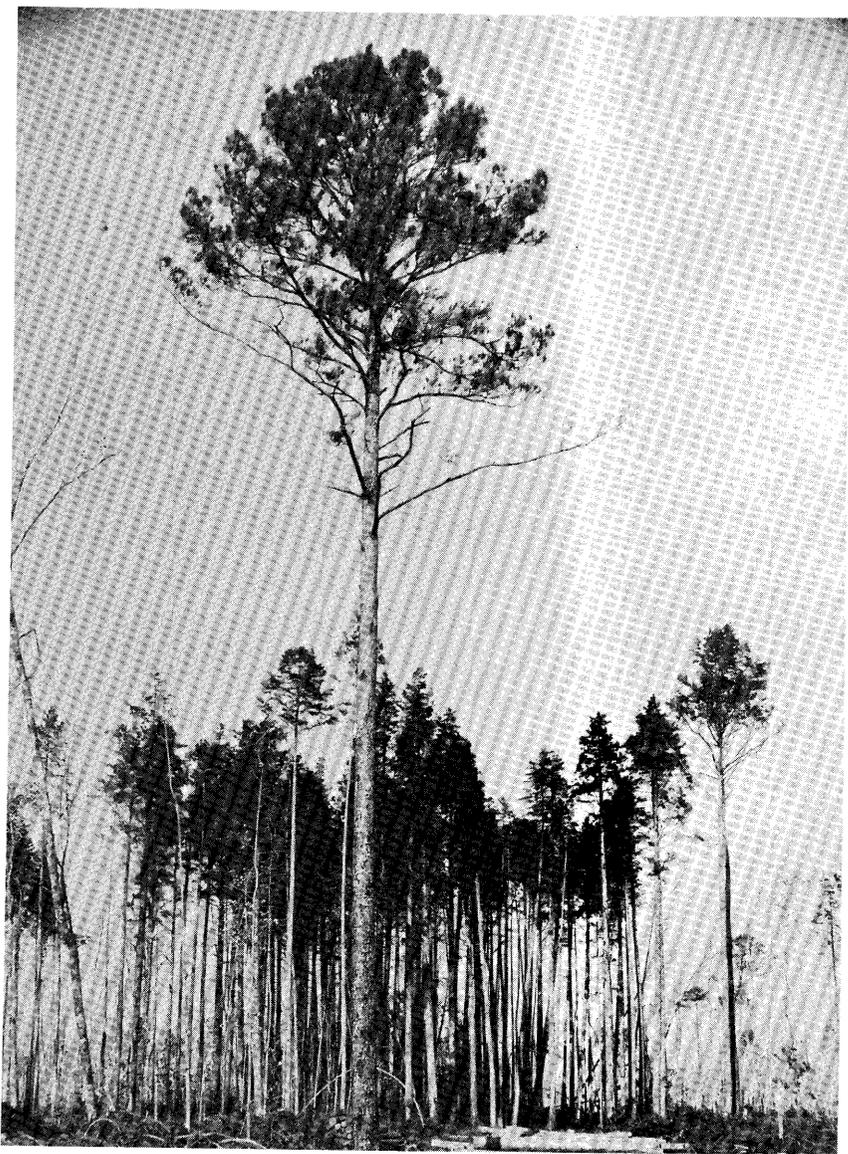


Figure 3-8.—Pond pine near edge of white-cedar cutting.

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the best sites, trees of this age should average 16 to 18 inches in diameter and 70 feet in height. On average sites, trees will be about 12 to 13 inches in diameter and 60 feet in height; on poor sites, 8 to 10 inches and 50 feet. Rotation age in well-stocked natural stands is considered to be 40 to 45 years, and at this age yields of 20, 15, and 10 cords per acre are predicted for high, average, and poor sites. Yields from plantations will probably exceed these values.

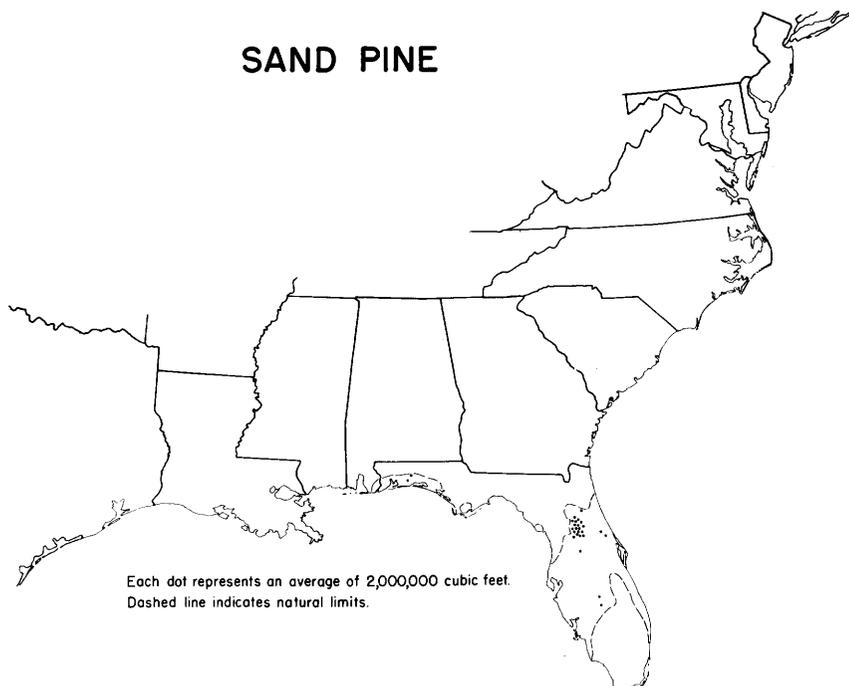


Figure 3-9.—The range and volume of sand pine—Choctawhatchee in western Florida, Ocala in central Florida. (Drawing after Sternitzke and Nelson 1970.)



Figure 3-10.—Dense stand of 35- to 40-year-old Ocala sand pine on an average site in north-central Florida.

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Sand pine trees often develop a lean from high winds, but uprooting is not common. They are easily killed by fire.

SHORTLEAF PINE (*Pinus echinata* Mill.)

Shortleaf pine has the widest range of any of the southern pines and, of the four principal species, extends farthest north; it does not, however, extend as far south in Florida as do the other three. It grows in 22 States over more than 440,000 square miles (fig. 3-11). Although the standing inventory is about half that of loblolly, shortleaf is still far more abundant than longleaf and slash combined.

Though it grows in an area classified as humid, it is the least exacting of the southern pines with regard to temperature and moisture. The 50° F. average temperature line in the northeast closely parallels the northern limit of shortleaf. In Oklahoma and Texas the 40-inch annual precipitation line marks the southwestern boundary of the range. Shortleaf pine is best developed in Arkansas, north Louisiana, and in the southern Piedmont, where precipitation ranges from 45 to 55 inches a year and averages 50 inches. Within the shortleaf region, temperatures range from a midwinter mean temperature of 26° F. in New Jersey to a midsummer mean of 80° F. in southeast Texas.

Site indices for shortleaf range from 50 to 100 and are related to the depth of the surface soil and consistency of the subsoils. The best sites are fine sandy loams or silt loams without distinct profile but with good

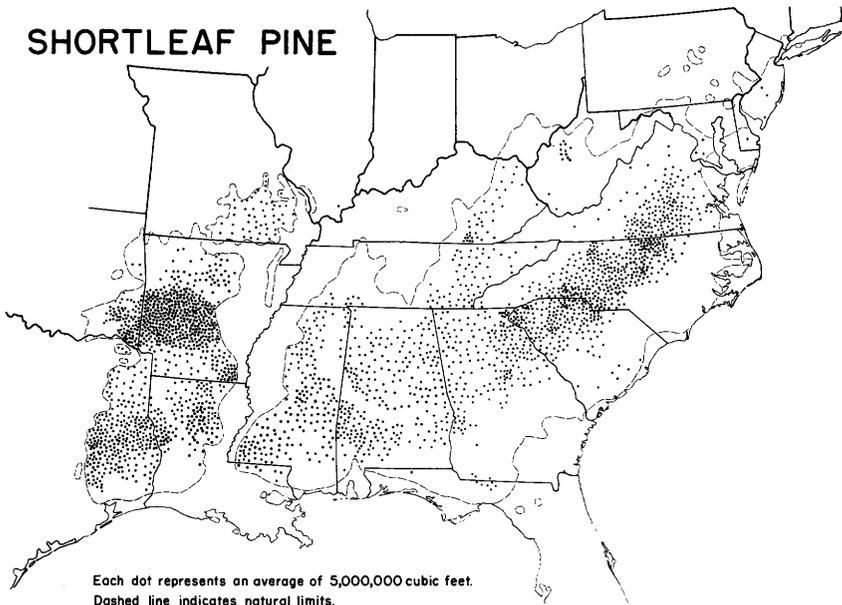


Figure 3-11.—The range and volume of shortleaf pine. (Drawing after Sternitzke and Nelson 1970.)

internal drainage. Growth is good on friable subsoils, especially where surface soil is over 9 inches deep, but poor on plastic subsoils. Generally, shortleaf pine does not grow on soils with a high calcium content or high pH. In southern New Jersey, shortleaf pine grows at elevations as low as 10 feet. In the mountains of the Southeast it is found on valley floors and up to 3,300 feet.

Shortleaf stocks from different geographic sources, when planted in one locality, differ in ability to survive and grow (Posey et al. 1970). Current research strongly indicates that the pattern of growth is similar to that described for loblolly.

In a North Carolina observation, more than 90 percent of growth took place from April through August. In south Arkansas, in trees 3 to 9 feet tall, 96 percent of the growth was complete by the end of July. Average height growth ranges from 2.3 to 2.8 feet per year.

The J-shaped crook which appears in the stem within 60 days after seed is sown is characteristic. The stem is generally prostrate as shoot growth begins, but subsequently turns upward, forming the crook.

Following a burn or injury, a young shortleaf usually sprouts profusely from buds in the vicinity of the crook, but trees over 6 or 8 inches in diameter seldom sprout vigorously. Most sprouts eventually die, leaving two and sometimes three stems to grow to maturity (fig. 3-12 left). Propagation by cuttings is very difficult, by grafting somewhat less so.

On good sites shortleaf pines attain heights of 80 to 100 feet and diameters of 2 to 3 feet (fig. 3-12 right). Heights of 130 feet and diameters of 4 feet have been recorded.



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Figure 3-12.—(Left) Typical double-boled shortleaf pine, which probably resulted from sprouting following fire damage in the early life of the stand. (Right) A 90-year-old stand of shortleaf pine in Arkansas.

On sites with indices of 70 to 80, a fully stocked unthinned stand will yield from 49 to 57 cords (including bark) of pulpwood per acre at age 35. At this age the average height of the dominant trees is 55 to 64 feet and the average diameter 7.5 to 8.6 inches. On similar sites, 60-year-old dominants average 77 to 88 feet in height and 11.0 to 12.3 inches in diameter; even-aged stands yield from 27 to 35 M b.f. (thousand board feet) per acre, International $\frac{1}{4}$ -inch log rule at 60 years.

In young plantations, growth in merchantable height adds appreciably to volume. The average cubic-foot volume, outside bark, of shortleaf trees of different diameters at 13, 16, and 18 years of age in a plantation in southern Illinois was as follows:

Diameter	13 years	16 years	18 years
<i>Inches</i>		<i>Cubic feet</i>	
4	0.98	0.98	1.06
5	1.58	1.80	1.97
6	2.39	2.75	3.12
7	3.25	3.70	4.57
8	—	4.75	6.37

Natural pruning takes place more slowly on shortleaf pine than on loblolly or longleaf. Lateral branches on the lower 20 feet of shortleaf stems remain alive an average of 8 years. Shortleaf is quite fire resistant, and is windfirm throughout most of its range.

SLASH PINE (*Pinus elliotii* Engelm. var. *elliotii*)

Slash pine is one of the most important pines in the Southeastern States and one of the two southern pines worked for naval stores. The least widespread of the principal southern pines, its natural range extends from the Coastal Plain of southern South Carolina to central Florida and southeastern Louisiana (but not west of the Mississippi River). Nearly half of the entire inventory is in Georgia. The range has been extended across the Mississippi by planting, as in east Texas where plantation-grown trees reproduce naturally. The northernmost natural growth of slash pine is believed to be in Georgetown County, S.C., about latitude $33\frac{1}{2}^{\circ}$ N. Successful plantations have been established as far north as Tennessee.

South Florida slash pine (*Pinus elliotii* Engelm. var. *densa* Little & Dorman) is known only in Florida and has only recently been distinguished as a distinct botanical variety; its range extends from the lower Florida Keys north to Lake Okeechobee and then in two prongs along both coasts as far north as central Florida. While the range map (fig. 3-13) includes both varieties, the following paragraphs deal only with typical slash pine (fig. 3-14).

The range is characterized by wet summers and drier falls and springs. The annual precipitation averages about 50 inches. Average annual temperature is 63° F.; there are occasional extremes of 106° and 0° F.

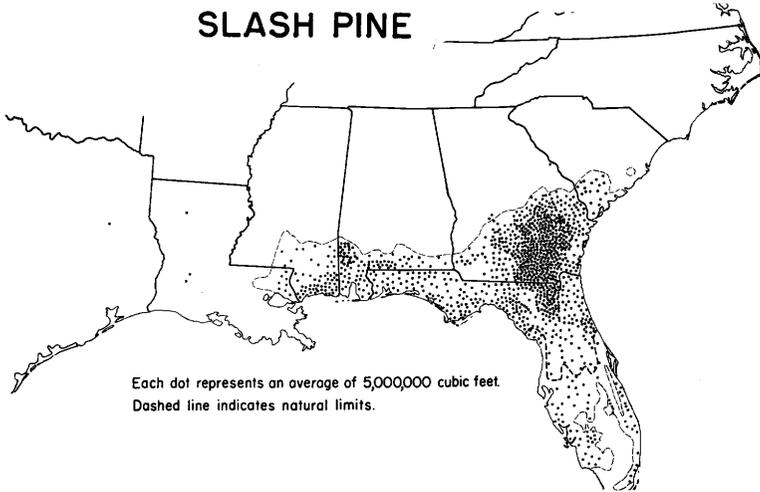


Figure 3-13.—The range and volume of slash pine. The dashed line in central Florida indicates the northern limit of *var. densa*. (Drawing after Sternitzke and Nelson 1970.)

The soils within the natural range are usually sandy and often have poorly drained hardpans 18 to 24 inches below the surface. Slash pine makes its best growth on margins of the shallow, poorly drained depressions known as ponds. The typical flatwoods sites, which include incompletely drained soils and hardpan soils, are probably next in productivity. Deep, well-drained pure sands or the poorly drained lands (crawfish flats)



Figure 3-14.—A row-thinned, 25-year-old plantation of slash pine in Sabine Parish, La. D.b.h. averages 8.4 inches. The self-pruning tendency of the species is evident.

are least productive. Topography and elevation vary only slightly in the natural range.

Height growth usually begins early in March; the species makes most of its growth in March, April, and May. Several flushes may occur in one season, the first being the greatest. Radial growth begins about the same time and is generally completed before November; studies in north Florida, however, have shown that some radial growth occurs between November and March.

Under normal conditions, 5-year-old seedlings will average 10 feet in height; on the very best sites, and with a minimum of competing vegetation, seedlings may reach 20 feet at 5 years. Early root growth of young trees is extensive; trees interplanted in south Georgia slash pine plantations only 1 year after establishment are usually suppressed.

Young slash pines will on occasion sprout from the stump. Grafting and air layering have been successful.

The typical variety of slash pine (var. *elliottii*) exhibits considerable inherent variation from place to place (Squillace 1966). Such long-term provenance tests as have been made suggest that stocks from northeast Florida and south Georgia survive planting less well than stocks from farther west, especially where climate or site is adverse (Snyder et al. 1967).

Mean annual growth in cords on the best slash pine sites culminates at about 20 years of age, and falls off gradually thereafter. On one of the better sites on the Olustee Experimental Forest, near Lake City, Fla., a managed stand produced 60 cords of pulpwood per acre in 27 years, a mean annual growth of 2.2 cords.

Slash pine prunes itself well, particularly in dense stands.

Site index in the slash pine belt ranges from 50 to 110, but a large percent of all sites fall in the 70- and 80-foot class. Average diameter and volume per acre for several managed stands on class 80 sites were:

<u>Age and number of trees</u>	<u>Average d.b.h. 100 largest trees</u>	<u>Cords</u>
	<i>Inches</i>	<i>Number</i>
Age 8 years		
210	3.8	—
385	3.6	—
720	3.4	—
Age 18 years		
170	9.4	13
325	8.6	18
630	7.9	25
Age 23 years		
170	10.2	17
240	9.4	24
500	8.9	34

The culmination of mean annual growth occurs sooner on good sites than on poor ones. In plantations on 100-foot sites, culmination occurs before age 25 for all degrees of stocking from 200 to 1,000 trees per acre; on site index 60, culmination occurs several years later. On poor sites stocking has very little influence on increment rates.

In the Middle Coastal Plain of Georgia and the Carolina sandhills, yields of 20-year-old, old-field slash pine plantations averaged about 32 cords per acre; site index was 80 feet, and the original plantation spacing had been 8 by 8 feet. A volume of 7 M b.f. (Scribner rule) per acre seems adequate for a 50-year rotation on this site. Several fairly heavy thinnings will be necessary to maintain this volume.

If thinnings are to increase diameter growth, they should be made before the stand reaches an age of 20 years. Thinning at older ages will result in little more than maintenance of the established diameter growth rate. Early thinnings, on the other hand, will develop the adequate crowns needed for favorable diameter growth rates during later years.

Even-aged management is generally favored over all-aged. The seedlings are easily killed by fire.

SPRUCE PINE (*Pinus glabra* Walt.)

Spruce pine is found mainly in southern Alabama and Mississippi, and in southeastern Louisiana (fig. 3-15). It occurs either singly or in groups on moist sites in association with hardwoods and is reportedly more shade-

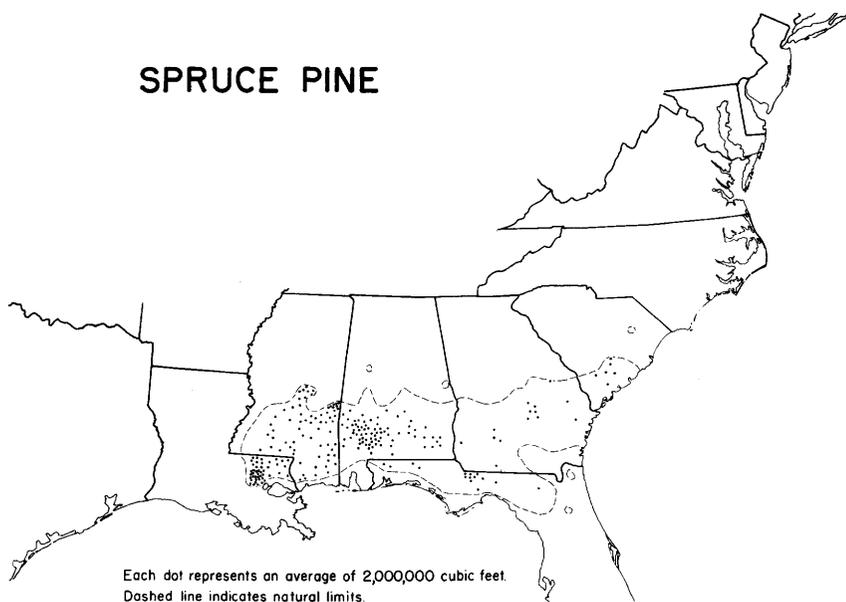


Figure 3-15.—The range and volume of spruce pine. (Drawing after Sternitzke and Nelson 1970.)

tolerant than the other southern pines (fig. 3-16). The tree is found on sandy loam soils intermediate between dry sandy soils and alluvial bottom land (Harlow and Harrar 1958, p. 101). As with slash pine, the range is characterized by wet summers.

Trees may grow to diameters of 2 or 3 feet and heights of 100 feet or more; large individuals usually occur as isolated specimens. The tree is distinguished by its bark, which is dark gray, relatively smooth, closely furrowed, and without plates.

No yield data typical of the species are at hand. In a sampling of trees from the major commercial range, Manwiller² found the following relationships between diameter and total height; each value is the average

² Manwiller, F. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station Final Report FS-SO-3201-1.1, dated May 1, 1972.



Figure 3-16.—A 12-inch spruce pine, 50 years old, near Lucedale, Miss.

for 12 trees randomly selected within a specified category of age and growth rate (more than 6 or less than 6 rings per inch).

Growth rate and age class (years)	Growth rate	D.b.h.	Tree height
	<i>Rings per inch</i>	<i>Inches</i>	<i>Feet</i>
Slow			
15	8.4	4.9	38.0
30	9.4	6.7	50.5
45	9.5	10.6	67.5
Fast			
15	4.6	8.0	49.0
30	4.8	12.1	70.5
45	5.3	16.9	83.5

TABLE-MOUNTAIN PINE (*Pinus pungens* Lamb.)

Table-Mountain pine is found chiefly on dry, gravelly, or rocky slopes and tablelands in the mountains of West Virginia, Virginia, and North Carolina (fig. 3-17). These three States encompass nearly 90 percent of the estimated standing inventory.

Over the major portion of the range, the annual precipitation is well distributed through the year and averages 45 to 50 inches; average annual

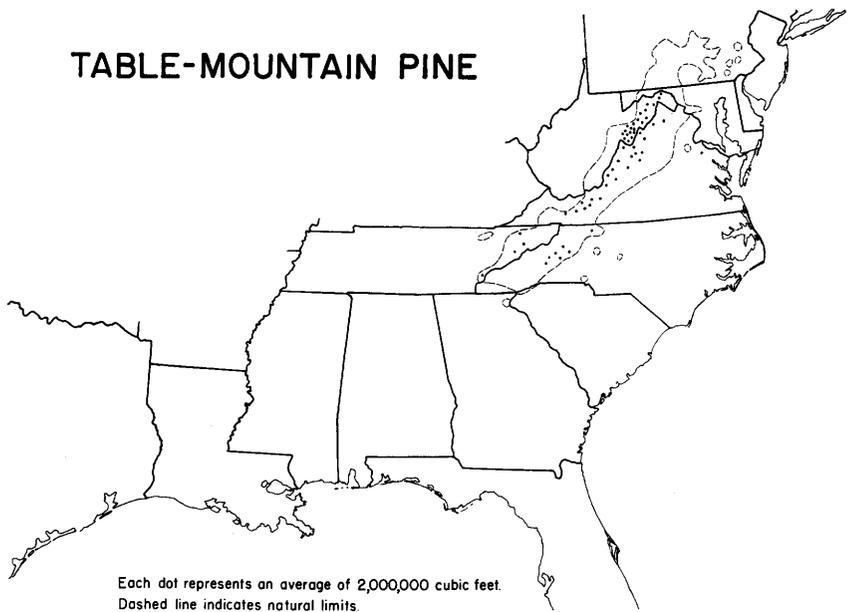


Figure 3-17.—The range and volume of Table-Mountain pine. (Drawing after Sternitzke and Nelson 1970.)

temperature is 55° F. The heaviest concentration of Table-Mountain pine is found at elevations from 2,000 to 4,000 feet.

Seasonal height growth usually begins in April; the tree makes most of its height growth in April, May, and June. Radial growth is usually complete by September. The tree is fire resistant. It occasionally sprouts from the stump if decapitated; these sprouts usually die back in a year or so.

Most trees are rough in appearance, although single 90-year-old, straight specimens have been observed that measured 1½ feet in diameter and 95 feet high. Usually the limbs are retained (fig. 3-18). Open-grown trees are seldom more than 20 or 30 feet in height and have pendulous, cone-laden branches that extend nearly to the ground.

Yield data are lacking.

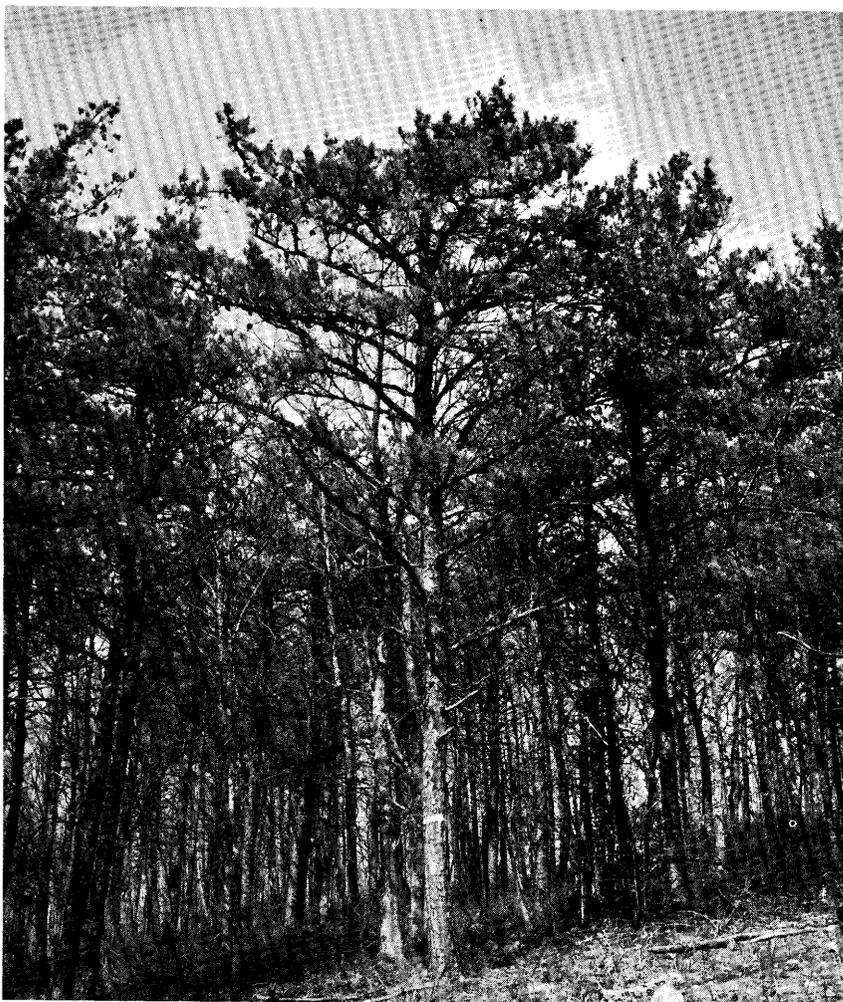


Figure 3-18.—A 9-inch Table-Mountain pine, 50 years old, near Blacksburg, Va.

VIRGINIA PINE (*Pinus virginiana* Mill.)

Virginia pine, most abundant of the minor southern pines, grows generally throughout the northern parts of the Piedmont and foothills of the mountains from central Pennsylvania southwestward to northeastern Mississippi, Alabama, and northern Georgia. Half of the standing inventory is in Virginia and North Carolina (fig. 3-19).

The average annual precipitation in most of the range of Virginia pine varies from 40 to 50 inches, and is fairly well distributed throughout the year. In general, the climate in its range is classed as humid. Average summer temperatures are from 70° to 75° F.; average winter temperatures are from 25° to 40° F.

The species grows best on sandy loam or sandy clay loam; it generally does poorly on shaly soils and on very sandy soil, such as dune sands along the coast. It thrives only in moderately well-drained to well-drained soils, and is distinctly less tolerant of wet sites and impeded drainage than pitch pine or loblolly. Virginia pine generally tolerates soil acidities ranging from pH 4.6 to 7.9. It comes in freely on abandoned farmlands throughout its range and develops best at elevations of 100 to 2,500 feet.

The seedlings are more tolerant of drought than those of most pines. On better sites, trees may average 20 to 25 feet in height at the end of 10 years. Height growth is initiated about the first of April and is 80-percent complete by mid-June.

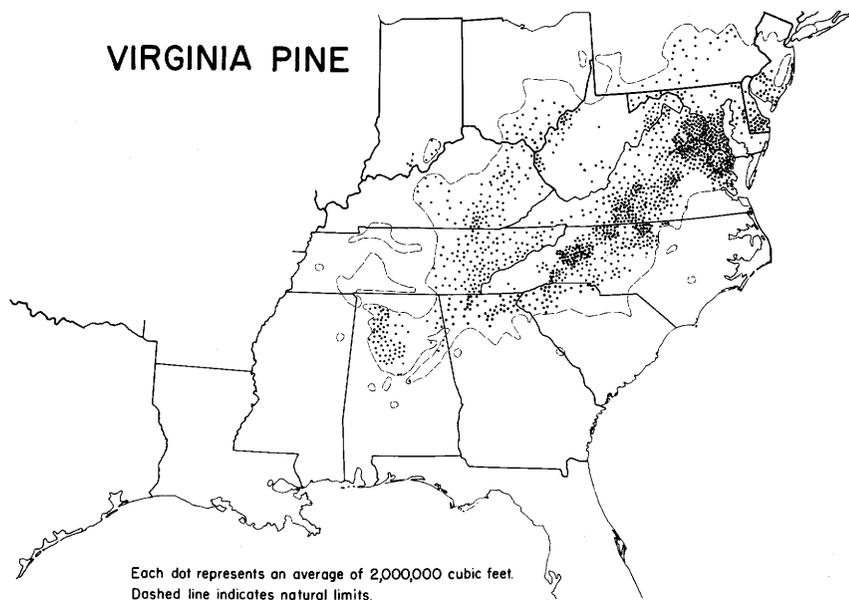


Figure 3-19.—The range and volume of Virginia pine. (Drawing after Sternitzke and Nelson 1970.)

Sprout growth on Virginia pine is rare. Propagation from cuttings has been demonstrated.

On average sites well-stocked stands may have as many as 1,600 stems per acre at 20 years of age. The number drops to about 200 in 70-year-old stands. The average merchantable volume per acre in North Carolina for site index 60 is 1,600 cu. ft. at 20 years and 5,050 cu. ft. at 70 years. Volumes for Maryland are intermediate between the higher values for North Carolina and the lower values for Pennsylvania. In a regional study extending from Maryland to South Carolina, merchantable volumes per acre for fully stocked, pure, 60-year-old stands ranged from 2,210 cu. ft. for site index 55 to 8,600 cu. ft. for site index 80.

On best sites the trees reach a height of 120 feet at maturity, but the average height varies from 50 to 75 feet at 50 years. A growth-rate capability of a cord per acre per year is possible over a large area.

The mean annual growth rate for merchantable stands reaches its maximum at 40 to 50 years for pulpwood and 70 years for sawtimber in Pennsylvania.

Natural pruning in Virginia pine is very slow (fig. 3-20). Virginia pine will not respond to thinning if the stands are more than about 15 years old. Opening up older stands is not advisable because this species is subject to windthrow and breakage by wind, ice, and sleet; residual trees exposed by partial cuttings are especially vulnerable. Saplings stands are often severely damaged by wet heavy snow. Because of its very shallow root system, Virginia pine is less windfirm than most southern pines.

Young Virginia pines are particularly vulnerable to fires because of their thin bark. Surface fires may considerably damage older trees.

3-2 DISTINGUISHING FEATURES OF THE SPECIES

While small specimens of dry wood can be identified as southern pine, in distinction from wood of other pines, no practical method has been found for narrowing the identification to a single species. Experienced botanists and foresters can usually identify standing trees positively, but there is no foolproof method for use by people initially encountering the 10-species group.

The illustrations in this section, while perhaps insufficient to permit positive identification of all specimens, depict the chief features by which the species are recognized.

Ward's (1963) key to the pines of Florida (reprinted here) is useful in distinguishing among seven of the 10 southern pines. The alphabetically arranged illustrations and descriptions which follow should permit identification of pitch, Table-Mountain and Virginia pines, as well as those in the key.

Key to southern pines found in Florida (Ward 1963).

- Sheath longer than 1.3 cm.; needles 20-40 cm. long, 3 per fascicle; dormant buds 1.5-3 cm. long, silvery-white; cones 12-28 cm. long. *P. palustris*
- Sheath shorter than 1.5 cm.; needles 5-25 cm. long, 2 or 3 per fascicle; dormant buds less than 2 cm. long, generally brownish or grayish; cones under 16 cm. long.
- Needles consistently 3 per fascicle; phellogen³ lines in cross-section of bark inconspicuous, similar in color to surrounding cork.³
- Open cones essentially as broad as long; short branchlets persisting on lower trunk. *P. serotina*
- Open cones 1.5 times longer than broad; branchlets not persisting on trunk. *P. taeda*
- Needles 2 per fascicle, or in 2's and 3's; phellogen³ lines conspicuous, lighter colored than surrounding cork.³
- Needles over 13 cm. long; cones 7-16 cm. long, not persisting.
- Seedlings with slender stems and scattered buds; needles in 2's and 3's on same tree; open cones usually with flattened bottom. *P. elliotii* var. *elliotii*
- Seedlings with thick shortened stems and clustered buds; needles predominantly in 2's, or in 2's and 3's; opened cones usually with rounded bottom. *P. elliotii* var. *densa*
- Needles under 13 cm. long; cones under 7 cm. long, persisting on tree for several years.
- Bark of small branchlets (6-12 mm.) loose, blackish, flaking off to reveal orange-tinged inner layers; a small percentage of 3-needle fascicles usually present. *P. echinata*
- Bark of small branchlets tight, gray; no 3-needle fascicles present. Cones opening promptly at maturity, when fully open 1.2-1.7 times longer than broad, tending to be ellipsoidal; cone scales flexible; moist, moderately drained habitats. *P. glabra*
- Cones either remaining closed for several years after maturity or opening promptly, when fully open 1.0-1.2 times longer than broad, tending to be conical with a flat bottom; cone scales stiff and inflexible; dry, excessively drained habitats.
- Some or all cones remaining closed for one or more years; trees usually in uniform-aged stands. *P. clausa* var. *clausa*
- Cones opening in the fall of the year they are produced; trees usually in stands of mixed ages. *P. clausa* var. *immuginata*

LOBLOLLY PINE

Pinus taeda L. (fig. 3-2) has fascicle sheaths shorter than 0.6 inch; dormant buds are shorter than 0.8 inch and have reddish-brown scales. The needles are 6 to 9 inches long, slender, sometimes twisted, and usually three but occasionally two to the fascicle. This is in contrast with slash pine, which usually has two but sometimes three needles. The cones are

³ Ward used "phellogen" to mean periderm, and "cork" to mean surrounding rhytidome or old phloem tissue.



Figure 3-20.—Persistent branches in an old-field stand of Virginia pine.

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2 to 6 inches long, usually have sharp prickles, and when open are about 1.5 times longer than they are broad (fig. 3-21). In a cross section of the bark, the periderm layers are inconspicuous and similar in color to the surrounding tissue; this is in contrast to slash pine where the periderm layers are conspicuously lighter colored than the surrounding tissue. In contrast with pond pine, branchlets do not persist on the trunk of loblolly pine. According to Ward (1963) "The needles of this tree are appreciably more slender and flexible than those of *P. elliotii*, enabling the two species to be distinguished at a glance, particularly when dried, without examination of needle number. The cones are equally diagnostic, those of *P. elliotii* being glossy chestnut-brown when unopened or newly opened, turning gray only after extensive weathering, while those of *P. taeda* usually become gray and dull even before opening."

LONGLEAF PINE

Pinus palustris Mill. (fig. 3-4) is distinguished by the length of the fascicle sheath (longer than 0.5, commonly 0.6 to 1.5 inches), the length (8 to 18 inches) and number (three to the fascicle) of its needles, the length (0.6 to 1.2 inch) and silvery-white color of its dormant buds, and the length (6 to 10 inches) of its cones (fig. 3-22ABCD). Experienced foresters have little trouble in distinguishing a standing longleaf by its long, bright green, densely tufted needles. When a longleaf tree is felled and the stump observed, the diameter of the pith and second annual ring permits identification (fig. 5-2).

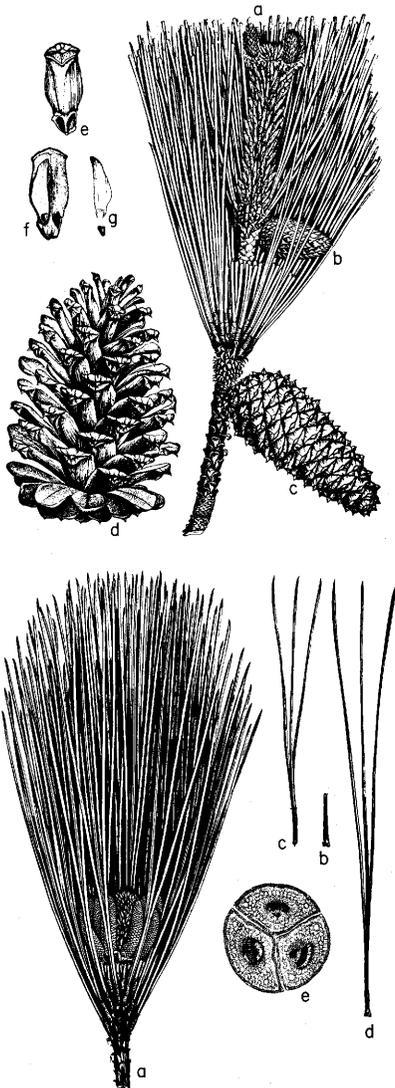


Figure 3-21.—Loblolly pine.

(Top)

- a, branch bearing two subterminal aments of female flowers at end of terminal shoot;
- b, immature yearling conelet;
- c, mature, 2-year, closed cone (2 to 6 inches long);
- d, mature cone, open after shedding seed;
- e, dorsal side of cone scale with stout reflexed prickle;
- f, ventral (inner) view of same with seed in place;
- g, seed and wing detached.

(Bottom)

- a, needles and male flowers;
 - b, fascicle of young leaves in the spring;
 - c and d, mature needles (6 to 9 inches long);
 - e, cross section of base of needle bundle.
- (Drawings after Mohr 1896.)

Young trees are distinguished by a grass stage (fig. 3-22Ae), which may last 3 to 6 years (sometimes 12 or more) before height growth begins.

Where their ranges overlap, longleaf and loblolly pines often cross to form natural hybrids called Sonderegger pines (*Pinus x sondereggeri* H. H. Cham.). In needle length and in shape and size of cones the hybrids are intermediate between the two parent species.

PITCH PINE

Pinus rigida Mill. (fig. 3-6) is not included in Ward's key. By its three needles this pine should be distinguishable from the two-needled sand, Virginia, Table-Mountain, and spruce pines. Because its needles

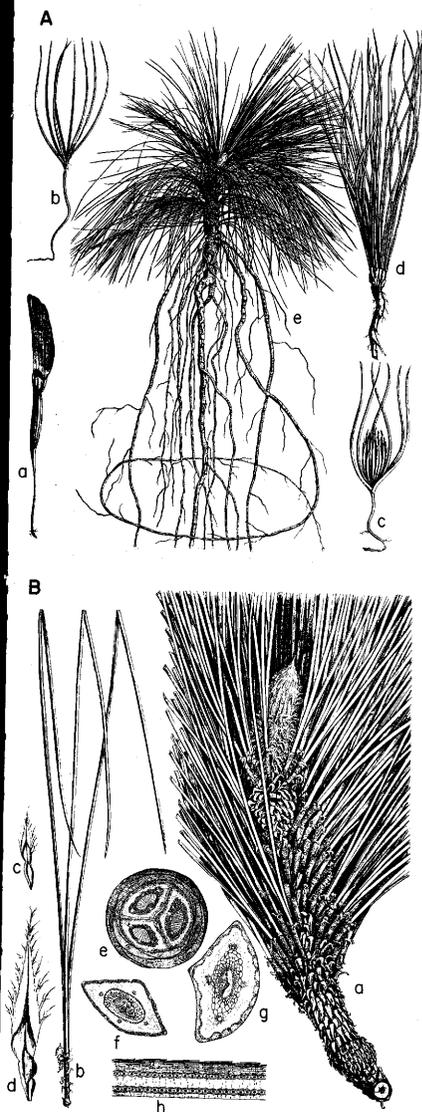


Figure 3-22AB.—Longleaf pine.

(A)

- a, germinating seed;
- b, seedling in early spring with eight cotyledons just unfolded;
- c, seedling a few weeks older showing central cluster of primary leaves just unfolding;
- d, seedling at beginning of second season showing bundles of true foliage leaves (secondary); primary leaves have disappeared;
- e, 3- to 4-year-old tree with characteristic large root system; stem is nearly 1 inch thick.

(B)

- a, branch with terminal spring shoot of the season with characteristic, large (longer than 1/2-inch) silvery-white winter bud; the bundles of leaves arise from the axils of the leaf bracts of the last two seasons; the first leaves of the second year are already shed;
- b, detached bundle of mature leaves (8 to 18 inches long) with sheath (0.6 to 1.5 inches long);
- c, scale of sheath;
- d, same further magnified (actual length 3/8- to 1/2-inch);
- e, cross section through base of leaf bundle;
- f, cross section of immature leaf;
- g, cross section of mature leaf;
- h, longitudinal section of dorsal side of a mature leaf showing two rows of stomata and the serrated edge.

are short (3 to 5 inches), it can be distinguished from loblolly, slash, and longleaf. In comparison with the three-needled pond pine, it has much shorter needles (pond pine needles are 6 to 8 inches) and smaller cones (pitch pine cones are 2 to 3.5 inches in length) with more persistent prickles, and it usually grows on drier sites.

Pitch pine can be distinguished from shortleaf by its stout, stiff, usually somewhat twisted needles standing out at right angles to the twig (often in tufts on the trunk); shortleaf needles are also 3 to 5 inches in length and sometimes grow from dormant buds along the trunk, but they are

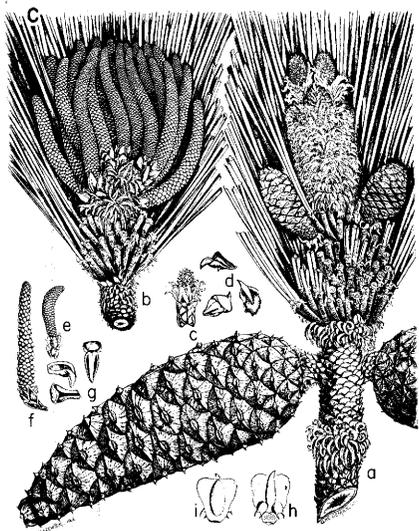
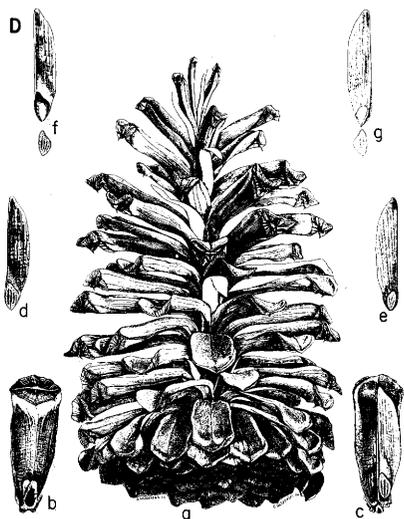


Figure 3-22CD.—Longleaf pine.

(C)

- a, branch with two female aments (second week of March), at the end of terminal young shoot of the season densely covered with fimbriate silvery bract subtending the leaf buds, which are still hidden in their axils; below are two immature cones of one season's growth (October);
- b, branch with male flowers closely surrounding the apex of the young shoot;
- c, female ament with basal scales forming the calyx-like involucre;
- d, carpellary or seed-bearing scales of female flowers more advanced, lateral, ventral, and dorsal views;
- e, detached male flower with basal involucre scales, before opening (dehiscence);
- f, male flower, after discharge of the pollen;
- g, three detached anthers, lower sides showing longitudinal slits of the pollen sacs just opening; lateral view of an effete anther; another seen from upper side showing the transverse semilunar crest;
- h, detached female flower seen from above; the cuspidate carpellary, or seed scale, bears two strongly bifid naked ovules at its base;
- i, female flower viewed from below, dorsal side; the bract almost covers the carpellary scale, leaving only the tip of the latter and the cusps of the ovules visible.

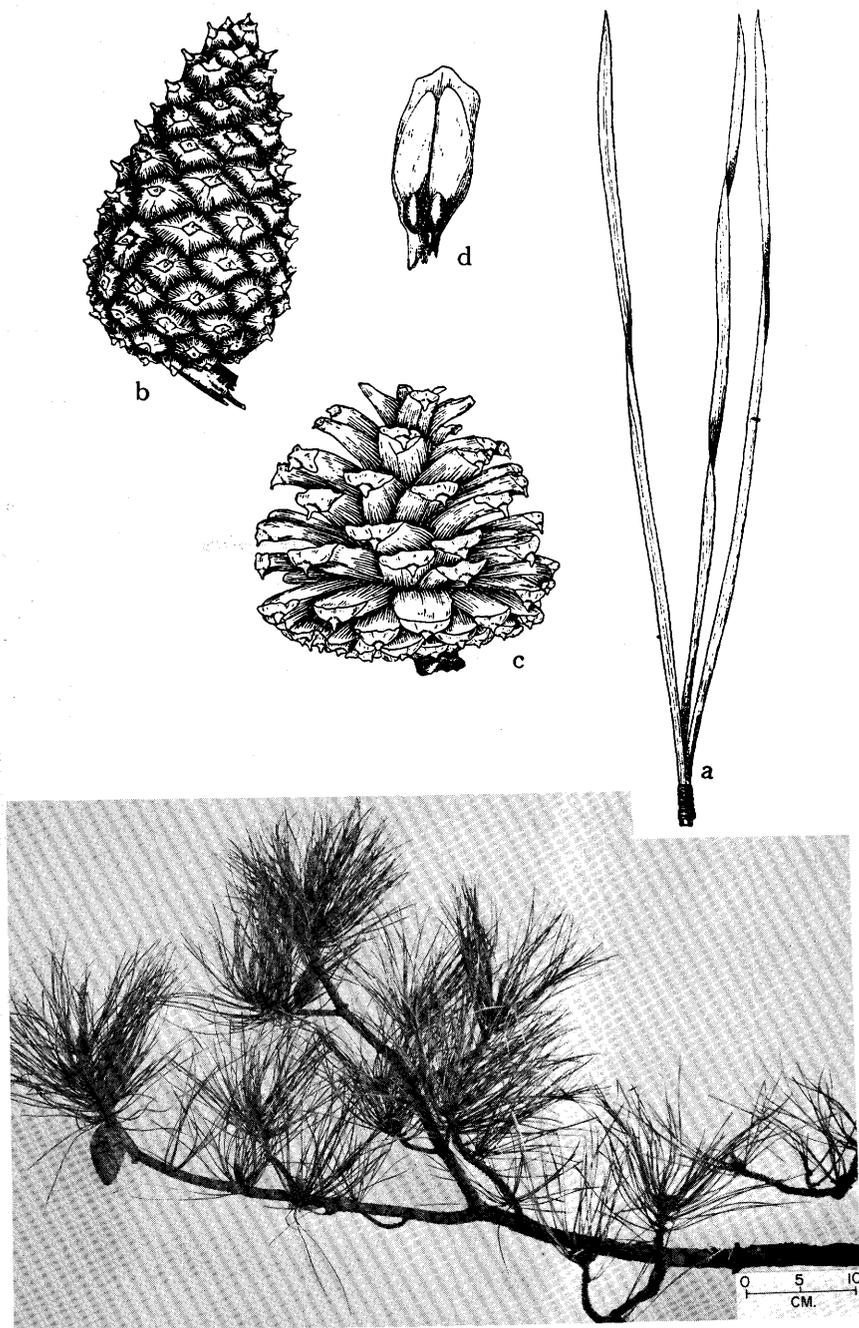
(D)



- a, mature open cone, after shedding seed;
- b, cone scale seen from lower and dorsal side showing the apophysis with low umbo and small, weak prickles;
- c, cone scale seen from upper or ventral side with seed in place;
- d, seed, upper side;
- e, seed detached from c, lower side;
- f, seed detached from wing, upper side;
- g, the same seen from lower side.

(Drawings after Mohr 1896.)

mostly in two's and are slender and flexible. Figures 3-23 and 3-26 permit comparison of the two species. A cross section of a pitch pine needle is shown in figure 14-2 (top).



520 914

Figure 3-23.—Pitch pine. (Top) a, cluster of needles (full-size); b, unopened cone (full-size); c, opened cone (half-size); d, cone scale with seeds (full-size). (Bottom) Branch and cones. (Drawing reprinted by permission from *NORTH AMERICAN TREES*, 2nd edition, by Richard J. Preston, © 1961, Iowa State University Press, Ames, Iowa.)

POND PINE

Pinus serotina Michx. (fig. 3-8) is identified in Ward's key by its needle sheath (less than 0.6 inch long), needle length (commonly 6 to 8 inches), number of needles per fascicle (consistently three), length and color of dormant buds (less than 0.8 inch long and brownish or grayish), cones (2 to 3½ inches long and, when open, as broad as they are long), the inconspicuous dark periderm lines in a cross section of the bark, and the short branches persisting on the lower trunk. The shape of the closed cones is distinctive among the southern pines (fig. 3-24), except for pitch pine. The cones are armed with weak, often deciduous prickles.

SAND PINE

Pinus clausa (Chapm.) Vasey (fig. 3-10) has two flexible, slender needles per fascicle that measure 2 to 3½ inches in length. Because of its limited range (fig. 3-9) it is seldom confused with the other two-needled southern pines. Ward identifies it not only by needle characteristics but also by the tight gray bark of its branchlets, the shape of the cones when open (1.0 to 1.2 times longer than broad, conical, and with a flat bottom), its stiff cone scales, and its dry habitat. The sand pine of north-central Florida (Ocala race) has serotinous cones and occurs in even-aged stands, while the west Florida sand pine (Choctawhatchee race) occurs in uneven-aged stands and has cones that consistently open at maturity without being subjected to forest fires (fig. 3-25).

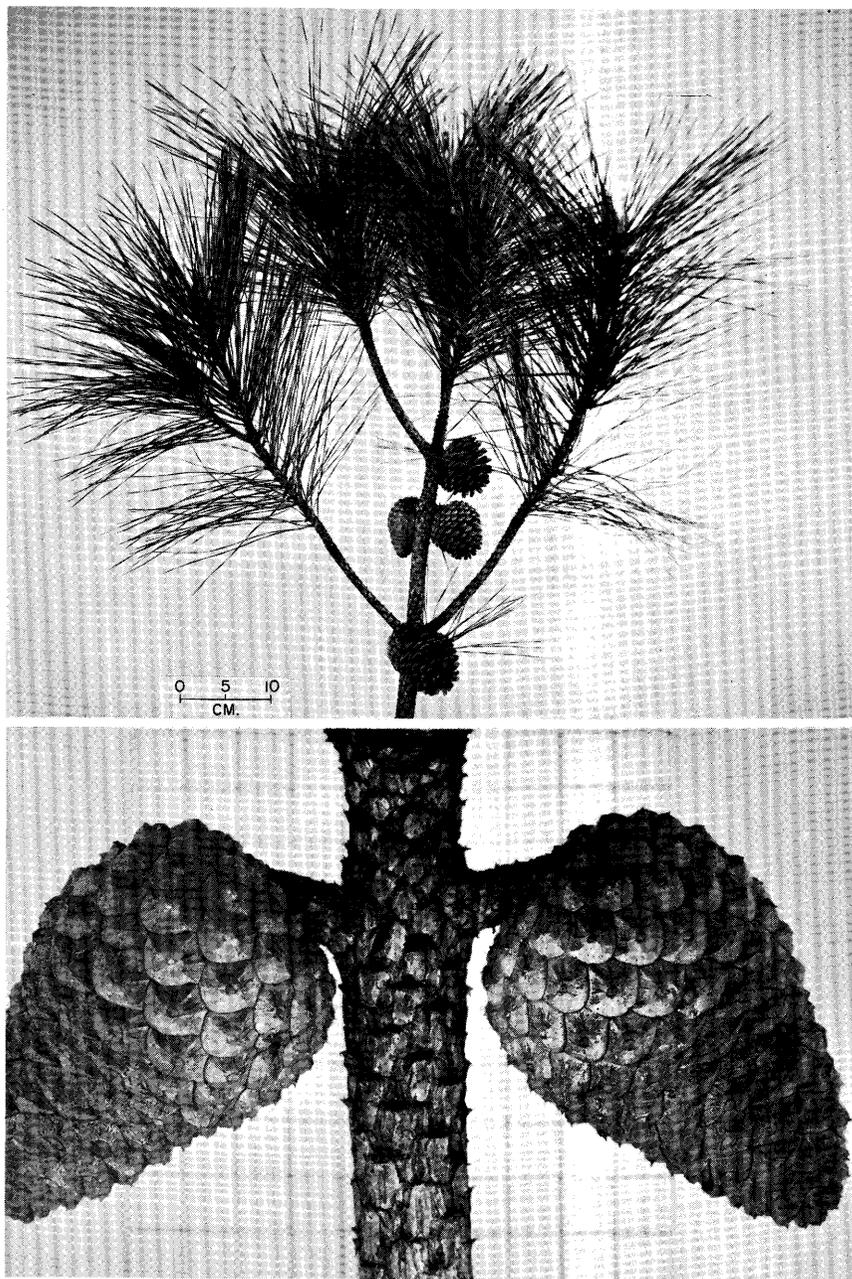
SHORTLEAF PINE

Pinus echinata Mill. (fig. 3-12) has fascicle sheaths shorter than 0.6 inch, and reddish brown dormant buds shorter than 0.8 inch. The needles are 3 to 5 inches long, slender, flexible, and mostly two but also three to a fascicle (fig. 3-26); they sometimes develop from dormant buds along the trunk. The cones are 1½ to 2½ inches long; their small size and persistence for several years makes the tree fairly easy to recognize. In contrast to the tight gray bark on branchlets of the two-needle sand and spruce pines, shortleaf pine branchlets have loose blackish bark that flakes off to reveal orange-tinged inner layers.

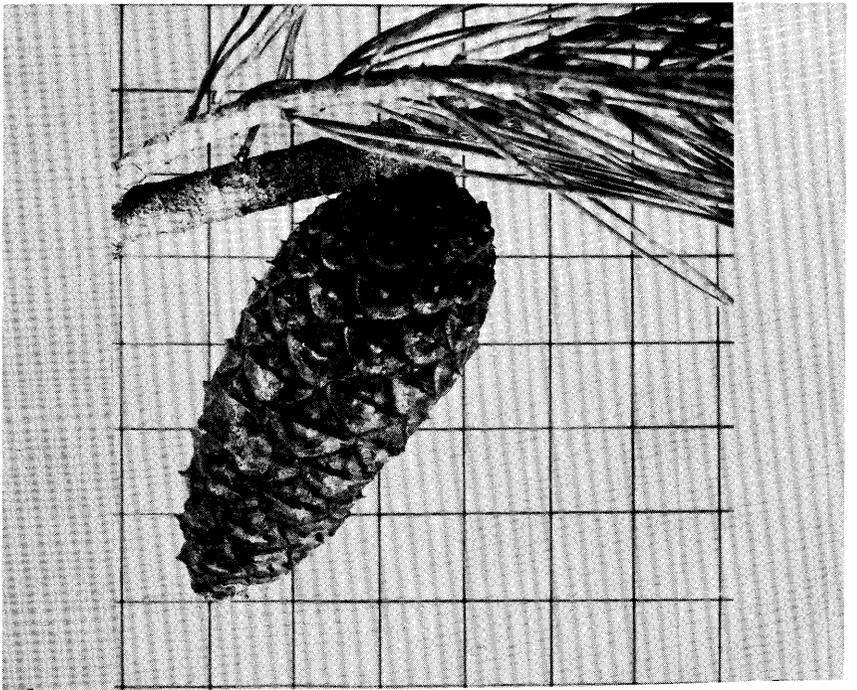
Occasional trees are difficult to distinguish from loblolly. According to Wahlenberg (1960), bark of loblolly pine "can usually be distinguished from that of shortleaf because the surface shows few, if any, of the resin blisters so abundant on most specimens of that species." (See fig. 12-5.)

SLASH PINE

Pinus elliottii Engelm. (fig. 3-14) has two geographically distinct varieties. Var. *elliottii* is of dominant commercial importance, as it grows over a much wider range (fig. 3-13). It is distinguished by fascicle sheaths



520 915
Figure 3-24.—Pond pine. (Top) Foliage and open cones. (Bottom) Closed cones (photo against 1-cm. grid).



520 916
Figure 3-25.—Sand pine. (Top) Open-coned Choctawhatchee sand pine. (Bottom) Closed cone of Ocala sand pine (1-cm. grid).

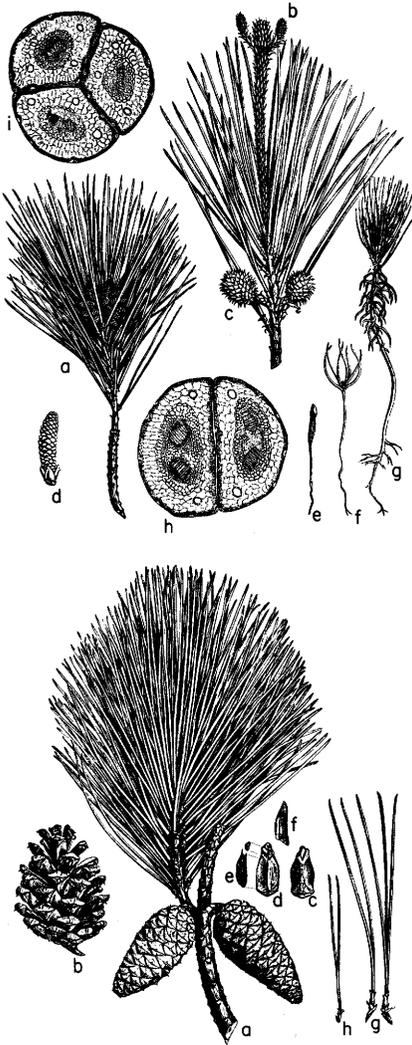


Figure 3-26.—Shortleaf pine.

(Top)

a, branch from a lower limb bearing male inflorescence with flowers in a dense cluster (first week of April, southern Alabama);

b and c, branch with two subterminal aments of female flowers, below which are two immature cones of one season's growth;

d, detached male flower showing basal involucre scales;

e, germinating seed (February);

f, same seedling 1 month later (March) with seven cotyledons in the midst of which the terminal bud shows the primary leaves appearing;

g, seedling about the close of the first season with terminal cluster of true (secondary) leaves, below which are seen the withered primary leaves;

h and i, transverse section through base of two- and three-leaved leaf bundles.

(Bottom)

a, branch with 2-year-old mature closed cones (October);

b, mature cone (1½ to 2½ inches long);

c, dorsal (outer) side of cone scale showing apophysis;

d, ventral view of same, seed in place;

e, seed detached from wing;

f, seed with wing intact;

g and h, leaves are 3 to 5 inches long.

(Drawings after Mohr 1896.)

shorter than 0.6 inch, and reddish brown dormant buds shorter than 0.8 inch. The dark-green glossy needles are over 5 inches long (usually 7 to 10 inches) with two or three to the fascicle; they are less slender and flexible than the needles of loblolly. In a cross section of the bark, the periderm layers are usually conspicuous and lighter in color than the surrounding tissue. Cones are 3 to 6 inches long and are a glossy chestnut brown when unopened or newly opened; they are not persistent. Opened cones usually have a flattened bottom (fig. 3-27). Seedlings have slender stems and scattered buds.

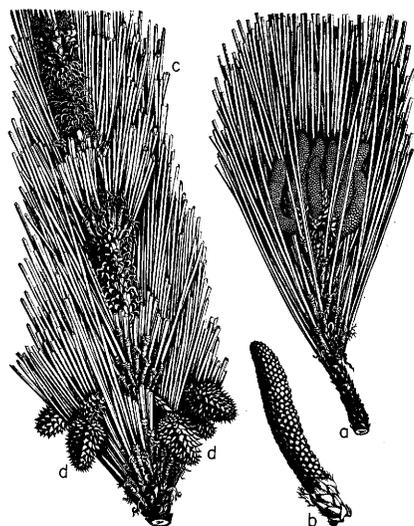
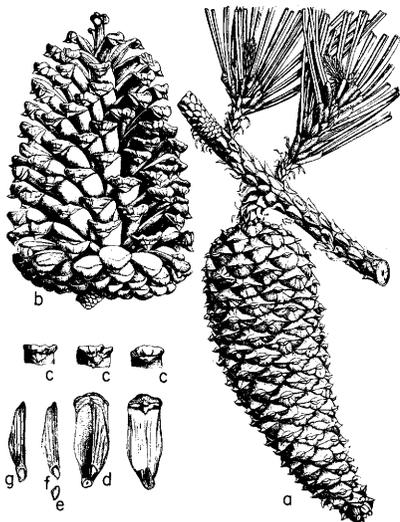


Figure 3-27.—Slash pine.

(Top)

- a, branch with male flowers;
- b, male flower (approximately 1.1 inches long) detached showing basal involucral bracts;
- c, branch with three subterminal female flowers;
- d, characteristically reflexed yearling conelets.



(Bottom)

- a, mature, 2-year, closed cone (3 to 6 inches long);
- b, mature cone open after shedding seed;
- c, tips of cone scale showing variation in form of apophysis and stout prickle;
- d, ventral side of cone scale with seed in place (left), and dorsal side (right);
- e and f, seed and wing detached;
- g, seed and wing intact.

(Drawings after Mohr 1896.)

The other variety, var. *densa* Little & Dorman, occurs naturally only in the southern two-thirds of Florida and is commonly called South Florida slash pine.

It is distinguished from typical slash pine in that its seedlings develop a thick, even carrotlike stem that does not elongate appreciably for several years after germination. The seedling terminates in a dense bunch of many hundreds of needles that appear to protect the buds from fire. Thus the tree has a grass stage resembling that of longleaf.

Ward's key notes that the open cones of var. *densa* usually have rounded bottoms, whereas those of var. *elliottii* have flat bottoms. He has further observed, "As based on one-cone samples from 49 different populations,

the length/width ratio of the open cones is significantly different between the two varieties, and the length alone is highly significant, but the variance is too excessive for these characters to be considered reliable [for identifying single trees]".

Length of open cones:

var. *elliottii* n=25, mean = 12.4 cm., standard deviation = 2.5 cm.

var. *densa* n=24, mean = 10.1 cm., standard deviation = 2.4 cm.

Length/width ratio of open cones:

var. *elliottii* n=25, mean = 1.48

var. *densa* n=24, mean = 1.38

Stems of var. *densa* have, as the name implies, a high proportion of latewood. The mature tree has an irregularly forked upper stem and a broad crown that is sometimes helpful in distinguishing it from var. *elliottii*. It is not commercially used for naval stores.

Features observable with a microscope help distinguish the varieties:

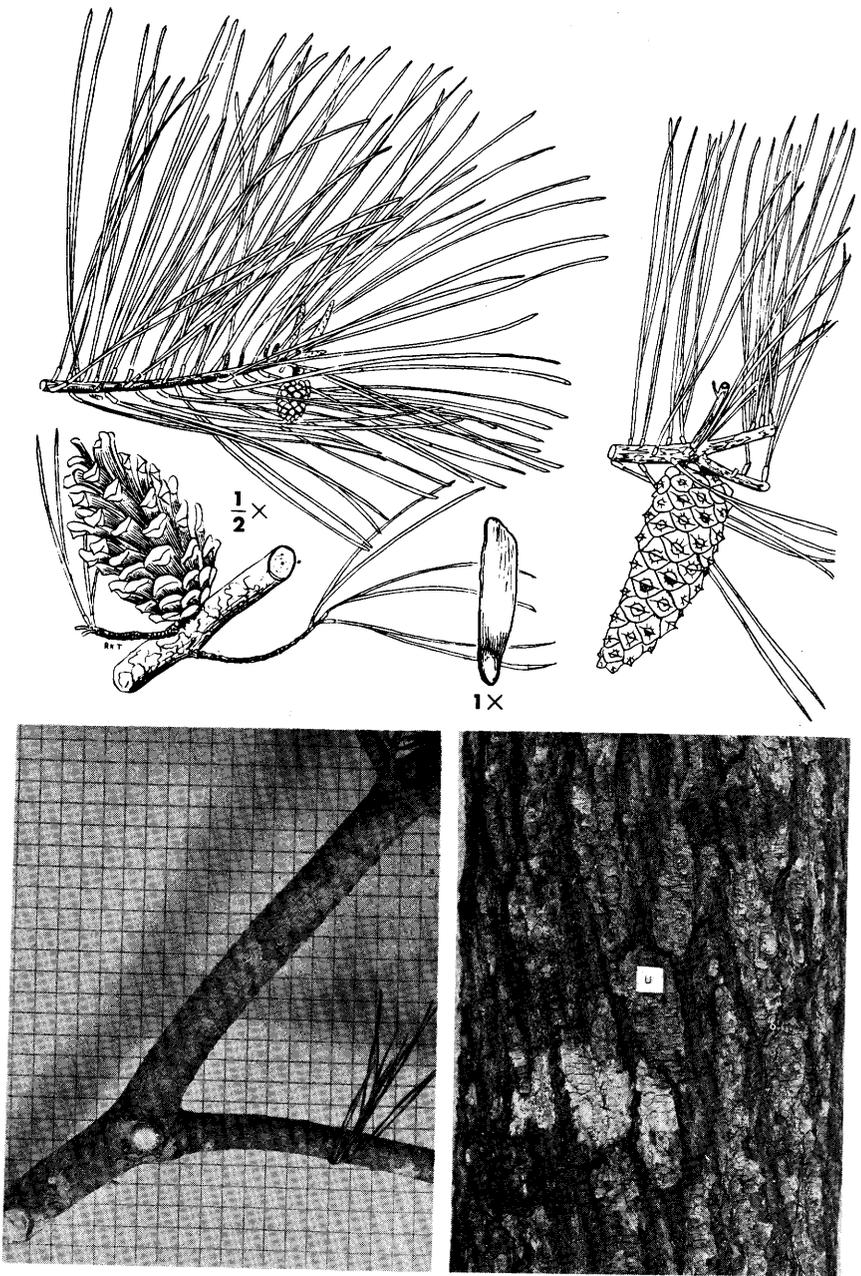
Feature	Var. <i>elliottii</i>	Var. <i>densa</i>	Reference
Number of resin canals per needle.....	3-5	3-9	DeVall (1941ab)
Thickness, i.e., number of cells, of leaf hypoderm (the sheath of cells underlying the external epidermis).....	2 (infrequently 3)	3 or 4 (infrequently 2 or 5)	Little and Dorman (1954)

SPRUCE PINE

Ward's key provides identification for *Pinus glabra* Walt. (fig. 3-16) on the basis of its short, slender needles (about 3 inches long, two to a fascicle), the tight gray bark of its branchlets, the prompt-opening cones that are 1.2 to 1.7 times longer than wide when open (fig. 3-28), the flexible cone scales, and the tendency of the tree to grow on moist sites. Men familiar with the tree readily identify its thin, gray, furrowed bark that does not flake off in the manner of the rest of the southern pines, but instead resembles oak bark. Cones persist on the tree for several years.

TABLE-MOUNTAIN PINE

The fact that the natural range of *Pinus pungens* Lamb. (fig. 3-18) is distinct from the range of sand and spruce pines (also two-needled pines) simplifies identification. The number and length (1½ to 3½ inches) of

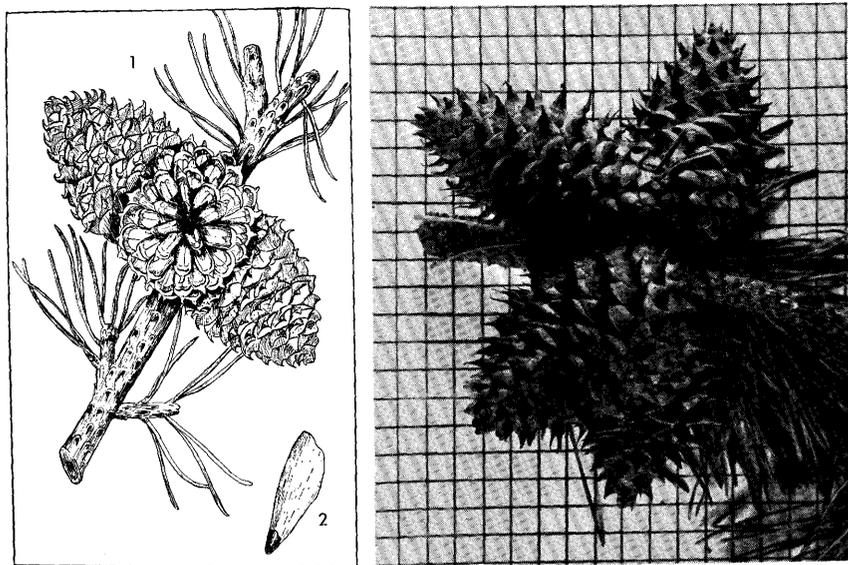


520 917
 Figure 3-28.—Spruce pine. (Top) Sketch of needles, cones, flowers, and seed. (Left) Tight, gray bark of branchlet (photo against 1-cm. grid). (Right) Relatively thin, gray, furrowed bark somewhat resembling oak bark; white spot in center is 1 cm. square. (Drawings after West and Arnold 1946, p. 7, by permission of University of Florida Press ©.)

its needles distinguishes it from all of the other pines except shortleaf and Virginia pine. Whereas shortleaf needles (3 to 5 inches long) are slender and flexible (fig. 3-26), the needles of Table-Mountain pine are rigid and often twisted. The 2- to 3½-inch-long cones, borne in clusters of three to eight, are readily distinguishable from the cones of Virginia pine (fig. 3-30)—as well as all other southern pines—because they are commonly knoblike and armed with a stout hook or claw. While cones gradually open and shed seeds over a period of 1 to 3 years, they commonly remain on the branches for 15 to 20 years and hence are available for identification (fig. 3-29).

VIRGINIA PINE

Pinus virginiana Mill. (fig. 3-20) can be distinguished from Table-Mountain pine by its cones (figs. 3-30 and 3-29) as just described. Its range does not overlap that of sand and spruce pines (figs. 3-9, 3-15, 3-19). It can be distinguished from the other six species by the shortness of its stout, usually twisted needles (two to the fascicle) which commonly range from 1½ to 3 inches long. Unlike many pines, Virginia pine produces cones in all parts of the crown. Empty cones may remain on a tree for 15 years, and usually persist for at least 5 years.



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 Figure 3-29.—Table-Mountain pine. (Left) 1, foliage and cones (⅓-scale); 2, seed (½-scale). (Right) Closed cone (photo against 1-cm. grid). (Drawing from p. 64, Guide to southern trees, by E. S. Harrar and J. G. Harrar; © 1946 by the McGraw-Hill Book Company; used with permission of the McGraw-Hill Book Company.)

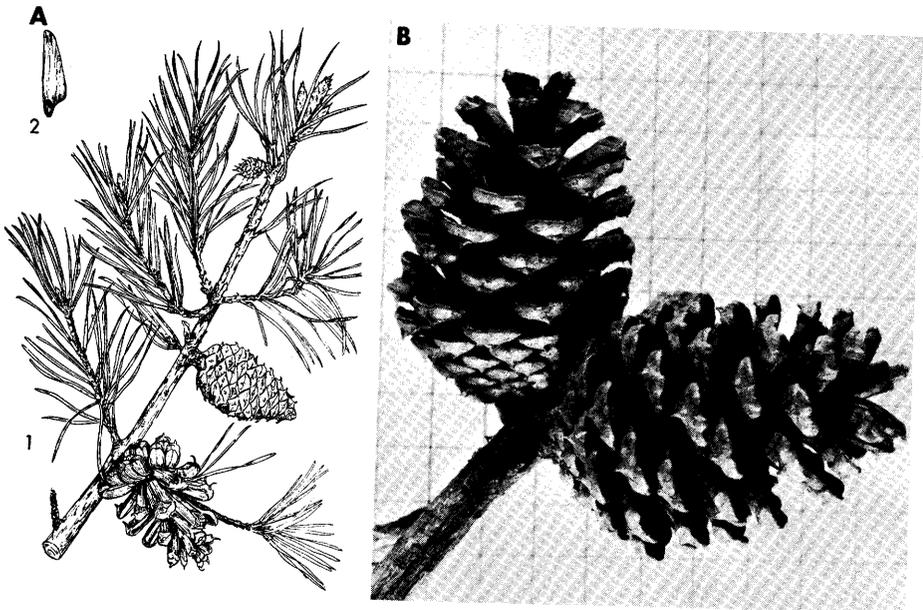


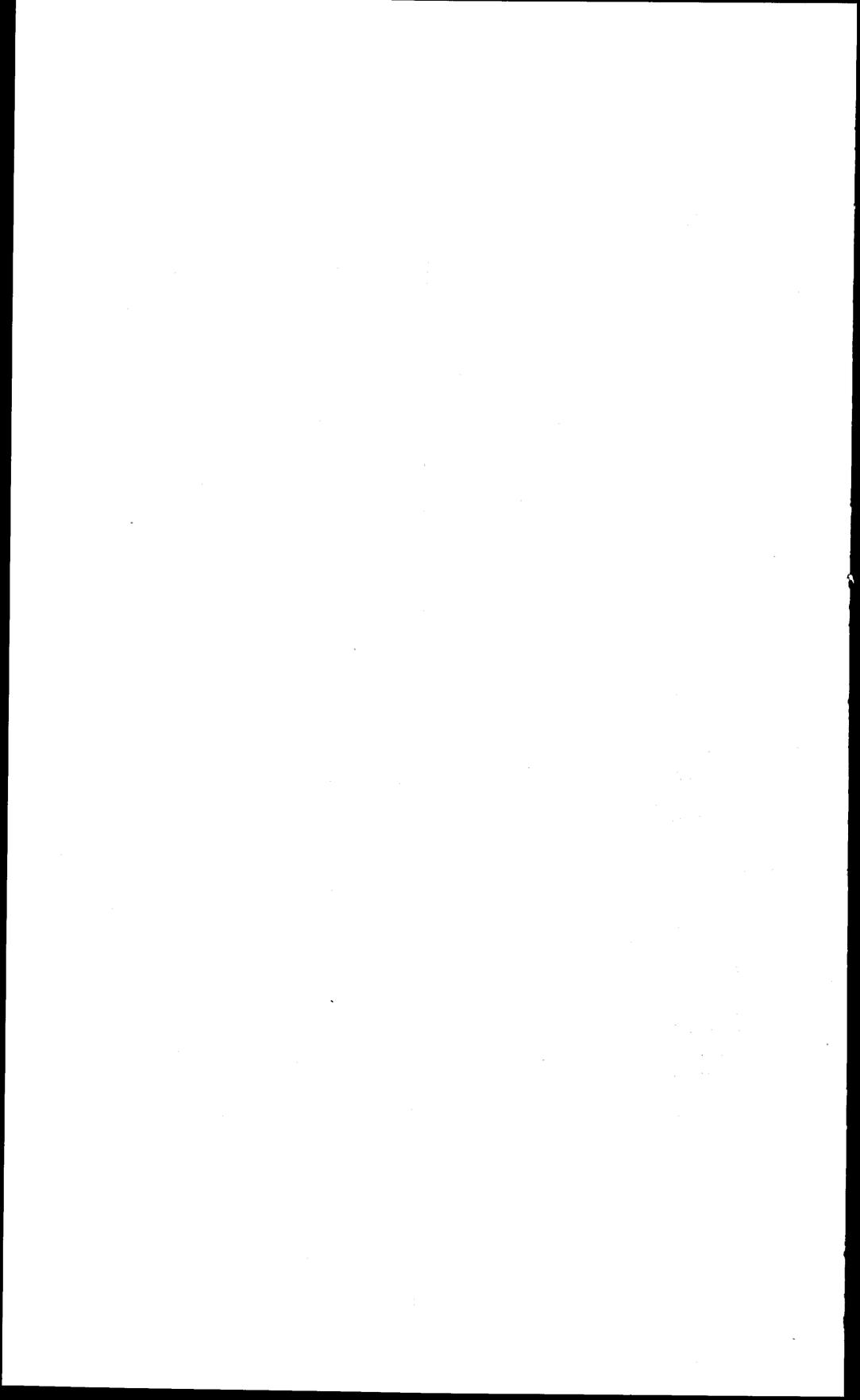
Figure 3-30.—Virginia pine. (A) 1, foliage and cone (quarter-scale); 2, seed (half-scale). (B) Opened cones; photo against 1-cm. grid. (Drawing from p. 66, Guide to southern trees, by E. S. Harrar and J. G. Harrar; © 1946 by the McGraw-Hill Book Company; used with permission of the McGraw-Hill Book Company.)

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3-3 LITERATURE CITED

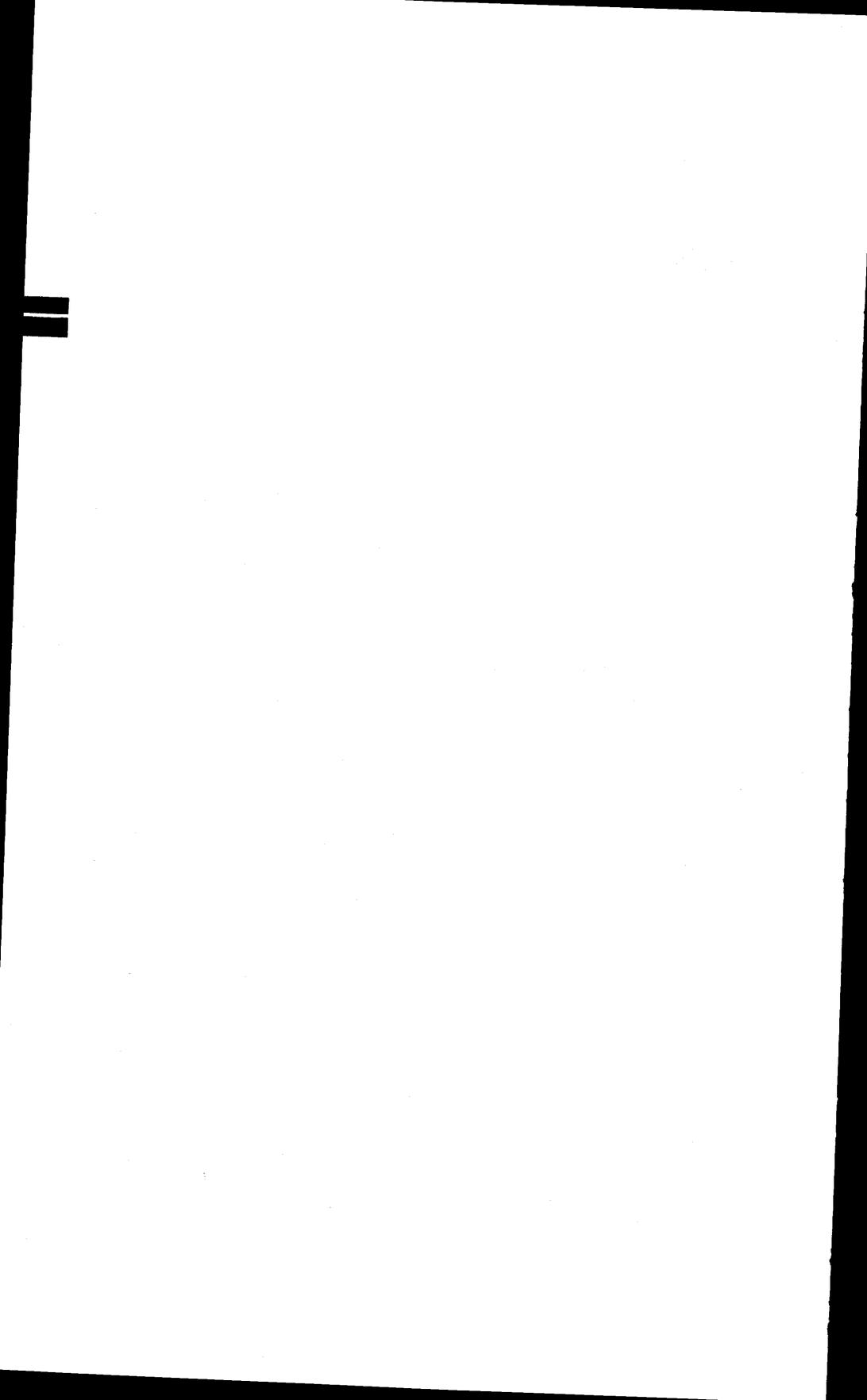
- Critchfield, W. B., and Little, E. L., Jr.
1966. Geographic distribution of the pines of the world. USDA Misc. Pub. 991, 97 pp.
- DeVall, W. B.
1941a. The taxonomic status and ecological variations of certain southern pines. M. S. Thesis. Univ. Florida. 125 pp.
- DeVall, W. B.
1941b. The taxonomic status of *Pinus caribaea* Mor. Proc. Fla. Acad. Sci. 5: 121-132.
- Harlow, W. M., and Harrar, E. S.
1958. Textbook of dendrology. Ed. 4, 561 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Harrar, E. S., and Harrar, J. G.
1946. Guide to southern trees. 712 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Henry, B. W., and Wells, O. O.
1967. Variation in brown-spot infection of longleaf pine from several geographic sources. USDA Forest Serv. Res. Note SO-52, 4 pp. South. Forest Exp. Sta., New Orleans, La.
- Little, E. L., Jr., and Dorman, K. W.
1954. Slash pine (*Pinus elliottii*), including South Florida slash pine—nomenclature and description. USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap. 36, 82 pp.
- Mohr, C.
1896. The timber pines of the Southern United States. USDA Div. Forest. Bull. 13, 160 pp.
- Posey, C. E., Bridgewater, F. E., and Walker, N.
1970. Effect of seed origin on tracheid length, specific gravity, and volume of shortleaf pine in Oklahoma. Forest Sci. 16: 66-70.

- Preston, R. J.
1961. North American Trees—a handbook designed for field use. Ed. 2, 395 pp. Ames, Iowa: Iowa State University Press.
- Saucier, J. R., and Clark, A.
1970. Wood density surveys of the minor species of yellow pine in the Eastern United States. USDA Forest Serv. Res. Pap. SE-63, 16 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Snyder, E. B., Wakeley, P. C., and Wells, O. O.
1967. Slash pine provenance tests. J. Forest. 65: 414-420.
- Squillace, A. E.
1966. Geographic variation in slash pine. USDA Forest Sci. Monogr. 10, 56 pp.
- Sternitzke, H. S., and Nelson, T. C.
1970. The southern pines of the United States. Econ. Bot. 24: 142-150.
- USDA Forest Service.
1965. Silvics of forest trees of the United States. USDA Agr. Handbook 271, 762 pp.
- Wahlenberg, W. G.
1960. Loblolly Pine. 603 pp. N.C.: Duke Univ. Sch. Forest.
- Wakeley, P. C.
1944. Geographic source of loblolly pine seed. J. Forest. 42: 23-32.
- Wakeley, P. C., and Bercaw, T. E.
1965. Loblolly pine provenance test at age 35. J. Forest. 63: 168-174.
- Ward, D. B.
1963. Contributions to the flora of Florida—2, *Pinus* (*Pinaceae*). CASTANEA 28(1): 1-10.
- Wells, O. O., and Wakeley, P. C.
1966. Geographic variation in survival, growth, and fusiform-rust infection of planted loblolly pine. USDA Forest Sci. Monogr. 11, 40 pp.
- Wells, O. O., and Wakeley, P. C.
1970. Variation in longleaf pine from several geographic sources. Forest Sci. 16: 28-42.
- West, E., and Arnold, L. E.
1946. The native trees of Florida. 212 pp. Gainesville: Univ. Fla. Press.



Part II—CHARACTERIZATION OF WOOD

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5	ANATOMY
6	CHEMICAL CONSTITUENTS
7	SPECIFIC GRAVITY
8	WOOD-WATER RELATIONSHIPS
9	PHYSICAL PROPERTIES
10	MECHANICAL PROPERTIES
11	DEFECTS AND GRADES OF TREES AND LOGS



4

Physiology of Wood Formation

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4

Physiology of Wood Formation¹

In trees of the temperate zone, wood formation centers around the seasonal activity of the vascular cambium and the differentiation of its derivatives. The cambium may be viewed as a thin cylinder of generative cells surrounding the woody portion of the stem and protected by layers of inner and outer bark. Each growing season the cambium forms a layer of wood and a layer of bark that is one-tenth to one-sixth as thick as the layer of wood. Most of the wood cells (**xylem**) become thick-walled and lignified; each new layer of inner bark (**phloem**) pushes the older, nonfunctional phloem outward as the stem enlarges. Successive **cork cambia** are formed in the older portion of the inner bark to produce outer layers of suberized cork cells and lignified stone cells. Tissues outside the cork cambia die, and eventually are sloughed off. The activity of the cork cambium gives trees their characteristic bark patterns. (See chapter 12 for a more complete description of bark formation.)

Water from tree roots is conducted upward through the outer portion of the woody cylinder by tensions created in the crown, and is distributed to the cambial cells and to other living cells by osmotic forces. Food in the form of sugar, synthesized in the leaves, is transported through the living inner bark (**functional phloem**) to the cambium, where cell divisions are taking place. Sugars are also conducted radially and stored, mostly as starch, in the horizontal rays.

In all woody species examined thus far, developmental events in the crown are closely related to formation of wood along the bole. Thus, in viewing the physiology of wood formation, one must look at growth patterns throughout the tree. Basic concepts of wood formation are derived from studies of numerous tree species, and in this review these are cited where appropriate. Discussion of environmental effects, however, is based primarily on studies of the southern pines.

¹ With minor editorial changes and additions, sections 4-1, 4-2, and 4-3 are taken from Brown (1970) by permission of Claud L. Brown and the Forest Products Research Society.

Before discussing some of the current concepts relating to the physiology of cambial activity and the differentiation of xylem derivatives, about which the wood technologist is so concerned, we need first to look at the physical nature of the vascular cambium itself.

4-1 THE VASCULAR CAMBIUM

Researchers have not always agreed upon what constitutes the **vascular cambium**. Hartig (1853) came to the conclusion that the cambium is a biseriate layer of cells in which two initials lie adjacent to each other so that one produces xylem cells in one direction and the other produces phloem cells in the opposite direction. Some years later Sanio (1873) suggested that the cambium itself consists of only a single layer of cells; and that each time a division occurs in the **cambial initial** one of the **daughter cells** remains as the cambial initial, while the other cell becomes a xylem or phloem **mother cell**. These mother cells usually divide once or more before their derivatives differentiate and mature into xylem or phloem cells (fig. 4-1).

When one views a radial section of stem during the height of cambial activity, the continued **mitotic activity** (cell division) on either side by the xylem and phloem mother cells makes it difficult, if not impossible, to point out the exact location of the cambial initials. Hence, from time to time objections have been raised concerning the validity of assuming the cambium to be only one cell in thickness. Bailey (1923) pointed out, however, that if the cambium were not **uniseriate** (one cell wide) the radial continuity of differentiating xylem and phloem cells across this lateral **meristem** could not long exist. For example, if a xylem mother cell rather than a cambial initial underwent a **pseudotransverse division** (fig. 4-2) to increase the girth of the cambium, then there would be no phloem counterpart, and new tiers of discontinuous cells would arise on the xylem side of the cambium. Bannan (1957) found such divisions occurring occasionally in the xylem mother cell zone of conifers but not in a ratio high enough to cause serious radial discontinuity.

Most workers today consider that the cambium is a functionally uniseriate layer, but that the width of the xylem and phloem mother cell zone varies with seasonal activity, vigor, and cycle of **periclinal divisions**, i.e., divisions that increase the number of cells in each radial file (fig. 4-3). Frequently the term **cambial zone** is used to describe the entire radial width of the actively dividing xylem and phloem mother cells, including the layer of cambial initials (fig. 4-1). The concept of a functionally uniseriate cambium does not require the cambial initials to be tangentially aligned. That is, adjacent cambial initials may be radially offset according to their immediate state of mitotic activity. A standardized and useful terminology for describing various cell types and tissues associated with secondary activity has been suggested by Wilson et al. (1966).

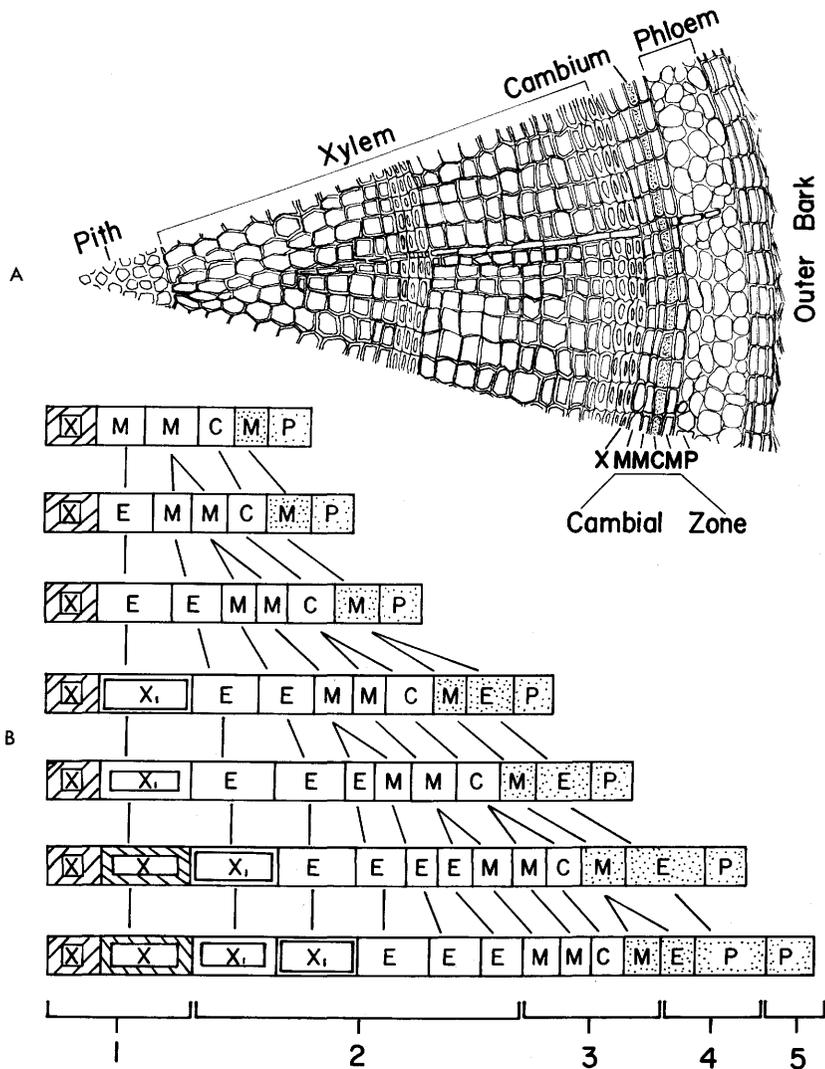


Figure 4-1.—(A) Portion of a transverse section of a young dormant pine stem showing arrangement of tissues. The cambial zone consists of four tiers of radially aligned cells which give rise to new xylem and phloem elements during the growing season. The cambial initials, C, are stippled; cells to the left and right are xylem and phloem mother cells, M, respectively; these are bordered by the previous season's mature xylem, X, and phloem, P, elements. (B) Diagrammatic presentation of how cambial activity might proceed in early spring showing a theoretical sequence of xylem and phloem formation from cells comprising the cambial zone. Cells to the right of the cambial initials, C, are stippled, indicating phloem elements. Xylem and phloem mother cells are labeled M; cells labeled E are undergoing enlargement; cell wall thickening is occurring in xylem elements, X₁; mature xylem and phloem cells are labeled X and P, respectively. Numerals indicate various regions of development: 1, mature xylem; 2, zone of xylem differentiation; 3, cambial zone; 4, zone of differentiating phloem; and 5, mature phloem. (Drawings after Brown 1970.)

VASCULAR CAMBIUM

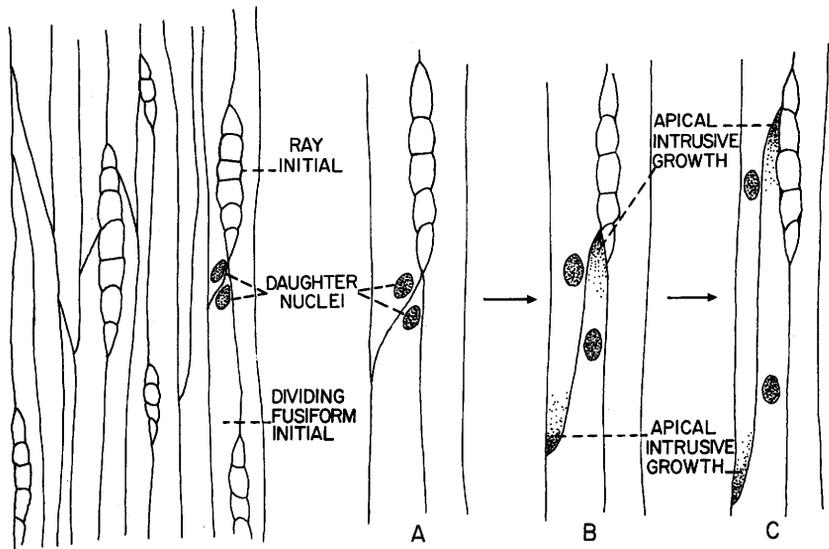


Figure 4-2.—(Left) Tangential view of a segment of vascular cambium showing pseudo-transverse division of fusiform initial. (A,B,C) Later stages of elongation by apical intrusive growth. This type of cell division gives rise to two new fusiform initials, thereby increasing the girth of the cambium. (Drawings after Brown 1970.)

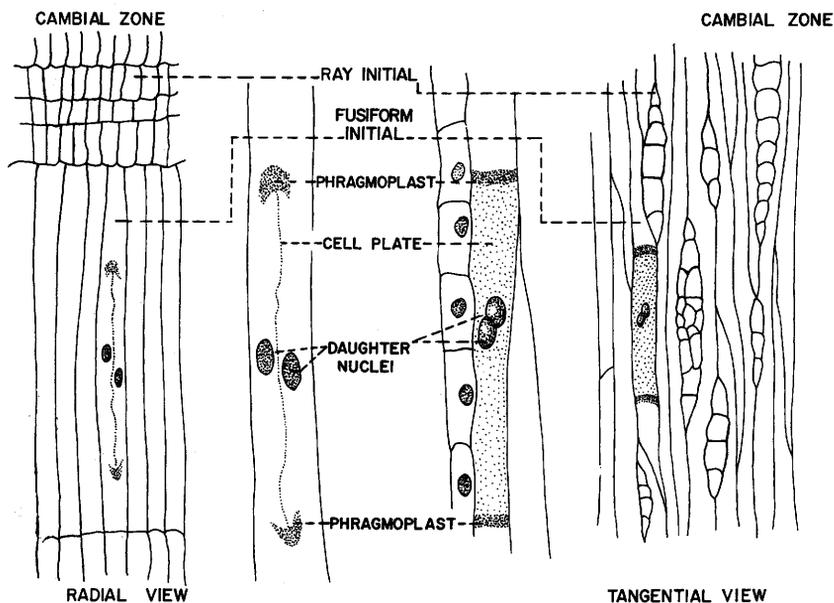


Figure 4-3.—Diagram of periclinal divisions in the cambial zone of a conifer showing radial and tangential views of the same process. This type of cell division gives rise to radial rows of xylem and phloem derivatives. (Drawing after Brown 1970.)

CAMBIAL ORIGIN AND CELL TYPES

The vascular cambium is initially derived from **procambial** cells which differentiate acropetally from preexisting strands into the apex of the elongating primary shoot (fig. 4-4). Here, strands of vertically elongated procambial cells can be traced upward into the young leaves and into or near the base of the apical meristem proper in a pattern outlining the development of the future vascular system. Just beneath the active shoot apex certain of the procambial cells begin differentiating into phloem and

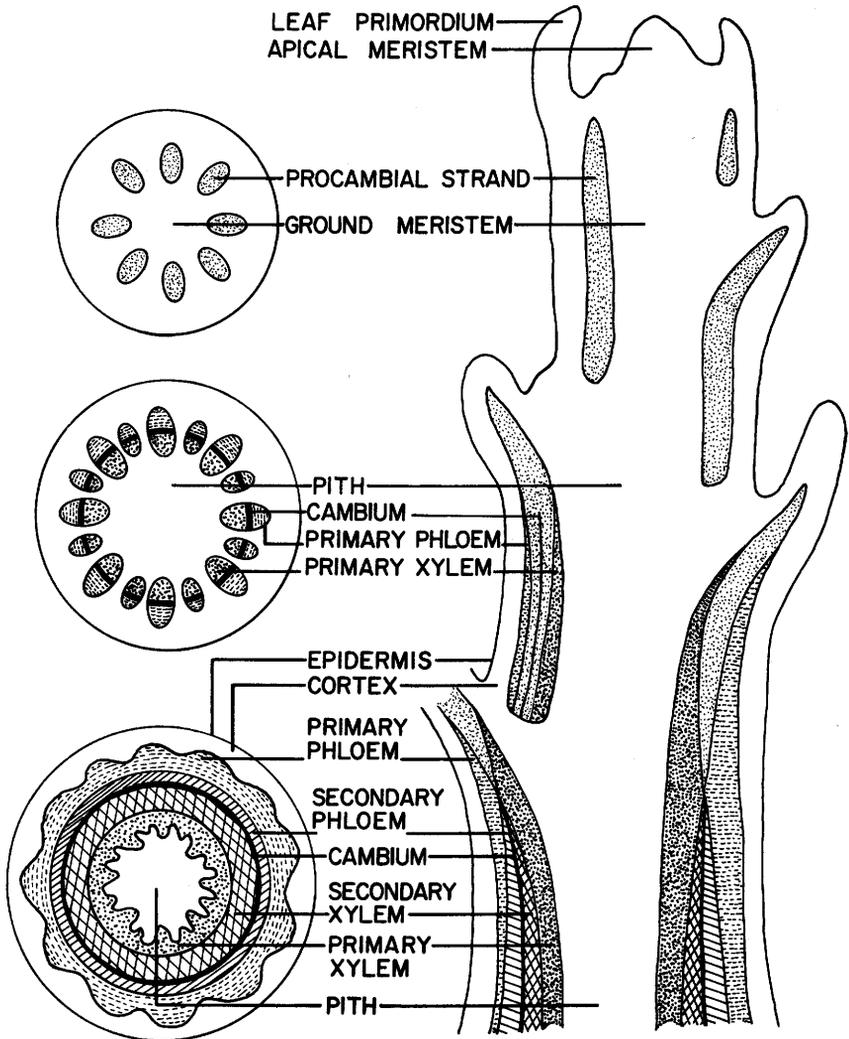


Figure 4-4.—Diagram of stem tip undergoing primary growth showing the pattern of differentiation of primary and secondary tissues at different levels beneath the apical meristem. (Drawing after Brown 1970.)

xylem elements. The first phloem elements, i.e., **sieve cells**, usually begin to differentiate acropetally along the outer margin of the procambial strand from the preexisting phloem elements of the preceding leaf trace. Usually the **primary phloem** begins to differentiate before the first **primary xylem** elements. From a nutritional standpoint this is what one would expect, because the mobilization and transport of sugars and other nutrients are crucial for the continued high metabolic activity of the shoot apex during extension growth.

The differentiation of primary xylem elements proceeds on the inner side of the procambial strands, commonly near the base of the young leaf or scale primordium, and from there it develops acropetally into the young appendage and basipetally until it connects with the mature primary xylem beneath. Following the maturation of the primary xylem and phloem the central portion of the vascular bundle remains meristematic and functions as the vascular cambium. The cambium becomes a continuous circular sheath in the maturing portion of the elongating woody shoot by the tangential differentiation of new cambial initials through the ground meristem connecting the separate vascular bundles.

The vascular cambium is made up of two cell types: (1) **fusiform initials**, and (2) **ray initials**. The former are elongated cells with tapering ends whereas the ray initials are much smaller and almost isodiametric in shape. Although the fusiform initials may appear to be only four- to six-sided to the inexperienced observer, Dodd (1948) found those of Scotch pine (*Pinus sylvestris* L.) to have on an average 18 faces. The configuration of fusiform initials in other conifers is similar but it varies among species. The dimensions and volume of the fusiform initials vary widely within the same tree with age and location, as well as among species. This was first clearly elucidated in Scots pine by Sanio (1872), and substantiated by later workers in both gymnosperms and angiosperms (Spurr and Hyvärinen 1954). Because the fusiform initials give rise to all the vertical elongate elements of the xylem and phloem, the many physiological factors affecting their initial and final dimensions are important to the kind and quality of wood produced.

The ray initials (fig. 4-3) give rise to tiers of horizontal rays connecting the food-conducting channels of the phloem with the living storage cells in the xylem. Food in the form of sugars moves radially from phloem cells, through adjacent ray cells, to the fusiform initials of the cambium and to living ray cells of the sapwood. The network of rays serves in lateral food movement and storage of reserve food for use in seasonal growth.

The cambium of the southern pines, like that of all conifers, is **non-storied**, i.e., the end walls of the fusiform initials overlap by varying degrees as a result of the pattern of cell division which increases the girth of the cambium to keep pace with the ever increasing interior cylinder of xylem. This type of division, in contrast to the true **tangential periclinal**

divisions (fig. 4-3) which add new xylem and phloem derivatives to the radial axis, occurs in a **pseudotransverse** manner (fig. 4-2) giving rise to the formation of obliquely radial walls, followed by the elongation of the cells at their apices (**apical intrusive growth**) until each daughter cell is as long as, or longer than the original fusiform initial (Bailey 1923).

The careful and extensive work of Bannan (1954, 1955, 1956, 1957) in northern white-cedar (*Thuja occidentalis* L.) has shown that during the first few years of rapid diameter growth pseudotransverse divisions are frequent and occur throughout the growth ring. The frequency of these divisions, accompanied by a high survival rate, normally results in the formation of short fusiform initials and consequently short tracheids. Later pseudotransverse divisions are less frequent, and restricted to the latewood zone in each growth ring, and fewer of the newly formed initials survive. In mature trees most of the pseudotransverse divisions are in the last formed latewood, and survival of the daughter initials is low, so that the surviving cells elongate rapidly into the spaces left by the aborted initials. Hence, the length of fusiform initials and tracheids increase until a maximum is reached for the species. Thereafter, yearly fluctuations in tracheid length reflect the many subtle and complex growth responses of the vascular cambium.

4-2 PHYSIOLOGY OF CAMBIAL ACTIVITY

ACTIVATION OF THE CAMBIUM

Well over a hundred years have passed since Hartig (1853) made the pertinent observation that radial growth usually begins at the base of expanding buds and spreads downward into the branches and trunk. The rate at which cambial activity progresses from the shoots to the base of the trunk varies significantly with species. Jost (1891) postulated that the stimulus which activated the cambium was hormonal in nature and in no way directly related to the then prevalent nutritional theory of cambial growth. Later, Jost (1907) essentially abandoned this theory and stated that the formation of new leaves and xylem is dependent upon nutritional factors and that correlative (hormonal) effects were not involved. In the years to follow, however, Kastens (1924) and Coster (1927, 1928) revived Jost's original ideas, and again postulated a hormonal stimulus. Until the 1930's the strongest evidence for hormonal stimulus came from numerous disbudding and ringing experiments (girdling), which established that buds and leaves produced some substance(s) which was removed, or whose downward movement was blocked, by these treatments.

The discovery and isolation during the late 1920's and early 1930's of natural growth-promoting substances in plants, suggested that indole-3-acetic acid (IAA), produced in active buds and elongating shoots, is the

hormonal stimulus activating the cambium in the spring (Zimmerman 1936; Avery et al. 1937; Söding 1937).

Although some workers conclude that auxin, i.e., IAA, is the sole stimulus activating the cambium in early spring, considerable evidence is accumulating that other substances, both promoters and inhibitors, are involved.

The periodicity of cambial activity is not solely a function of auxin level. For example, in early spring the dormant cambium is much more responsive to a given level of applied IAA in decapitated branches than it is later in the season, or in dormant branches before a period of winter rest (Reinders-Gouwentak 1941). This may indicate that inhibitory substances have accumulated during the previous growing season and must be removed during a period of rest before IAA can exert its effect on cambial activity. It may be also that the levels of other growth-promoting substances, such as gibberellins and cytokinins, which interact with natural inhibitors and native auxin are so low that the latter cannot exert full effect.

In contrast to the hypothesis that buds must always be present to activate the cambium of deciduous trees (Wareing 1951, 1958), experiments by Münch (1938) with eastern white pine (*Pinus strobus* L.), showed that activation of the cambium with disbudded shoots was possible; it was inhibited only when the shoots were disbudded and defoliated simultaneously. Thus in evergreen conifers the stimulus can apparently be derived from older, as well as young, developing leaves. Münch also found cambial activity to be completely inhibited immediately below a bark girdle, but a short distance lower the cambium became more active than in non-girdled stems. Such studies indicate that the initiation of cambial activity in conifers may be less dependent on actively growing buds and leaves than in the angiosperms. They also suggest that once the cambium is activated it can perhaps supply its own source of auxin and other growth factors quite independently of a continuous basipetal flow from the developing or mature shoots in the crown. Jacquot (1950), using cambial explants (i.e., excised tissue) of several woody species, was also able to obtain cambial activity in vitro for periods of 6 to 8 weeks without an **exogenous** (i.e., outside metabolic) source of auxin.

In more recent experiments with diffuse and ring-porous hardwoods, Wareing (1958) and Wareing et al. (1964) have shown the interacting role of IAA with gibberellic acid (GA) in activating the cambium and controlling the pattern of differentiation in the newly formed derivatives. In the completely disbudded control shoots of English sycamore (*Acer pseudo-platanus* L.), "Robusta" poplar (*Populus robusta* Schneid. (X *P. angulata* x *P. nigra plantierensis*)), and European ash (*Fraxinus excelsior* L.), there was no evidence of renewed cell division in the cambium, whereas in both IAA- and GA-treated stems new cambial derivatives were formed. When IAA was applied alone, new xylem elements were formed in dis-

continuous groups around the periphery of the stem with little evidence of any cell division occurring between the groups. In the shoots treated with GA alone, cell divisions occurred throughout the cambium, producing an inner continuous layer of xylem derivatives which failed to differentiate further into normal xylem elements. When IAA and GA were applied together to the disbudded shoots, however, a wide zone of new, normally differentiated xylem developed. Thus, only IAA and GA together stimulated cambial activity and produced normal wood.

Whether or not gibberellin plays a comparable role in stimulating cambial activity in gymnosperms, especially in the southern pines, has not yet been demonstrated. Concentrations or levels of GA which promote internodal elongation of various angiosperms tend to inhibit or have no growth promotion effect on conifers (Nelson 1957; Westing 1959; and Kraus and Johansen 1960). It may be that the conifers already possess a supra-optimal level of gibberellin or gibberellinlike substances, since the structure of these compounds resembles other terpenoids plentiful in these plants. This is purely speculative, however, and a precise quantitative study of the seasonal levels of IAA, GA, and cytokinins at various distances along the bole of woody plants is urgently needed to elucidate the pattern of hormonal control over cambial activity. Conclusive studies are difficult because, as Wareing et al. (1964) point out, disbudded stems contain small quantities of auxins and other growth factors, so that external application of one may be sufficient to bring about cambial cell division in the presence of low concentrations of the others.

All of the recent studies relating to cambial physiology indicate, however, that the activation and continued activity of the cambium in woody plants involves more than just the presence of IAA coming from expanding buds. The work of Wareing et al. (1964), as well as numerous other studies, shows that IAA's role in the differentiation of mature xylem elements may be more prominent than its role in cell divisions per se. Although IAA has some effect on cell divisions in the cambium (likely in the presence of cytokinin) it appears that the effect of GA is much greater. GA exerts little or no apparent effect upon xylem differentiation and the maturation of normal xylary elements. Initiation of cambial activity is apparently a complex interaction between the levels of more than one type of growth promoter (IAA and GA, and perhaps the cytokinins) and the level of inhibitors. The inhibitors are either counterbalanced by a high concentration of growth promoters, or reduced to a lower level during a period of winter rest.

PRODUCTION, DIFFERENTIATION, AND MATURATION OF TRACHEIDS

Because the radial diameter and cell wall thickness of the conifer tracheid vary with the season in which the tracheids are produced, and because these differences greatly influence wood quality, we need to look at this sequence of events from a physiological viewpoint.

Following the rehydration and swelling of the cambium in early spring, cell divisions begin to occur in the xylem mother cells lying adjacent to the cambial initials; divisions then begin in the initials themselves, until a peak rate of cell production is reached a few weeks later (Bannan 1954; Wilson 1964; Wilson and Howard 1968). In white pine, for example, the cambial zone in winter is only four to eight cells wide, but in the spring it thickens to 10 to 15 cells wide in fast-growing trees. From the spring peak, the width of the zone gradually decreases again to the dormancy level at the end of the summer. Two quantitative studies have been made of the distribution of mitoses across the cambial zone in northern white-cedar and eastern white pine (Bannan 1955; Wilson 1964). Both of these show a peak frequency in the center of the zone.

During the period of most frequent cell division, in late spring and summer, radial enlargement of xylem mother cells is rapid but only slight, since they redivide when 10 to 15 μm . wide. (A micrometer is 10^{-6} meter.) Cells which do not divide further continue to enlarge, and they may reach radial diameters of 40 to 50 μm . The final radial diameter depends largely on the seasonal growth pattern or environmental conditions imposed upon the trees during this period.

The number of cells in the zone of enlargement is a function of the rate of their entry from the cambial zone, the duration of enlargement, and their final loss into the zone of maturation where cell walls thicken and lignify. Moehring et al.², in observations of 27-year-old loblolly pines, noted that 17 to 40 days were required for cells to enlarge. During the phase of division and enlargement, cells possess only their primary walls.

Secondary wall formation begins as enlargement ceases (Wilson and Howard 1968). The mechanism of secondary cell wall formation is beyond the scope of this text; the interested reader is referred to reviews by Wangaard (1970) and Berlyn (1970). The factors determining the number of cells undergoing wall thickening are the rate of entry into this zone, the duration of the process, and loss of cells at maturity. The time is a function of rate of cell wall thickening and the final thickness attained (Wodzicki and Peda 1963). In 27-year-old loblolly pine, Moehring et al.² observed that 12 to 55 days were required—after completion of cell enlargement—for completion of wall thickening. Thus, the radial diameter and wall thickness of a mature tracheid are determined at the time the cell finishes these separate phases of differentiation. Radial diameter is greatest in tracheids formed early in the season; it generally decreases gradually during the summer until the last-formed tracheids are radially flattened and similar in shape to the cells of the cambial zone. Cell wall thickness is at a minimum in the early-formed tracheids but gradually

² Moehring, D. M., Grano, C. X., and Bassett, J. R. Wood formation in 27-year-old loblolly pine under irrigation and simulated drought. USDA Forest Service, Southern Forest Experiment Station Final Report FS-SO-1115-2.3, dated May 21, 1970.

increases until a maximum is reached near the end of the season; it often decreases again in the last formed cells at the very end of the season (Wodzicki 1962).

Various researchers have concluded that the two variables, radial cell diameter and cell wall thickness, are independent of each other, although in nature they are commonly associated in growth ring formation (Wodzicki and Witkowska 1961; Larson 1962; Zahner and Oliver 1962). By manipulating photoperiod, light intensity, and water stress, one can produce tracheids, at least in seedlings and young trees, possessing almost any combination of radial diameter and wall thickness. Such experimental results support the concept of hormonal control over growth ring formation (Wareing 1958; Larson 1960), because such treatments directly affect shoot extension and leaf formation which in turn control the levels of growth hormones produced.

Briefly, the concept of hormonal control relates the production of high levels of diffusible and downwardly transported auxin (presumably IAA, associated with shoot extension and leaf development) with the formation of large diameter cells of the earlywood type. Conversely, the cessation of shoot growth accompanied by reduced levels of diffusible auxin is related to the initiation of latewood formation. Thus, environmental conditions would indirectly affect the number and radial size of developing cells by directly affecting shoot and root development and hence altering levels of IAA. As already pointed out, the normal increase in wall thickening and the accompanying decrease in cell diameters during growth ring formation, although seasonally correlated, are apparently controlled by independent physiological processes. Larson (1964) suggests that the phase of cell wall thickening is highly correlated with current net photosynthate production and distribution. For example, during periods of rapid shoot and leaf development most of the photosynthate is mobilized and used in these rapidly growing centers. Following cessation of terminal growth, current photosynthate is shunted or reshuttled into the bole and incorporated into cell walls.

One of the apparent anomalies of the auxin concept of growth ring formation is that the transition from large diameter earlywood tracheids first occurs near the base of the tree and moves upward, whereas the cessation of cambial activity (cell division) apparently occurs in the opposite direction. Larson (1962) explains the formation of latewood at the base of the tree in terms of an auxin gradient along the bole. For example, during the early surge of shoot growth in the spring a high level of auxin is produced all along the bole and large diameter earlywood cells are produced. As shoot extension slows down and ceases the levels of transported auxin begin to decrease so that the cambial cells farthest from the source are affected first, and the transition to narrow lumen cells begins at the base. In the upper portion of the bole and crown, the auxin level from the developing leaves remains sufficiently high to permit the forma-

tion of earlywood tracheids during most of the season. This pattern of auxin distribution or gradient would thus account for the production of juvenile wood possessing poor growth-ring differentiation some distance beneath the crown. Even the cells produced late in the season in the upper bole are more like earlywood than latewood in lumen size and radial diameter. This type wood is found throughout the central core of the tree bole, and progresses upward as the tree grows in height. Finally during the latter period of seasonal growth, the auxin level drops even lower and cambial activity ceases.

The real anomaly now arising is the pattern of ultimate cessation of cambial activity. If, as most studies indicate, cambial activity ceases first in the twigs because the auxin supply there reaches a critical level, then the cambium lower down the bole would have to produce a sufficient level of auxin autonomously if latewood formation is to continue. This pattern of activity lends support to the concept of the formation of some type of inhibitor in the foliage which, translocated downward, interacts with auxin, gibberellins, and perhaps other growth factors, in bringing about the formation of latewood and the ultimate cessation of radial growth. It should be recalled that in the studies of Wareing (1958) and Wareing et al. (1964) gibberellin had a greater effect in the initiation of cambial activity than auxin (IAA) alone. It undoubtedly continues to play a major rôle in the process of cell division throughout the season.

It is also of interest to note that cell wall thickening, another feature of latewood formation, normally begins at the base of the tree and moves upward although it is not necessarily synchronized with the pattern of cell enlargement previously described. If, however, this aspect of latewood formation is related to net assimilation or reshuttling of photosynthate from the crown to the bole as suggested by Larson (1964), then one might expect a reverse pattern of cell wall thickening in older and larger trees. Cells nearest the site of photosynthate production, i.e., in the lower crown and upper bole, should logically be the first to assimilate this carbohydrate into cell wall material.

Wodzicki (1964, 1965), in studying the formation of latewood in European larch (*Larix decidua* Mill.), suggests that wall thickness is mediated by the formation of an inhibitor in the foliage during seasonal development. He finds that the levels of water-soluble inhibitors in the leaves and cortex of larch and Scotch pine are more highly correlated with the maturation of xylem cells than are decreasing levels of auxin.

Balatinecz and Kennedy (1968) followed in considerable detail the seasonal pattern of indolic compounds in 40-year-old European larch in Ontario. They reported high levels of auxin activity along the bole in spring when earlywood is being formed and lower levels of auxin with increased concentration of a phenolic growth inhibitor, during the season of latewood formation. They supported the concept that endogenous growth substances control the mechanism of growth-ring formation trans-

lating the effects of physical environmental factors into biochemical mechanisms of control.

One can conclude that auxin alone can no longer be accepted as the singularly most important hormone involved in activation of the cambium, the production and differentiation of cambial derivatives leading to growth-ring formation, or the cessation of cambial activity. It becomes increasingly obvious that the seasonal levels of several types of growth promoters, viz. auxin, gibberellins, and cytokinins, operating in the presence of different levels of natural growth inhibitors, about which we know little, control the complex physiology of xylem formation.

4-3 EFFECT OF ENVIRONMENT ON WOOD PROPERTIES

Within the past decade, concomitant with the rapid upsurge in tree improvement activities, numerous studies have been made on the intra- and interspecific variability in anatomical characteristics of slash, loblolly, and other southern pines as they relate to wood quality (Kramer 1957; Jackson and Green 1958; Perry and Wang 1958; Goggans 1962; Thor 1964; Jackson and Morse 1965ab; Barefoot et al. 1966; Cole et al. 1966; Goddard and Cole 1966; Saucier and Taras 1966; Wangaard et al. 1966; Wheeler et al. 1966). Specific gravity and fiber length were studied by most of these authors because these properties affect the strength of lumber and the yields of kraft pulp and paper.

While these and other wood properties are markedly influenced by the conditions under which trees are grown, the relative significance of these environmental factors and their degree of control over specific properties have yet to be satisfactorily evaluated. Thor and Bates (1970), for example, found that only a small amount of the variation in shortleaf pine wood properties was accounted for by site variables.

The literature reveals much confounding data and many conflicting viewpoints on such basic relationships as the effect of growth rate on specific gravity and fiber length in different species. Inadequate understanding of the patterns of variation within individual trees caused much confusion. Only recently have such variables as age and position been properly accounted for in sampling trees for study (Spurr and Hsuing 1954; Spurr and Hyvärinen 1954; Zobel and Rhodes 1955; Larson 1957; Dinwoodie 1961).

SPECIFIC GRAVITY

Although specific gravity is a gross measurement reflecting the sum of numerous variables within successive individual growth rings, it has been investigated more than any other wood property. This is because specific gravity strongly affects the strength of lumber and yield and quality of kraft pulp and paper.

Specific gravity varies significantly within the tree with height and radial position outward from the pith, both of which are functions of age. Thus, the core, or so-called **juvenile wood** has a lower specific gravity than outer or mature wood (Spurr and Hsuing 1954; Zobel and Rhodes 1955; Larson 1957). The relatively low specific gravity of wood from young trees and the tops of mature trees reflects their high ratio of juvenile to mature wood. This relationship must be taken into account in evaluating the effects of environmental factors on wood specific gravity.

In one of the earlier studies of the effect of environment on the wood of loblolly pine, Zobel and Rhodes (1955) found little correlation between specific gravity and growth rate, soil moisture (moist vs. dry sites), site index, soil characteristics, or stand density. They did, however, find a relatively good correlation between percent of latewood and specific gravity.

Larson (1957), in an extensive study of environmental effects on the specific gravity of slash pine, obtained essentially the same results, i.e., the percentage of latewood accounted for more than 60 percent of the total variation in specific gravity, and tree age had a controlling effect on percent of latewood in cross sections of the stem. The latewood percentage increased from about 40 percent at age 6 to about 60 percent at age 20, and thereafter tended to remain fairly uniform. Within the range normally encountered in managed stands of slash pine, rate of growth, i.e., ring width, had essentially no effect on either specific gravity or latewood percentage.

In these studies, Larson found no relationship between percent of latewood and mean plot age, stand density, site index at 50 years, site quality at 25 years, or length of growing season. The only stand variables that accounted for between-plot variation were those related to the moisture-holding capacity of the soil; high soil moisture produced the lowest percent of latewood. The percentage of latewood increased with increasing June and July precipitation and decreased with increasing January and February precipitation. The multiple regression of the two variables, June-July rainfall and depth to a fine-textured horizon, accounted for 55 percent of the total variation in percent of latewood. Larson, like Zobel and Rhodes (1955), concluded that differences in specific gravity of slash pine existed after all quantitative sources of variation had been accounted for, and that these differences probably represented genetic variation among individual trees.

McElwee and Zobel (1963), in studying pond pine in the Coastal Plain of North Carolina, found highly significant variations in specific gravity within and between plots, but no strong relationship between rings per inch and specific gravity. Age accounted for only 3 percent of the variation in specific gravity of mature wood, and growth rate accounted for only 7 percent.

Other workers have attempted to relate stem diameter and crown class of

individual trees to specific gravity. Statements are often found in the literature that for immature trees of the same age, the largest or dominant trees usually have the lowest average specific gravity while the suppressed trees usually have the highest. Paul (1927), for example, compared five open-grown longleaf pines with a similar number of adjacent forest grown trees of the same age (25 years old) and found that the outer growth rings of the latter had the highest specific gravity. Also, Bray and Paul (1930) thinned three longleaf pine plots (30 to 35 years old) to different degrees and found that the plot with the highest mean diameter had the lowest mean specific gravity. Marts (1949) found that reduction in crown size of longleaf pine by pruning reduced overall diameter growth, and increased specific gravity in the lower bole by reducing the proportion of earlywood produced there. In other studies relating to silvicultural treatments Paul (1958) found that loblolly, shortleaf, and longleaf pine, after release from varying degrees of competition by thinning, may produce wood with either higher or lower wood density than before, depending again upon the ratio of earlywood to latewood in the annual ring.

From these and other studies, it is obvious that environmental factors which influence wood specific gravity are largely those that directly affect the percentage of latewood. Correlation between specific gravity and any one factor of the environment is usually poor because the decrease in cell diameter and the increase in cell wall thickening which produce latewood are ultimately controlled by independent physiological processes.

These may be influenced to varying degrees by any of several environmental factors affecting growth such as temperature, light intensity, day length, and water stress. Only when some environmental factor such as soil moisture becomes limiting does it affect tracheid size and/or cell wall thickening enough to show a good correlation between that factor and specific gravity.

During the period of earlywood formation which accompanies rapid shoot growth and needle formation, the level of auxin in the cambial zone throughout the tree is adequate for the radial enlargement of differentiating tracheids in the xylem mother cell zone which results in earlywood tracheids. As water stress develops, crown growth slows, and auxin levels decline, causing the shift from earlywood to latewood (Larson 1963; Zahner et al. 1964).

Although photoperiod has been most useful as a tool in studying the effects of shoot growth and needle extension on early- and latewood formation, there is no evidence that day length per se is involved in latewood formation in the southern pines. Most conifers of the temperate zones begin to form latewood when day lengths are at or near maximum (June-July).

Richardson (1964) found that the influence of temperature on cell diameter in first-year seedlings of redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is sim-

ilar to its effect on tracheid length; increasing night temperature up to 25° C. results in increased radial diameters. The same relationship also held true for seedlings of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Monterey pine (*Pinus radiata* D. Don). Richardson (1964) also reported that variation in light intensity and height growth per se had no direct effect upon tracheid diameter.

The relationship between specific gravity and the ratio of earlywood to latewood within individual growth rings in the southern pines is largely dependent upon the amount of wall thickening of individual cells. Wall thickening has been linked to nutrition, especially the availability of photosynthates (Oppenheimer 1945; Larson 1960, 1962, 1964). Wodzicki (1960) and Wodzicki and Witkowska (1961) in experiments with Polish larch seedlings (*Larix polonica* Rac.), however, found no correlations between cell wall thickness and the amount of foliage present which is directly related to total photosynthate produced. Also, in ringing experiments above and below a well-developed lateral shoot, cell wall thickening was affected more by short photoperiods than it was by increasing or reducing available photosynthate through blocking phloem transport by ringing.

Van Buijtenen (1958), on the other hand, found that variations in photoperiod or soil moisture had no apparent effect on tracheid wall thickness in seedlings of loblolly pine, but wall thickness decreased with increasing temperature. Zahner (1962), working with young loblolly pine trees, found a higher percentage of latewood in growth rings of trees grown under dry conditions.

Richardson (1964) studied Douglas-fir and redwood, which vary little in wall thickness across the growth ring when grown under constant environmental conditions, by varying such conditions as day and night temperatures, light intensity, and photoperiod. He found a clear inverse relationship between cell wall thickness and night temperature, but the effect of day temperatures was inconsistent. It was argued that the decrease in night temperature affected the level of carbohydrate available to the seedlings. Close correlations were also found between stem density and leaf weight. Richardson also found an increase in cell wall thickness in Sitka spruce and Monterey pine seedlings with increasing light intensity up to full sunlight. He interpreted these results as nutritional effects, supporting the hypothesis that cell wall thickness is largely determined by the level of available photosynthate.

These studies seem rather conclusive, and no doubt a critical level of available carbohydrate is essential for cell wall synthesis. Nevertheless, ringing the stems of most conifers, though significantly increasing carbohydrate levels above the girdle, does not ordinarily increase cell wall thickness. In addition, in every instance where defoliated internodal stem segments of Japanese larch (*Larix leptolepis* Endl.) and Japanese red pine (*Pinus densiflora* Sieb. and Zucc.) were supplied with high levels of sucrose

(2 to 15 percent), the cells differentiated in the cambial zone were the thin-walled, earlywood type rather than the thick-walled latewood type (Brown and Wodzicki 1969). It is also of interest that appropriate levels of exogenous IAA applied to decapitated pine seedlings result in the formation of thin-walled earlywood tracheids, whereas supra-optimum levels of IAA at similar carbohydrate levels result in the formation of exceedingly thick-walled, radially enlarged tracheids of the compression wood type (Larson 1962). Although one may argue that these results are obtained under abnormal experimental conditions, they indicate that cell wall thickening is mediated by a mechanism involving more than just the level of available carbohydrate.

TRACHEID LENGTH

As previously mentioned, tracheid length is an important feature of wood from the standpoint of several strength characteristics, especially in the manufacture of kraft paper from southern pines. Several reviews have been made of the voluminous literature covering variations in tracheids and fiber length in conifers and hardwoods (Spurr and Hyvärinen 1954; Richardson and Dinwoodie 1960; Dinwoodie 1961); data specific to the southern pines are treated in detail in section 5-8.

Numerous studies have essentially confirmed and added to the early observations of Sanio (1872) on tracheid variation within individual trees. At present it seems safe to make the following generalizations about tracheid length in southern pine: (1) bolewood tracheids are on the average longer than those of the branches, but may be shorter than those of the roots; (2) tracheid length increases from the pith outward until it reaches a maximum level at age 20 to 60 years after which it varies somewhat at random; and (3) tracheid length increases from the base of the stem upward until it reaches a maximum length and then decreases toward the top.

As Richardson (1964) has pointed out, attempts to correlate tracheid length with rate of stem diameter growth have resulted mostly in negative relationships, or in many cases no significant correlation. While there may be an association between tracheid length and environmental factors affecting growth, no causative relationship has yet been found. Little correlation has been found between the rate of growth and tracheid length in Monterey pine (Dadswell et al. 1961; Nichols et al. 1964), Scotch pine (Echols 1958), loblolly pine (Kramer 1957; Coggans 1962), Japanese red pine (Hata 1949), eastern white pine (Thor 1964), and Virginia pine (Thor 1965). Strickland and Goddard (1966), however, found negative relationships between tracheid length and growth rate, and tracheid length and specific gravity in slash pine. In a study of 8-year-old loblolly pine under intensive culture, Choong et al. (1970) observed that diameter growth was positively correlated with tracheid length ($r = 0.41$) in the outer sapwood only.

In a study of 72 spruce pines sampled throughout the major commercial range of the species, Manwiller³ found that fast-grown trees (less than 6 rings per inch 1 foot above ground level) in the three age classes he studied had longer tracheids than those in slower growing trees (more than 6 rings per inch) as follows; each value is a 12-tree average:

Tree age	Tree-average tracheid length	
	Slow-grown trees	Fast-grown trees
<i>Years</i>	----- <i>Millimeters</i> -----	
15	3.24	3.37
30	3.44	3.72
45	3.86	4.04

Manwiller's data did not show a strong correlation between wood specific gravity and tracheid length.

In these and other studies, significant differences in the average length of tracheids among trees of the same species growing on similar sites have also been found in slash pine (Jackson and Green 1958), loblolly pine (Kramer 1957; Jackson and Greene 1958; Zobel et al. 1960), pond pine (McElwee and Zobel 1963), eastern white pine (Thor 1964), and Virginia pine (Thor 1965).

Although all of these studies indicate considerable genetic variability in tracheid length, virtually nothing is known about the environmental component of tracheid variation in the southern pines because meaningful, controlled experiments have yet to be undertaken.

Richardson (1964) in his studies of Douglas-fir and redwood seedlings grown under constant light intensity and photoperiod, found a distinct relationship between tracheid length and temperature, with higher temperatures (7° to 23° C.) resulting in significantly longer tracheids. Night temperature showed greater effect than the daytime temperature. In other studies he found that tracheid lengths of Sitka spruce and Monterey pine increased with both night temperatures and light intensity. Also, within treatments, tracheid length was linearly related to height increment but was not associated with stem or leaf dry weight.

Additional evidence that temperature was causally related to tracheid length was obtained by placing "temperature bridges" at 25° C. (5° C. above ambient) around portions of the stem of Sitka spruce seedlings. After 6 weeks tracheid lengths were measured above, within, and below the bridge, and found to be consistently longer where the stem temperature was higher.

To test the effect of light intensity and the possible role of increased carbohydrate assimilation on tracheid length, girdling experiments were conducted and the length of tracheids compared above and below the

³ Manwiller, F. M. Characterization of spruce pine. USDA Forest Service Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1, dated May 1, 1972.

girdles. In all cases observed, tracheid lengths decreased rather than increased above the girdles. Richardson explained this anomaly as the result of pseudotransverse divisions occurring after girdling. The increased levels of carbohydrates above the girdle permit survival of the shorter derivatives which are normally lost by abortion because they contact fewer ray cells than the long ones. At any rate, increases in tracheid length with increased light intensity cannot be explained in terms of local increases in carbohydrate levels.

From these studies it is clear that tracheid length is highly dependent upon cambial characteristics which change with age and position along the bole, and is influenced to a lesser degree by processes of postcambial differentiation such as elongation following cell division. From the standpoint of auxin concentration alone, one would expect the longest tracheids to occur in close proximity to the rapidly elongating shoots in the crown, but this pattern does not occur. Therefore, in the absence of sufficient experimental data, we can do little more than describe the patterns of variation in tracheid length within and among trees.

FIBRIL ANGLE

The cellulose portion of the woody cell wall is organized into microfibrils. These threadlike structures of indefinite length are visible only with the electron microscope. In the thickest layer of the cell wall (middle, or S_2 layer of the secondary wall) the microfibrils are arranged more or less parallel to each other, but in a steep spiral with relation to the long axis of the cell. The angle they make with the longitudinal axis of the cell is called the **fibril angle** (see chapter 5, figs. 5-8, 5-12, 5-43 through 5-51).

Section 5-8 reviews the literature on fibril angle variation between species, within species, and within trees. In brief, both tracheid length and wall thickness are negatively correlated with fibril angle; earlywood has higher fibril angles than latewood and corewood has higher angles than outer wood.

The variation in fibril angle shows consistent patterns within individual trees. It normally decreases with distance from the pith until average angles of about 10° are first reached in loblolly pine in the sixth to 10th ring (Pillow et al. 1953). This corresponds roughly to the core of "juvenile wood" present in the sampled trees. Thus, although there is a correlation between fibril angle and ring width, this relationship is a function of age and not of growth rate per se. Once minimal fibril angles are reached, fluctuations in ring width have little effect on this property.

Jackson and Morse (1965b), studying the variation in fibril angle of plantation grown trees of slash and loblolly pine, found a highly significant correlation between fibril angle and specific gravity in a 28-year-old stand of loblolly pine. Fibril angle was inversely related to specific

gravity. There were also highly significant differences in fibril angles among individual trees based on wood samples taken at breast height. Because the sampled trees were practically the same diameter at age 28 (6.8 to 7.0 inches) on a fairly uniform site, these data implied a genetic influence upon this characteristic. To test this possibility further, Jackson and Morse (1965b) analyzed open and controlled pollinated slash and loblolly pine progenies and found significant correlations in fibril angle between parents and their offspring. The progeny from parents with a relatively large fibril angle possessed larger fibril angles than did those from parents with relatively small fibril angles.

Virtually nothing is presently known about the physiological or biochemical mechanism of microfibril orientation in the middle portion of the secondary cell wall of the conifer tracheid. Wardrop (1951) found a high negative correlation between tracheid length and fibril angle in Monterey pine, and Echols (1955) obtained a similar negative linear relationship between tracheid length and fibril angle in slash pine. Because cellular elongation has ceased prior to deposition of the S_2 layer it seems unlikely that any simple causal relationship between auxin levels and orientation of the microfibrils can be evoked to explain this pattern of organized growth and development. Mühlethaler (1965), in discussing the problems of fibrillar arrangement in relation to the fine structure of cellular components, pointed out the complex nature of the problem. Although the problem does not appear insurmountable, it will take some time to answer the questions involved. For a further discussion of fibril orientation and the mechanism of cell wall formation, the reader is referred to reviews by Wangaard (1970) and Berlyn (1970).

SILVICULTURAL ASPECTS OF QUALITY CONTROL

From time to time researchers have suggested ways in which the forest manager may exercise some control over the quality of wood produced (Paul 1963; Van Buijtenen [1968]; Klem 1968). Paul (1963) suggested that in second growth coniferous stands initial close spacings and crowding which reduces crown development will narrow the amount of earlywood produced, thereby increasing the ratio of latewood and wood specific gravity. This in theory would tend to reduce the radial size of the central core of "juvenile wood" and increase the proportion of "mature wood." Paul proposed that natural methods of reproduction would provide the high density of stocking needed, and that subsequent thinnings could be made once desirable height growth was obtained. Under such systems the rotation age would necessarily be lengthened. He also suggested that for volume production of low-density wood, trees may be grown as widely spaced as possible for maximum utilization of light but close enough still to permit some degree of self pruning. Such trees would be expected to

have shorter clear boles, more knots, and a high proportion of sapwood as compared to trees grown under more restricted stand conditions.

Perry and Wang (1958) pointed out that it is impossible to reduce the core wood of young trees by initial close spacings without reducing the volume of later-formed wood to an even greater extent. Because core wood extends from the base of the tree to the top, the volume of core wood could only be reduced by growing trees slowly throughout their entire rotation. The evidence for increasing the wood specific gravity of southern pines by reducing their growth is nonexistent, and as Perry and Wang have suggested, it is not possible to alter the volume of core wood without drastically altering the volume of the tree. As said somewhat differently by Spurr and Hsuing (1954) "a fast-growing tree will produce a higher volume of high density wood in later life than a slow-growing tree despite the low density wood of its core."

Although slow-grown trees may produce a higher quality product from the standpoint of form, knot size, and losses from shrinkage and degrade, it does not follow that the greatest volume of dry matter per acre will be produced under such conditions. In fact, among the southern pines the greatest volumes of usable dry matter per acre are produced under rapidly growing short term (30 to 40 year) rotations.

In general, it appears that the most practical approach to better control over wood quality is to narrow the range of individual tree variation through selection and breeding for such properties as wood specific gravity and tracheid length to obtain a more uniform raw material. Then, with these improved strains, the silviculturist should strive to obtain the fastest growth rate possible commensurate with maintaining good form, natural pruning, and total site utilization.

4-4 GENETIC MANIPULATION OF WOOD QUALITY

Progress toward genetic control of wood morphology in the southern pines has been summarized by Zobel⁴. He concluded that genetic manipulation can develop disease-resistant, fast-growing trees with straight stems, small branches, and low compression wood content. Zobel also noted that tracheid length, wood specific gravity, and bark thickness can be modified through genetic selection.

Zobel's findings on heritability are in essential agreement with those reported by Goggans (1964); their ranking of characteristics according to

⁴ Zobel, B. Genetic manipulation of wood of the southern pines, including chemical characteristics. Paper presented at a General Meeting of the International Academy of Wood Science, held at North Carolina State University, Raleigh, N.C. March 10-12, 1971.

the ease with which they can be altered in a selection program may be summarized as follows:

Ease of change by genetic selection and characteristics

Easiest

- Tracheid length, latewood
- Percent of latewood in tree
- Specific gravity of tree
- Tracheid diameter, earlywood
- Tracheid length, earlywood
- Bark thickness

Intermediate

- Specific gravity, latewood
- Double wall thickness, latewood
- Tracheid diameter, latewood
- Ratio of wall thickness to radial diameter, earlywood

Most difficult

- Ratio of wall thickness to radial diameter, latewood
- Double wall thickness, earlywood
- Specific gravity, earlywood

4-5 LITERATURE CITED

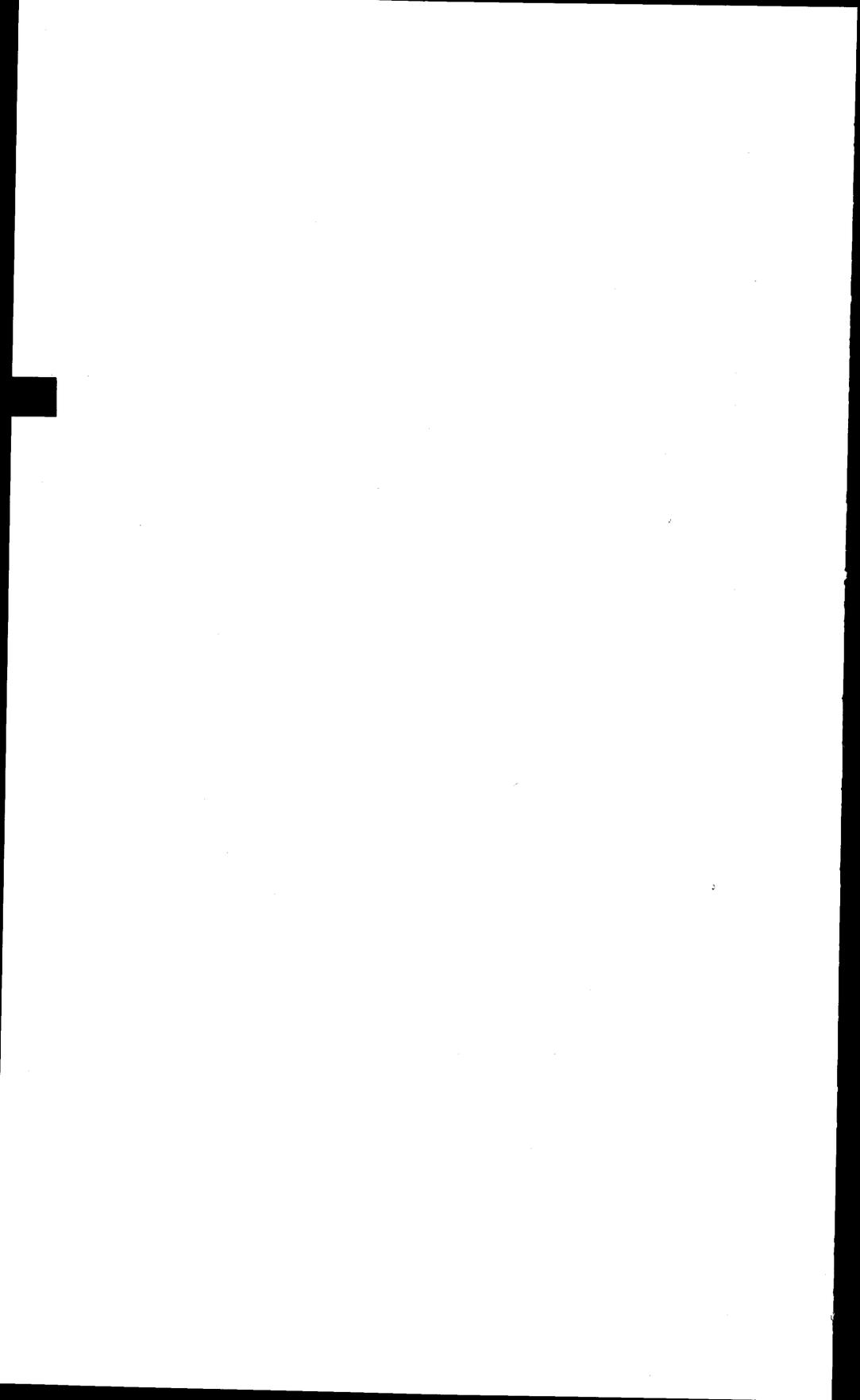
- Avery, G. A., Jr., Burkholder, P. R., and Creighton, H. B.
1937. Production and distribution of growth hormone in shoots of *Aesculus* and *Malus*, and its probable role in stimulating cambial activity. *Amer. J. Bot.* 24: 51-58.
- Bailey, I. W.
1923. The cambium and its derivative tissues. IV. The increase in girth of the cambium. *Amer. J. Bot.* 10: 499-509.
- Balatinecz, J. J., and Kennedy, R. W.
1968. Mechanism of earlywood-latewood differentiation in *Larix decidua*. *TAPPI* 51: 414-422.
- Bannan, M. W.
1954. Ring width, tracheid size, and ray volume in stem wood of *Thuja occidentalis* L. *Can. J. Bot.* 32: 466-479.
- Bannan, M. W.
1955. The vascular cambium and radial growth in *Thuja occidentalis* L. *Can. J. Bot.* 33: 113-138.
- Bannan, M. W.
1956. Some aspects of the elongation of fusiform cambial cells in *Thuja occidentalis* L. *Can. J. Bot.* 34: 175-196.
- Bannan, M. W.
1957. The relative frequency of the different types of anticlinal divisions in conifer cambium. *Can. J. Bot.* 35: 875-884.
- Barefoot, A. C., Hitchings, R. G., and Ellwood, E. L.
1966. Wood characteristics and kraft paper properties of four selected loblolly pines. III. Effect of fiber morphology in pulps examined at a constant permanganate number. *TAPPI* 49: 137-147.
- Berlyn, G. P.
1970. Ultrastructural and molecular concepts of cell-wall formation. *Wood and Fiber* 2: 196-227.
- Bray, M. W., and Paul, B. H.
1930. The evaluation of second-growth longleaf pine pulp wood from trees of varying rate of growth. *USDA Forest Serv. Forest Prod. Lab. R996*, 19 pp.
- Brown, C. L.
1970. Physiology of wood formation in conifers. *Wood Sci.* 3: 8-22.
- Brown, C. L., and Wodzicki, T. J.
1969. A simple technique for investigating cambial activity and the differentiation of cambial derivatives. *Forest Sci.* 15: 26-29.

- Choong, E. T., Box, B. H., and Fogg, P. J.
1970. Effects of intensive cultural management on growth and certain wood properties of young loblolly pine. *Wood and Fiber* 2: 105-112.
- Cole, D. E., Zobel, B. J., and Roberds, J. H.
1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. *TAPPI* 49: 161-166.
- Coster, C.
1927. Zur Anatomie und Physiologie der Zuwachszonen und Jahresringbildung in den Tropen. I-III. *Ann. Jard. Bot. Buitenzorg* 37: 49-160.
- Coster, C.
1928. Zur Anatomie und Physiologie der Zuwachszonen und Jahresringbildung in den Tropen. IV. *Ann. Jard. Bot. Buitenzorg* 38: 1-114.
- Dadswell, H. E., Fielding, J. M., Nicholls, J. W. P., and Brown, A. G.
1961. Tree-to-tree variations and the gross heritability of wood characteristics of *Pinus radiata*. *TAPPI* 44: 174-179.
- Dinwoodie, J. M.
1961. Tracheid and fibre length in timber: a review of the literature. *Forestry* 34: 125-144.
- Dodd, J. D.
1948. On the shapes of cells in the cambial zone of *Pinus silvestris* L. *Amer. J. Bot.* 35: 666-682.
- Echols, R. M.
1955. Linear relation of fibrillar angle to tracheid length, and genetic control of tracheid length in slash pine. *Trop. Woods* 102, pp. 11-22.
- Echols, R. M.
1958. Variation in tracheid length and wood density in geographic races of Scotch pine. *Yale Univ. Sch. Forest. Bull.* 64, 62 pp.
- Goddard, R. E., and Cole, D. E.
1966. Variation in wood production of six-year-old progenies of select slash pines. *TAPPI* 49: 359-362.
- Goggans, J. F.
1962. The correlation, variation, and inheritance of wood properties in loblolly pine (*Pinus taeda* L.). *N.C. State Coll. Sch. Forest. Tech. Rep.* 14, 155 pp.
- Goggans, J. F.
1964. Correlation and heritability of certain wood properties in loblolly pine (*Pinus taeda* L.). *TAPPI* 47: 318-322.
- Hartig, T.
1853. Ueber die Entwicklung des Jahrringes der Holzpflanzen. *Bot. Zeitung* 11: 553-560, 569-579.
- Hata, K.
1949. Studies on the pulp of "Akamatsu" (*Pinus densiflora* Sieb. et Zucc.) wood. I. On the length, diameter and length-diameter ratio of tracheids in "Akamatsu" (*Pinus densiflora* Sieb. et Zucc.) wood. *Kagawa-Ken Agr. Coll. Tech. Bull.* 1(1): 1-35.
- Jackson, L. W. R., and Greene, J. T.
1958. Tracheid length variation and inheritance in slash and loblolly pine. *Forest Sci.* 4: 316-318.
- Jackson, L. W. R., and Morse, W. E.
1965a. Tracheid length variation in single rings of loblolly, slash, and shortleaf pines. *J. Forest.* 63: 110-112.
- Jackson, L. W. R., and Morse, W. E.
1965b. Variation in fibril angle of slash and loblolly pine. *Ga. Forest Res. Council. Res. Pap.* 34, 5 pp.
- Jacquot, C.
1950. [Some factors determining the cycle of cambial activity in some forest trees.] *Rev. Forest. Franc.* 11, pp. 605-610.
- Jost, L.
1891. Ueber Dickenwachstum und Jahresringbildung. *Bot. Zeitung* 49: 485-495.
- Jost, L.
1907. Lectures on plant physiology. 564 pp. Oxford: Oxford Univ. Press.
- Kastens, E.
1924. Beiträge zur kenntnis der funktion der Siebröhren. *Mitt. Inst. Allg. Bot. Hamburg* 6(1): 33-70.

- Klem, G. S.
1968. Quality of wood from fertilized forests. TAPPI 51(11): 99A-103A.
- Kramer, P. R.
1957. Tracheid length variation in loblolly pine. Tex. Forest Serv. Tech. Rep. 10, 22 pp.
- Kraus, J. F., and Johansen, R. W.
1960. A test of gibberellic acid on longleaf pine. J. Forest. 58: 194.
- Larson, P. R.
1957. Effect of environment on the percentage of summerwood and specific gravity of slash pine. Yale Univ. Sch. Forest. Bull. 63, 89 pp.
- Larson, P. R.
1960. A physiological consideration of the springwood summerwood transition in red pine. Forest Sci. 6: 110-122.
- Larson, P. R.
1962. Auxin gradients and the regulation of cambial activity. In Tree growth, pp. 97-117. T. T. Kozlowski, ed. N.Y.: Ronald Press.
- Larson, P. R.
1963. The indirect effect of drought on tracheid diameter in red pine. Forest Sci. 9: 52-62.
- Larson, P. R.
1964. Some indirect effects of environment on wood formation. In the formation of wood in forest trees, pp. 345-365. M. H. Zimmerman, ed. N.Y.: Academic Press.
- Marts, R. O.
1949. Effect of crown reduction on taper and density in longleaf pine. Southern Lumberman 179(2249): 206-209.
- McElwee, R. L., and Zobel, B. J.
1963. Some wood and growth characteristics of pond pine. Forest Genet. Workshop Proc. 1962: 19-25. Macon, Ga.
- Mühlethaler, K.
1965. Growth theories and the development of the cell wall. In Cellular ultrastructure of woody plants, pp. 51-60. N.Y.: Syracuse Univ. Press.
- Münch, E.
1938. Untersuchungen über die Harmonie der Baumgestalt. Jahrb. Wiss. Bot. 86: 581-673.
- Nelson, T. C.
1957. Early responses of some southern tree species to gibberellic acid. J. Forest. 55: 518-520.
- Nichols, J. W. P., Dadswell, H. E., and Fielding, J. M.
1964. The heritability of wood characteristics of *Pinus radiata*. Silvae Genet. 13: 68-71.
- Oppenheimer, H. R.
1945. Cambial wood production in stems of *Pinus halepensis* (with anatomical and silvicultural notes). Palestine J. Bot. (Rehovot Ser.) 5: 22-51.
- Paul, B. H.
1927. Producing dense southern pine timber in second-growth forests. South. Lumberman 128(1668): 46-47.
- Paul, B. H.
1958. Specific gravity changes in southern pines after release. Southern Lumberman 197(2465): 122-124.
- Paul, B. H.
1963. The application of silviculture in controlling the specific gravity of wood. USDA Tech. Bull. 1288, 97 pp.
- Perry, T. O., and Wang, C. W.
1958. Variation in the specific gravity of slash pinewood and its genetic and silvicultural implications. TAPPI 41: 178-180.
- Pillow, M. Y., Terrell, B. Z., and Hiller, C. H.
1953. Patterns of variation in fibril angles in loblolly pine. USDA Forest Serv. Forest Prod. Lab. Rep. D1935, 31 pp.
- Reinders-Gouwentak, C. A.
1941. Cambial activity as dependent on the presence of growth hormone and the non-resting condition of stems. Ned. Akad. Wetensch. Proc. 44: 654-661. Amsterdam.

- Richardson, S. D.
1964. The external environment and tracheid size in conifers. In The formation of wood in forest trees, pp. 367-388. M. H. Zimmerman, ed. N.Y.: Academic Press.
- Richardson, S. D., and Dinwoodie, J. M.
1960. Studies on the physiology of xylem development. I. The effect of night temperature on tracheid size and wood density in conifers. *J. Inst. Wood Sci.* 6: 3-13.
- Sanio, K.
1872. Ueber die Grösse der Holz-zellen bei der gemeinen Kiefer (*Pinus silvestris*). *Jahrb. Wiss. Bot.* 8: 401-420.
- Sanio, K.
1873. Anatomie der gemeinen Kiefer (*Pinus silvestris* L.). II. *Jahrb. Wiss. Bot.* 9: 50-126.
- Saucier, J. R., and Taras, M. A.
1966. Wood density variation among six longleaf pine seed sources grown in Virginia. *J. Forest.* 64: 463-465.
- Söding, H.
1937. Wuchsstoff und Kambium-tätig-keit der Bäume. *Jahrb. Wiss. Bot.* 84: 639-670.
- Spurr, S. H., and Hsuing, W.
1954. Growth rate and specific gravity in conifers. *J. Forest.* 52: 191-200.
- Spurr, S. H., and Hyvärinen, M. J.
1954. Wood fiber length as related to position in tree and growth. *Bot. Rev.* 20: 561-575.
- Strickland, R. K., and Goddard, R. E.
1966. Correlation studies of slash pine tracheid length. *Forest Sci.* 12: 54-62.
- Thor, E.
1964. Variation in Virginia pine. Part I. Natural variation in wood properties. *J. Forest.* 62: 258-262.
- Thor, E.
1965. Variation in some wood properties of eastern white pine. *Forest Sci.* 11: 451-455.
- Thor, E., and Bates, A. L.
1970. Relationships of some wood properties of shortleaf pine with radial growth and site factors. *TAPPI* 53: 290-294.
- Van Buijtenen, J. P.
1958. Experimental control of environmental factors and their effect upon some aspects of wood anatomy in loblolly pine. *TAPPI* 41: 175-178.
- Van Buijtenen, J. P.
[1968]. Quality control begins in the woods. *TAPPI Fourth Forest Biol. Conf. Proc.* 1967: 102-110. Pointe Claire, Quebec.
- Wangaard, F. F.
1970. Mechanisms of cell-wall growth in secondary xylem. *Wood and Fiber* 2: 188-195.
- Wangaard, F. F., Kellogg, R. M., and Brinkley, A. W.
1966. Variation of wood and fiber characteristics and pulp-sheet properties of slash pine. *TAPPI* 49: 263-277.
- Wardrop, A. B.
1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. *Australian J. Sci. Res.* 4B: 391-414.
- Wareing, P. F.
1951. Growth studies in woody species. IV. The initiation of cambial activity in ring-porous species. *Physiol. Plant.* 4: 546-562.
- Wareing, P. F.
1958. The physiology of cambial activity. *J. Inst. Wood Sci.* 1(1): 34-42.
- Wareing, P. F., Hanney, C. E. A., and Digby, J.
1964. The role of endogenous hormones in cambial activity and xylem differentiation. In The formation of wood in forest trees, pp. 323-344. M. H. Zimmerman, ed. N.Y.: Academic Press.
- Westing, A. A.
1959. Effect of gibberellin on conifers: generally negative. *J. Forest.* 57: 120-122.
- Wheeler, E. Y., Zobel, B. R., and Weeks, D. L.
1966. Tracheid length and diameter variation in the bole of loblolly pine. *TAPPI* 49: 484-490.

- Wilson, B. F.
1964. A model for cell production by the cambium of conifers. In The formation of wood in forest trees, pp. 19-36. M. H. Zimmerman, ed. N.Y.: Academic Press.
- Wilson, B. F., and Howard R. A.
1968. A computer model for cambial activity. *Forest Sci.* 14: 77-90.
- Wilson, B. F., Wodzicki, T. J., and Zahner, R.
1966. Differentiation of cambial derivatives: Proposed terminology. *Forest Sci.* 12: 438-440.
- Wodzicki, T.
1960. Investigation on the kind of *Larix polonica* Rac. wood formed under various photoperiodic conditions. I. Plants growing in natural conditions. *Acta Soc. Bot. Poloniae* 29: 713-730.
- Wodzicki, T.
1962. A contribution to the rate of xylem cell formation and differentiation of tracheids in *Pinus sylvestris* L. *Acta Soc. Bot. Poloniae* 31: 219-227.
- Wodzicki, T.
1964. Photoperiodic control of natural growth substances and wood formation in larch (*Larix decidua* D.C.). *J. Exp. Bot.* 15: 584-599.
- Wodzicki, T.
1965. Annual ring of wood formation and seasonal changes of natural growth-inhibitors in larch. *Acta Soc. Bot. Poloniae* 34: 117-151.
- Wodzicki, T., and Peda, T.
1963. Investigation on the annual ring of wood formation in European silver fir (*Abies pectinata*, D.C.). *Acta Soc. Bot. Poloniae* 32: 609-618.
- Wodzicki, T., and Witkowska, L.
1961. On the photoperiodic control of extension growth and wood formation in Norway spruce (*Picea abies* (L.) Karst). *Acta Soc. Bot. Poloniae* 30: 755-764.
- Zahner, R.
1962. Terminal growth and wood formation by juvenile loblolly pine under two soil moisture regimes. *Forest Sci.* 8: 345-352.
- Zahner, R., and Oliver, W. W.
1962. The influence of thinning and pruning on the date of summerwood initiation in red and jack pines. *Forest Sci.* 8: 51-63.
- Zahner, R., Lotan, J. E., and Baughman, W. D.
1964. Earlywood-latewood features of red pine grown under simulated drought and irrigation. *Forest Sci.* 10: 361-370.
- Zimmerman, W. A.
1936. Untersuchungen über die räumliche und zeitliche Verteilung des Wuchsstoffes bei Bäumen. *Z. Bot.* 30: 209-252.
- Zobel, B. J., and Rhodes, R. R.
1955. Relationship of wood specific gravity in loblolly pine to growth and environmental factors. *Tex. Forest Serv. Tech. Rep.* 11, 32 pp.
- Zobel, B., Thorbjornsen, E., and Henson, F.
1960. Geographic, site and individual tree variation in wood properties of loblolly pine. *Silvae Genet.* 9: 149-158.



5

Anatomy

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5

Anatomy

The wood of the southern pines can be distinguished anatomically from the wood of other pines of the United States. An identification key can be found in Panshin et al. (1964, p. 399); the same text (p. 429) also provides a supplementary key to distinguish the four major species from each other. However, in spite of recent intensive efforts by Howard and Manwiller (1969) with a light microscope and Côté and Day (1969) with an electron microscope, no way has been found to differentiate positively among small dry samples of the 10 southern pines.

Among populations of some southern pine species there may be statistically significant differences in fiber length, cell wall thickness, fibril angle, tangential cell diameter, and other morphological characters. However, the great variation within species and within individual trees prevents use of such differences in identifying particular small pieces of dry wood.

Therefore, the descriptions and drawings on the following pages apply to all southern pines unless stated otherwise.

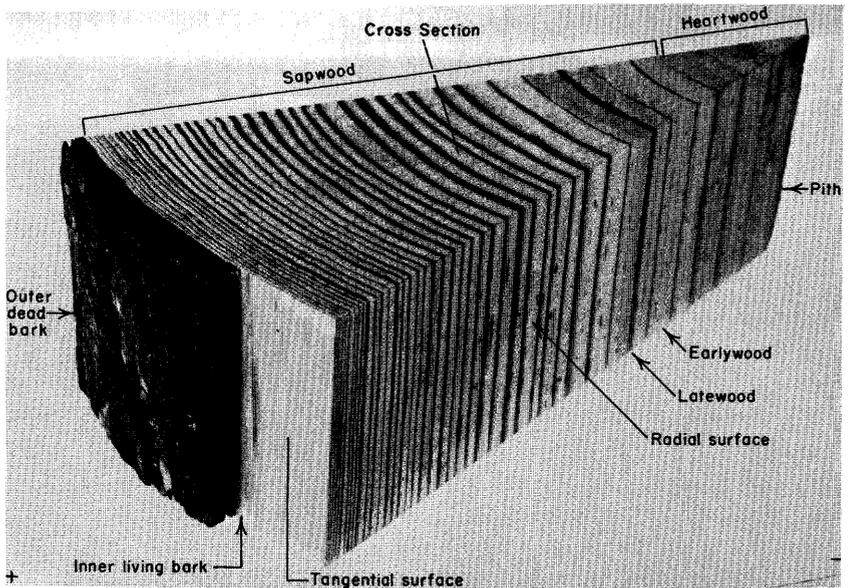
5-1 GROSS FEATURES

A wedge cut from a southern pine tree illustrates some of the features visible with the naked eye (fig. 5-1).

PITH

The dark-colored **pith** is the small central core of primary parenchymatous tissue originating at the growing tip (fig. 4-4). Wood near the pith is weak, has low specific gravity, and shrinks excessively in the longitudinal direction. When a surface containing pith is exposed to the weather, the pithy wood frequently curls loose from the surface to cause an unsightly defect. Generally speaking, solid-wood products that show pith on any surface must be processed and used with discretion.

Diameter of pith and the second annual ring afford a means of dis-



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Figure 5-1.—Section cut from the stem of a mature southern pine tree.

tinguishing longleaf from the three other major southern pine species (Koehler 1932). If the pith is 0.08 inch in diameter or smaller, the tree is not longleaf; if it is larger than 0.08 inch, the diameter of the second annual ring can be measured and the results interpreted from figure 5-2.

BARK AND WOOD

As described in chapter 4, wood is formed on one side, and bark on the other side of the cambial layer. In a limb-free stem of southern pine, roughly 90 percent of the volume is wood and 10 percent is bark. The anatomy of bark and data on bark thickness and volume are described in chapter 12.

PLANES IN WOOD

The three-dimensional structure of wood can be conveniently described in terms of three planes (fig. 5-1). The **cross section** or **transverse section** is exposed when wood is cut at a right angle to the grain. It is the surface exposed on the end of a log. The **tangential surface** is exposed when the bark is peeled from a tree or when veneer is rotary-cut; an element of this surface is perpendicular to the rays. A **radial section** is formed by a plane parallel to the grain of the tree and passing through the pith. A sawyer producing vertical grain flooring would expose this section, as would a slicer operator making quarter-cut veneer.

GROWTH RINGS

Growth rings in normal southern pine wood grown in temperate climates usually show an abrupt transition between the light-colored, thin-

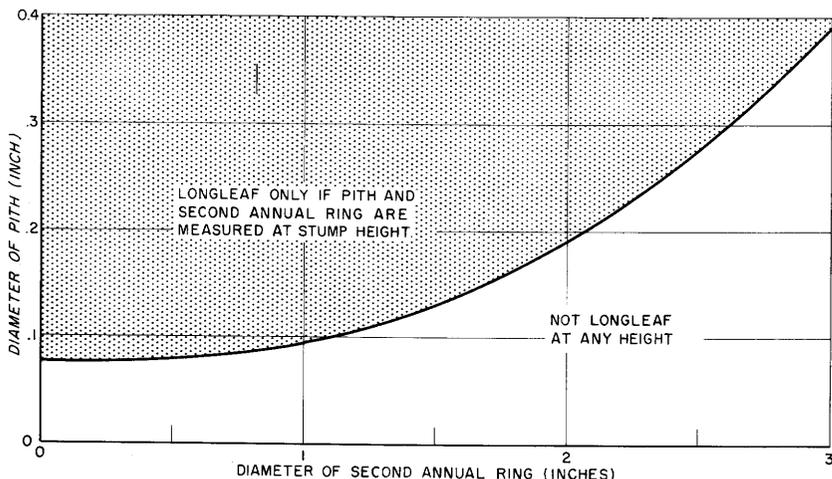


Figure 5-2.—Koehler's (1932) method of distinguishing longleaf from shortleaf, loblolly, and slash pine wood. If the pith is less than 0.08 inch in diameter, the timber is *not* longleaf pine. If it is over 0.08 inch, the diameter of the second annual ring around the pith should be measured. With these two figures, locate a point on the chart. Points below the curve indicate that the specimen is *not* longleaf; those above the curve indicate longleaf, providing the wood or log was cut at stump height. If the point is above the curve but the location of the cut is uncertain, apply this method to the opposite end, which may give a point below the curve and show that the timber is *not* longleaf.

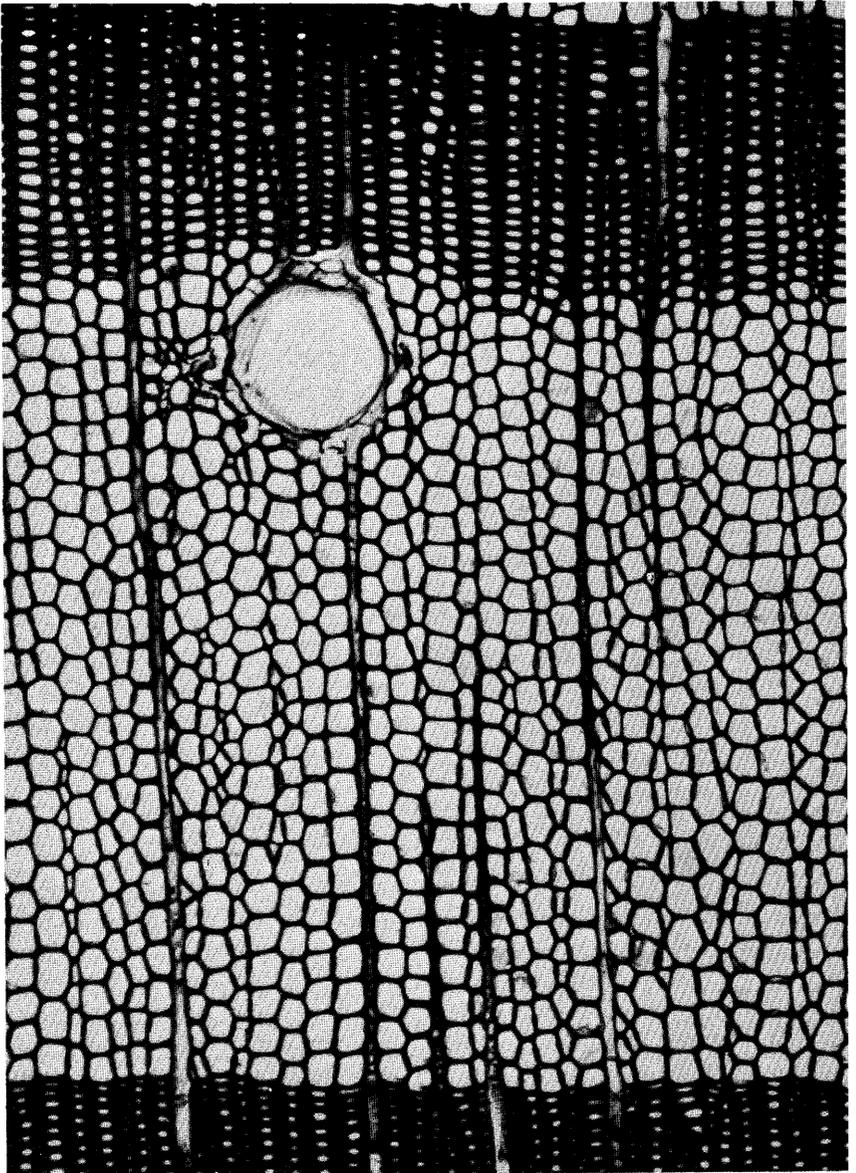
walled **earlywood** cells formed early in the growing season and the darker, thick-walled **latewood** cells (fig. 5-3). Mork (1928) defined latewood cells as those whose common double cell wall—between interior cavities (lumena)—is more than half their radial lumen diameter.

Total width of **annual ring**, i.e., the earlywood plus the latewood growth for one year, may range from as little as $\frac{1}{16}$ -inch to as much as an inch. Six annual rings per inch of tree radius—while not an average for all species—is common. Using tracheid diameters (table 5-5) of spruce pine as an example, and assuming half of the $\frac{1}{6}$ -inch-wide annual ring to be latewood, then one radial file of cells in the annual ring would contain 57 earlywood and 87 latewood tracheids. The relative proportions of earlywood and latewood in trees may vary greatly (see ch. 7). The physiological controls over width of annual rings and latewood formation are described in section 4-3.

SAPWOOD AND HEARTWOOD

Southern pines growing today—and those that will grow in the foreseeable future—will generally be utilized at ages less than 50 years. Up to this age, the southern pines commonly have little **heartwood**; most of the volume is light-colored **sapwood**.

In many ways it is fortunate that the southern pines contain so little heartwood. Light-colored woods are favored by the pulp industry; heartwood is not digested satisfactorily in the sulfite pulping process (Mac-



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Figure 5-3.—Transverse section of mature slash pine wood. Transition is abrupt from thin-walled earlywood cells to thick-walled latewood cells with lumens flattened in the radial dimension. The resin canal measures 0.22 mm. in diameter.

Kinney and Chaiken 1935). Sapwood is easier to treat with preservative (see ch. 8 for relative permeability) and more readily dried.

Sapwood of living southern pines has a higher moisture content but less extractives (table 6-7) than heartwood. Toxicity of some extractives, and the relative impermeability which reduces the amount of air and

water available for fungal growth make heartwood somewhat more durable than sapwood; few trees are left with enough heartwood to make this difference useful.

A color test to distinguish pine heartwood from sapwood is available (USDA Forest Products Laboratory 1954). To make this test, 5 g. of benzidine are dissolved in 23 cc. of 25-percent hydrochloric acid and 970 cc. of water. (Note: Concentrated chemically pure hydrochloric acid contains about 38 percent of the acid; to make a 25-percent solution, add 25 cc. of chemically pure concentrated acid to 13 cc. of water.) Next, a 10-percent solution of sodium nitrite is prepared. The two solutions are held separate until ready for a test, and then mixed in equal volumes. Within a few moments after application to pine wood, this mixture reacts with pinosylvan phenols in heartwood and produces a red color. The sapwood becomes a yellowish brown.

Heartwood is darker than sapwood, contains no living cells, and has tightly aspirated pits (fig. 5-9); sapwood in living trees contains some living cells, notably ray parenchyma. These cells, normally involved with food storage and conduction, change function in the heartwood-formation zone to produce, over several seasons, the pigments and gummy secretions prevalent in heartwood tissues (Garlick 1965). Frey-Wyssling and Bossard (1959) concluded that with increasing distance from the cambium, oxygen shortage triggers the changed metabolism. With restricted respiration, starch grains hydrolize and disappear. Phenols oxidize and polymerize to form pigments. Eventually the cells die. Harris (1965), in experiments with Monterey pine (*Pinus radiata* D. Don), concluded that extractives formed when the sapwood is converted to heartwood can be enriched over the years by the further addition of oleoresin; the enrichment depends on the exudation pressures in the sapwood that force oleoresin into the heartwood through the transverse resin canals.

The age of heartwood initiation and its rate of formation vary considerably. Old-growth southern pines that still maintain a rapid growth rate usually have a thicker sapwood layer than slow-growing trees. Thus, trees in the open or on moist sites are apt to have thicker sapwood than trees in crowded stands or on drier soils.

The following paragraphs brief the available information on heartwood occurrence in the southern pine species.

Loblolly pine.—MacKinney and Chaiken (1935) observed that the proportion of heartwood to merchantable volume varies directly with age and inversely with rate of growth; in loblolly pines from age 20 to 90 years it varies from 0 to more than 15 percent (fig. 5-4). Although heartwood may start to form by age 14, only negligible amounts were found in loblolly trees under 20 years of age on the Coastal Plain of Virginia, North Carolina, and South Carolina. Most trees showed maximum heartwood diameter at the stump, although nearly a quarter had heartwood diameters smaller at the stump than higher in the stem (MacKinney and Chaiken, 1935).

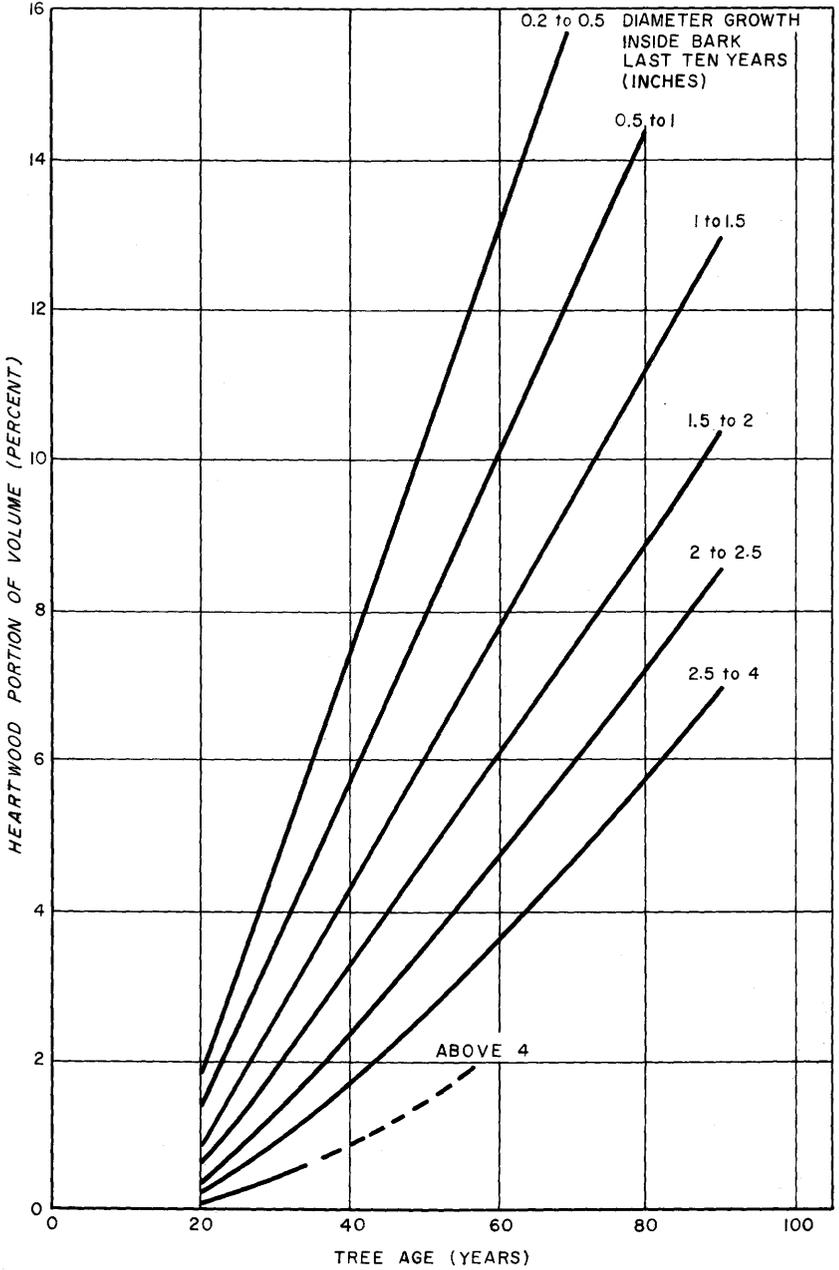


Figure 5-4.—Heartwood volume in loblolly pine. Data based on 680 trees. (Drawing after MacKinney and Chaiken 1935.)

In a North Carolina stand of even age, Paul (1932a) found that loblolly pines with small crowns, i.e., from closely stocked areas, had proportionately more heartwood than larger crowned trees:

<u>Crown width</u>	<u>Heartwood 16 feet above ground</u>
<i>Feet</i>	<i>Percent</i>
10	28
12	22
14	17
16	14
18	12
20	11
22	10
26	9
30	8
34	8

Longleaf pine.—Heartwood begins to form in longleaf at about age 20. A sample of longleaf logs that averaged 7.2 inches in diameter, and displayed an average of 24 rings (6.7 rings per inch) had 15 percent of their volume in heartwood (Martin 1962).

Bray and Paul (1934) tabulated heartwood content at various heights in three samples of longleaf pine 25 to 35 years of age:

<u>Height above ground</u>	<u>Heartwood</u>
<i>Feet</i>	<i>Percent</i>
Stump	3.0
4.5	3.6
9.0	4.2
13.5	5.1
18.0	4.6
31.5	2.3
40.5	1.0

As with loblolly, heartwood content is usually less in fast-growing trees in the open, than in slower growing trees in dense stands. Demmon (1936) found that turpentine increases the volume of heartwood because it retards growth. In a Florida stand of longleaf, this increase amounted to 5 to 10 percent by volume; at age 60, heartwood volume ranged from 12 to 23 percent (fig. 5-5).

Wahlenberg (1946, p. 31, 32) presents data on heartwood proportions in old-growth longleaf pine.

Sand pine.—Although published data are limited, it appears that sand pine has a relatively high proportion of heartwood; a sample of Choctawhatchee sand pine logs (averaging 6.7 inches in diameter, with 24 rings) had 52 percent of their volume in heartwood (Martin, 1962). In two trees (one Ocala race, the other Choctawhatchee) heartwood was first visible in disks less than 14 years old (table 5-1) and made up 40 and 54 percent of total volume.

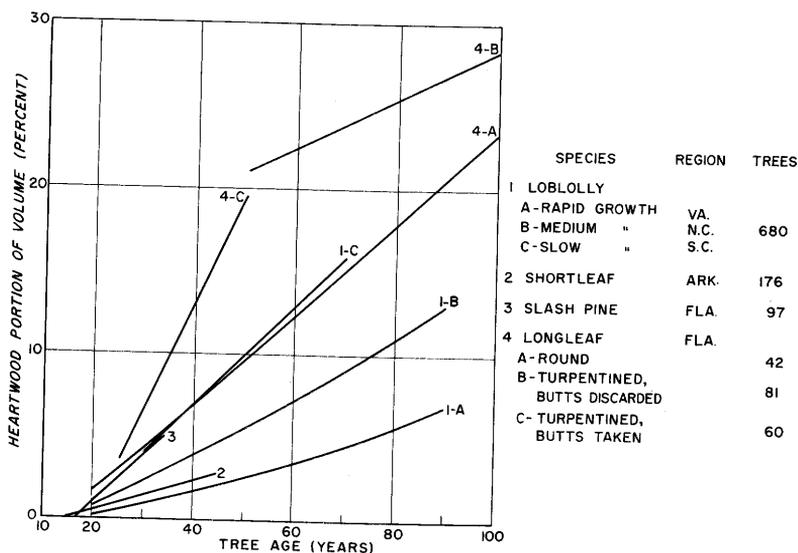


Figure 5-5.—Heartwood volume in the four major southern pines. (Drawing after Demmon 1936.)

Shortleaf pine.—Studies of 136 shortleaf pines in Arkansas showed that the percent of heartwood volume increased linearly (fig. 5-5) from zero at age 12 to 2½ percent at age 45 (Demmon 1936). In 32 trees 45 years of age, heartwood percentage was highest (7 percent) at a stem height of 4.5 feet (Bray and Paul 1934).

Slash pine.—Paul (1932b) reported that slash pine trees 8 to 16 years of age contained no heartwood, a 27-year-old stand had 3.7 percent, and a stand 30 to 35 years old 4.3 percent. Variation in heartwood percentage with age and height is shown in table 5-2. Demmon (1936) reported

TABLE 5-1.—Heartwood in single specimens of five species of southern pine¹

Pine species	Heartwood volume	Tree age	Tree D.b.h.	Tree height	Crown length	Disk age at
						first heartwood formation ²
	Percent	Years	Inches	Feet	Feet	Years
Pitch.....	12	65	10.2	50	25	22
Pond.....	27	67	16.2	85	47	<14 ³
Sand						
Ocala race.....	40	54	10.3	58	14	<15 ⁴
Choctawhatchee race...	54	59	18.2	69	56	<14 ⁵
Table-Mountain.....	5	50	9.1	33	23	15
Virginia.....	20	51	10.0	54	31	15

¹ Unpublished data incidental to USDA Forest Service Study FS-SO-3201-1.2.

² Disks taken at 4-foot intervals from stump to 4-inch top.

³ Heartwood diameter of 3.9-inch top disk was 0.7 inch.

⁴ Heartwood diameter of 3.3-inch top disk was 1.0 inch.

⁵ Heartwood diameter of 3.6-inch top disk was 1.4.

TABLE 5-2.—*Percentage of heartwood in slash pine*¹ (after Paul 1932b)

Height (feet)	Tree age 27	Tree age 30-35
Stump	—	2.9
4	3.2	4.6
12	5.0	5.6
20	3.9	4.3
28	2.7	2.7
36	1.1	.0

¹ Trees aged 8 to 16 years contained no heartwood.

that slash pine trees had less than 5 percent heartwood volume at age 30 (fig. 5-5, curve 3).

Spruce pine.—Manwiller¹, in an extensive sample of spruce pine trees from the major part of the commercial range, found that heartwood was seldom present in cross sections showing less than 20 years. His results are best stated in terms of a regression expression predicting heartwood volume (percent of total woody stem) in terms of live crown length (feet), as follows:

$$\text{Heartwood volume} = 9.515 - 0.174 (\text{crown length}) \quad (5-1)$$

Equation 5-1 accounted for 20.4 percent of the variation in heartwood content; standard error of the estimate was 3.6 percent of total volume of the woody stem.

Manwiller's data showed the following heartwood volumes for bark-free stems of spruce pine. Each value is a 24-tree average; tree growth rate was not significantly correlated with heartwood content.

Age class of tree	Heartwood volume
<i>Years</i>	<i>Percent</i>
15	0.0
30	1.3
45	3.5

Pitch, pond, Table-Mountain, and Virginia pines.—No published data describe heartwood volume in these species. Heartwood was measured in a single tree of each species in connection with a study of anatomical features (table 5-1). Trees of the last three species all showed heartwood by age 15, pitch pine by age 22. The 50-year-old Table-Mountain pine had only 5 percent of its volume in heartwood, while the 67-year-old pond

¹ Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1 dated May 1, 1972.

pine had 27 percent; Virginia and pitch pine trees were intermediate. Obviously these single-tree samples cannot statistically represent the species.

The USDA Forest Service, Southeastern Forest Experiment Station, is in the process of determining the heartwood content of existing populations of all six minor species. The information should be published by 1973.

5-2 INTRODUCTION TO MINUTE STRUCTURE AND ULTRASTRUCTURE

The tissues and cell types observable in a block of southern pine wood by light microscopy are shown in figure 5-6. Pine wood consists principally of closely packed vertical cells, called **longitudinal tracheids**. Associated are horizontal tissues called **rays**, extending radially toward the pith, and specialized tissues surrounding vertical ducts called **resin canals**. Tracheids and other cells are interconnected through openings in the cell walls called **pits**, in most of which characteristic borders form **pit chambers**.

Cell walls are composed of elements too small to be visible through the light microscope, which is limited to about 0.2 μm . (a micrometer is 10^{-3} mm.). Electron microscopy, resolving to about 25 A. (an angstrom unit is 10^{-4} μm .), reveals strands of **microfibrils**, some 100 to 300 A. in diameter, comprising the cellulose framework of the cell wall. These are in turn comprised of **elementary fibrils**, which presumably are cellulosic strands of the smallest possible diameter.

Sullivan (1968) has measured the diameters of elementary fibrils (synonymous with protofibrils) in the four major species of southern pine. Sullivan's published value for loblolly was originally 18.2 A., but he has since given the value tabulated below as correct.

<u>Species</u>	<u>Diameter</u>
	<i>Angstrom units</i>
Longleaf	25.3
Shortleaf	31.8
Loblolly	34.3
Slash	38.5

Text sections (5-3 through 5-7) on the structure of southern pine wood are condensed from Howard and Manwiller (1969), and Côté and Day (1969); excerpts from Thomas (1969), Thomas and Nicholas (1969), and Dunning (1968) are also included. These papers contain a wealth of illustrations of cell structure in southern pines.

5-3 STRUCTURE OF LONGITUDINAL ELEMENTS

Longitudinal elements of pine wood are longitudinal tracheids, strand tracheids, epithelial cells, and longitudinal parenchyma (fig. 5-6).

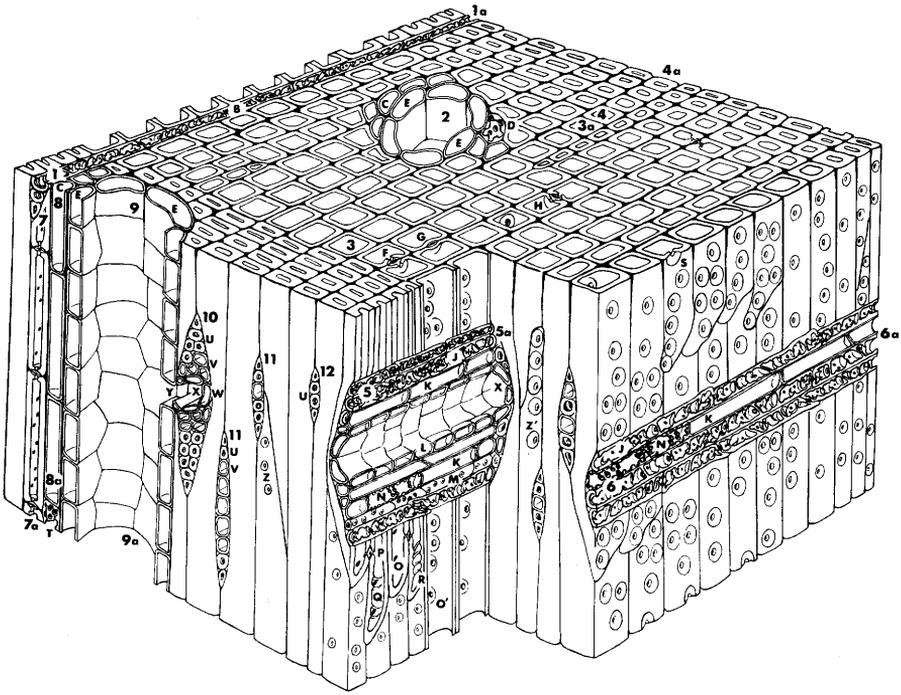


Figure 5-6.—Schematic drawing of typical southern pine wood. *Transverse view.* 1-1a, ray; B, dentate ray tracheid; 2, resin canal; C, thin-walled longitudinal parenchyma; D, thick-walled longitudinal parenchyma; E, epithelial cells; 3-3a, earlywood longitudinal tracheids; F, radial bordered pit pair cut through torus and pit apertures; G, pit pair cut below pit apertures; H, tangential pit pair; 4-4a, latewood longitudinal tracheids. *Radial view.* 5-5a, sectioned fusiform ray; J, dentate ray tracheid; K, thin-walled parenchyma; L, epithelial cells; M, unsectioned ray tracheid; N, thick-walled parenchyma; O, latewood radial pit (inner aperture); O', earlywood radial pit (inner aperture); P, tangential bordered pit; Q, callitroid-like thickenings; R, spiral thickening; S, radial bordered pits (the compound middle lamella has been stripped away, removing crassulae and tori); 6-6a, sectioned uniseriate heterogeneous ray. *Tangential view.* 7-7a, strand tracheids; 8-8a, longitudinal parenchyma (thin-walled); T, thick-walled parenchyma; 9-9a, longitudinal resin canal; 10, fusiform ray; U, ray tracheids; V, ray parenchyma; W, horizontal epithelial cells; X, horizontal resin canal; Y, opening between horizontal and vertical resin canals; 11, uniseriate heterogeneous rays; 12, uniseriate homogeneous ray; Z, small tangential pits in latewood; Z', large tangential pits in earlywood. (Drawing after Howard and Manwiller 1969.)

LONGITUDINAL TRACHEIDS

Longitudinal tracheids (figs. 5-6 and 5-7) make up more than 90 percent of the volume of southern pine wood. They are aligned radially, have overlapping ends, and taper to a point in tangential view, but are blunt and rounded radially. Usually, the last rows of latewood cells are flattened radially (fig. 5-3). Flattened lumens in latewood distinguish the southern pines from some other hard pines.

During heartwood formation, resin is sometimes secreted from the rays into adjacent tracheids, forming amorphous deposits, reddish-brown to

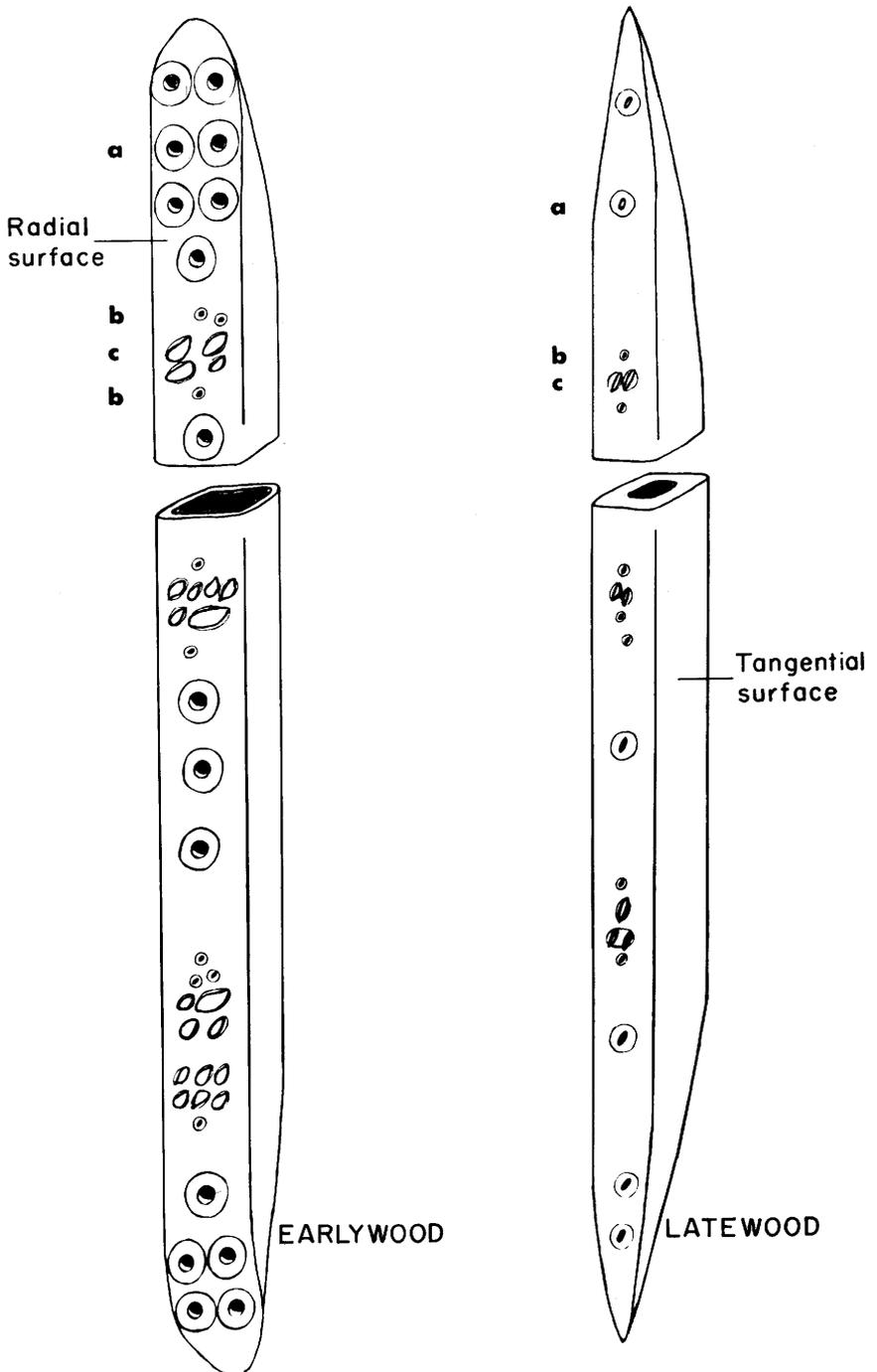


Figure 5-7.—Earlywood (left) and latewood (right) tracheids: a, intertracheid bordered pits; b, bordered pits to ray tracheids; c, pinoid pits to ray parenchyma. To simplify the drawing, tangential intertracheid pits have not been depicted. These pits are distributed along the length but are most frequent near the tracheid ends. (Drawing after Howard and Manwiller 1969.)

black, that partially or completely fill the cell as viewed in cross section. In longitudinal section the deposits appear as transverse plates across the lumen or as lumps on the tracheid wall. Occurrence of resinous tracheids is sporadic in the southern pines.

Organization of tracheid wall layers.—The cell wall of the mature tracheid consists of an outer **primary wall** and a **secondary wall** (fig. 5–8). Outside the primary wall is an **intercellular layer**, or **middle lamella**, composed largely of lignin. In the secondary wall, three layers are recognized; they are designated S_1 (outer), S_2 (middle), and S_3 (inner).

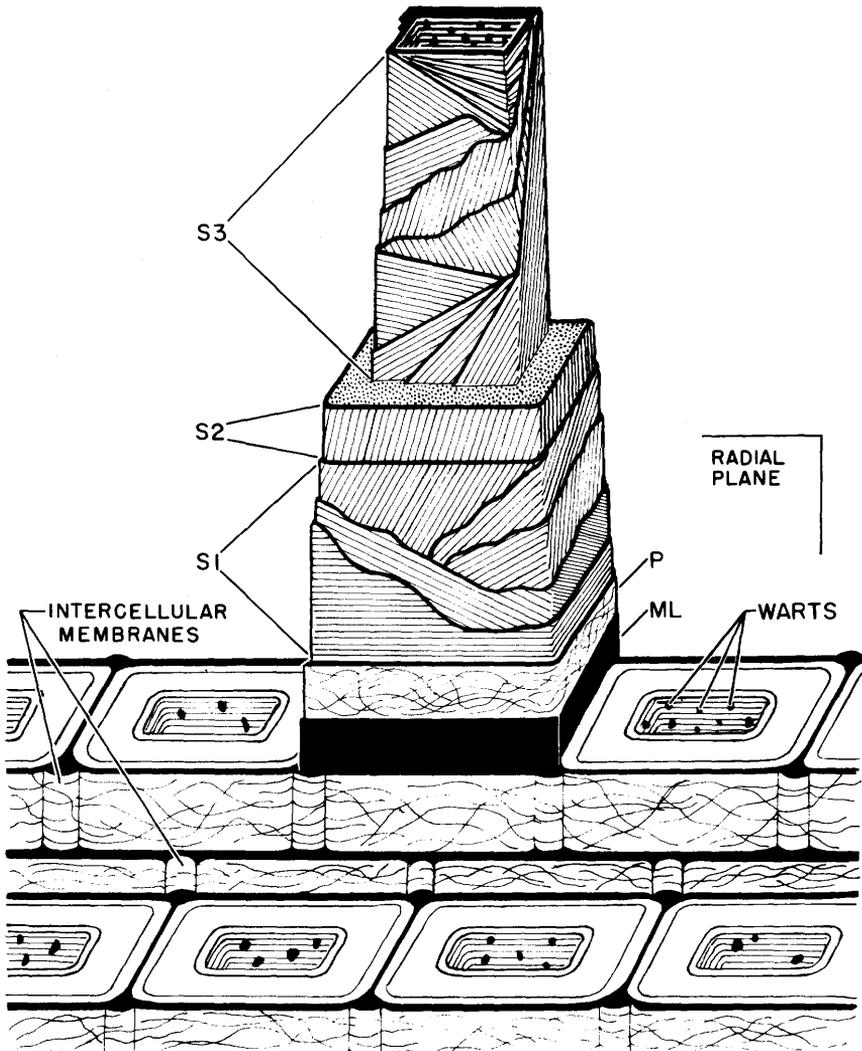


Figure 5–8.—Cell-wall structure of longleaf pine. A latewood longitudinal tracheid is exposed to show lamellae of the three layers of the secondary cell wall. Lines indicate alignment of microfibrils. ML is middle lamella. P is primary wall. S_1 , S_2 , and S_3 are layers of the secondary wall. (Drawing after Dunning 1969b.)

On the lumen side of the S_3 layer, and lining the lumen and pit chambers, may be a **warty layer** which some observers have termed "mud-like". These interior surfaces may also be more or less completely covered with encrustations.

Measurement of cross sections photographed by Côté and Day (1969, figs. 3 through 12) indicates that the middle lamella, the primary wall plus S_1 layer, and the S_3 layer are each about $1/3$ - μm . thick in earlywood, and about $1/2$ - μm . in latewood. Thickness of the S_2 layer varies in these sections from $1/2$ to $1 1/2$ μm . in earlywood, and from 3 to 7 μm in latewood. The middle lamella is generally thicker between radial files of cells than between cells in a file, and thickest at cell corners.

Three structural substances comprise the walls of wood cells. The framework is cellulose in the form of microfibrils. The matrix substances are hemicellulose and other noncellulosic carbohydrates. Lignin occurs in intercellular layers and with the matrix materials surrounding the microfibrils; it may also be a component of the warty layers and the encrustations in cell interiors (Meier 1955; Sachs et al. 1963; Dunning 1969b).

The outer envelope of longitudinal tracheids is the primary wall—a thin layer in which the cellulose microfibrils are rather loosely and randomly distributed. These fine strands are readily resolved with the electron microscope after some of the matrix substances have been removed (fig. 5–8). Matrix polysaccharides, especially hemicelluloses, and lignin are the dominant components of primary walls.

In secondary walls, the framework of cellulose microfibrils is dominant (fig. 5–8). Orientation of pine microfibrils is described in an abstract of Dunning's (1969a) findings:

"Inside the primary wall, the outer layer of the secondary wall (S_1) was found to consist of at least five lamellas: one with its fibrils lying nearly perpendicular to the fiber axis, one resembling a left-hand (S) helix pitched about 65° from the axis, and one resembling a right-hand (Z) helix about 60° from the axis. Below the last-mentioned lamella, several other lamellas go through gradual transition to the microfibril angle of the S_2 layer (central layer of the secondary wall). The S_2 layer was found to be made up of fibrils deposited in a Z helix with an angle to the axis of approximately 15° . The S_3 layer (inner layer of the secondary wall) was found to include at least 12 lamellas. These demonstrate a gradual stepwise transition of fibril orientation. If one visualizes a line segment which assumes the fibril direction of any given lamella in the S_3 , this line of orientation rotates in a clockwise motion (as seen from a point in the S_2) in stepping from one lamella to the next—moving from the S_2 to the lumen. Starting at the orientation of the S_2 , this rotation progresses more than 270° , ending with an S helix about 60° from the fiber axis. Then, a reversal in direction of rotation takes place with a few lamellas making a small counterclockwise rotation to the lumen-surface fibril orientation, which is nearly perpendicular to the fiber axis.

In addition to the studies of single fibers, some of the delignified chips were cleaved apart into radial shives, and the shive surfaces were replicated. The gaps between the adjacent fibers were found to be bridged over by nearly intact fibrillar membranes (presumably parent-cell walls). Practically all gaps were bridged over—some by multiple-membrane thicknesses."

Other diagrams of cell wall structure have been published (Kollmann and Côté 1968, p. 21; Wardrop 1969, fig. 4). Tracheid structure probably varies considerably within a tree, and among trees.

According to Wardrop (1969, p. 401), there is no structural connection between microfibrils of successive lamellae in the radial plane (of the tree). Other researchers suggest that successive lamellae have occasional structural connections. Treatments that remove lignin and matrix polysaccharides loosen the association between adjacent lamellae, permit shearing movements, and thus increase the flexibility of tracheids; if the primary wall remains, it appears as a loose sleeve surrounding the tracheid (Wardrop 1969). Wardrop and Davies (1961) and Jayme and Azzola (1964) have demonstrated in high-yield pulps that tracheids separate along the S_1 - S_2 interface when beaten or defibrated.

Typical cell-wall layering and some apparent variations that occur in all southern pines are illustrated in cross section in figures 5-9 and 5-10. The varying orientation of microfibrils in lamellae of the S_1 , S_2 , and S_3 layers is visible in figures 5-11 and 5-12. Warty layers and encrustations obscure S_3 layers in some specimens. Features shown are more or less common to all the southern pines, and not unique to the species chosen for illustration.

The warty layer.—In the southern pines, warts are found in the lumens of tracheids, around pit apertures, and inside pit chambers. They vary widely in size and distribution (figs. 5-9, 5-11, 5-12). In some cells the underlying S_3 is clearly visible; in others, the warts completely mask the S_3 .

Côté and Day (1969) reported that warts were difficult to find in the single slash pine examined but a few were present; because warts are occasionally sparse in certain portions of the tracheids of the other southern pines, their presence or absence cannot be used for identification.

Cell wall sculpturing.—The secondary walls of longitudinal tracheids in southern pine are sculptured externally by pit cavities (figs. 5-7 and 5-9) and internally by pit apertures as well as by occasional thickenings. The structure of pits is described in section 5-5.

Pit apertures are often slit-like in latewood, but circular and usually surrounded by an inward-bulging dome in earlywood (fig. 5-9). **Pit chambers**, when viewed after removal of the pit membrane, appear circular, usually warty, encrusted in latewood, especially heartwood (fig. 5-26) but generally unencrusted in earlywood. Size and shape of pit chambers and apertures vary with type of adjacent cell (sec. 5-5).

In southern pine longitudinal tracheids, two types of **wall thickenings** are present. **Spiral thickening** of the S_3 layer lining the lumen is found sporadically, usually in latewood; the thickenings usually extend for short distances along the tracheid length (fig. 5-13), sometimes with several groupings per tracheid (Howard and Manwiller 1969).

In latewood, some bordered pit apertures in radial walls are bounded by transverse thickenings (Howard and Manwiller 1969). The ridges closely

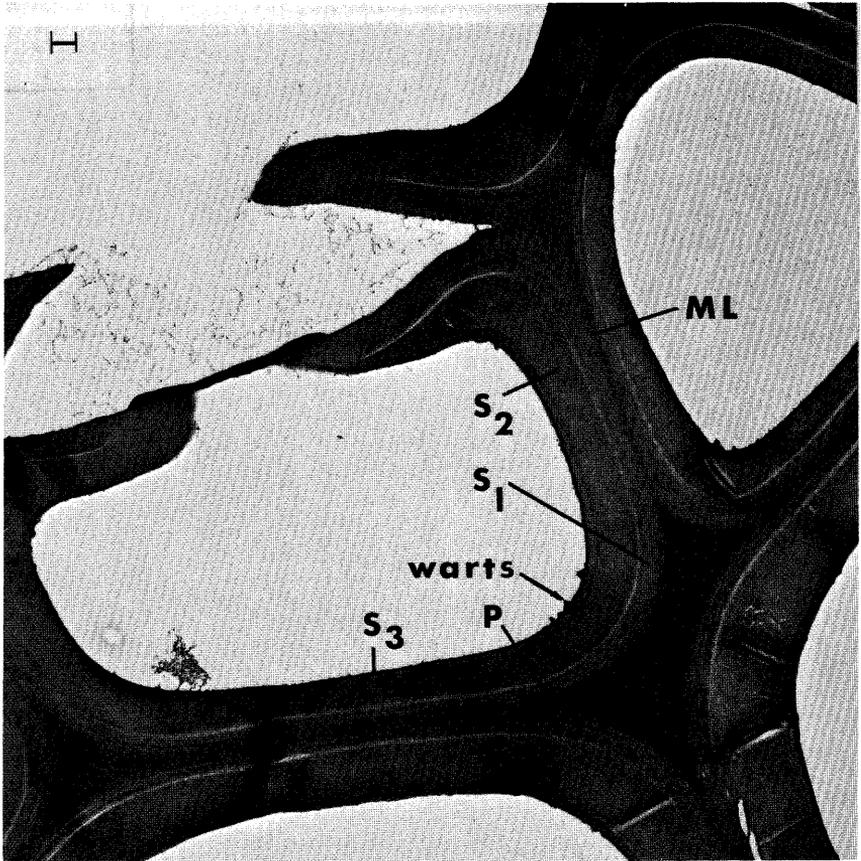


Figure 5-9.—Cell-wall layers of an earlywood longitudinal tracheid in cross section. The dark line bordering the cell lumen is warty layer; small protuberances are warts, seen in profile. At upper left is an aspirated bordered pit, its membrane tightly appressed against pit chamber wall of central tracheid, and invisible except for the thickened central torus, closing the pit aperture. ML is middle lamella; P is primary wall. Slash pine, var. *elliottii*, heartwood. Scale mark shows 1 μ m. (Photo from Côté and Day 1969.)

resemble the callitroid thickenings described in some *Callitris* species (Cronshaw 1961), extending across the aperture edges on the radial wall, flattening and disappearing on the tangential wall (fig. 5-14). Spiral thickenings sometimes appear in association with them. These callitroid thickenings appear on tangential pits and pits connecting longitudinal tracheids with rays.

In a limited sample, Howard and Manwiller (1969) observed that callitroid thickenings are most pronounced and frequent in pond pine; they are also well developed in pitch, shortleaf, slash, and loblolly pines. They are less pronounced and less frequent in longleaf, Table-Mountain, and spruce pine. In Virginia, South Florida slash, and both races of sand pine, they are very rare and poorly defined.

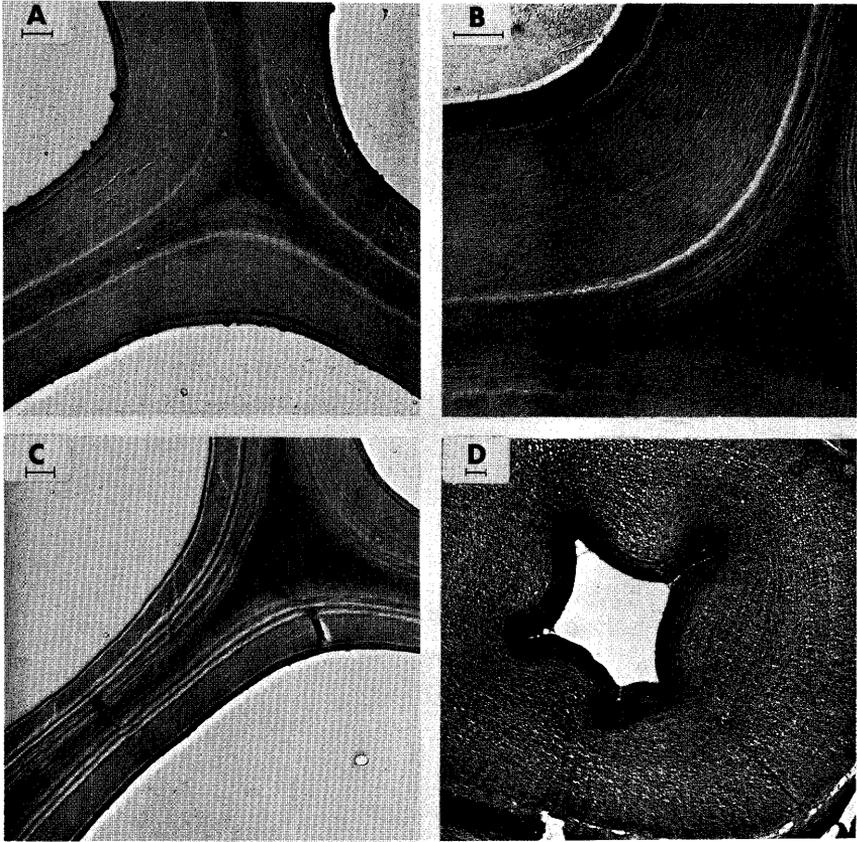


Figure 5-10.—Thickness of S_2 layer accounts for most of the difference between earlywood and latewood; variations in layering occur in all southern pine species. (A) Earlywood tracheid, Table-Mountain pine, heartwood. (B) Latewood tracheid, Virginia pine, heartwood. (C) Earlywood tracheid wall, appearing to have extra layers in S_2 region. Spruce pine, heartwood. (D) Latewood tracheid wall, apparently with extra layers in S_2 region. (After a hydrofluoric acid treatment to reveal the lignin skeleton.) Slash pine, heartwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

STRAND TRACHEIDS

Strand tracheids occasionally occur along vertical resin canals outside the parenchymatous tissue. They are shorter than the longitudinal tracheids and are characterized by pitted transverse ends and tiny bordered pits along the vertical walls (fig. 5-6(7-7a)).

EPITHELIAL CELLS

Of all the conifers, the pines have the largest and most numerous resin canals. Horizontal and vertical ducts interconnect to form a continuous system (fig. 5-6(9-9a, X, Y)).

The resin canals are lined with thin-walled epithelial cells which secrete

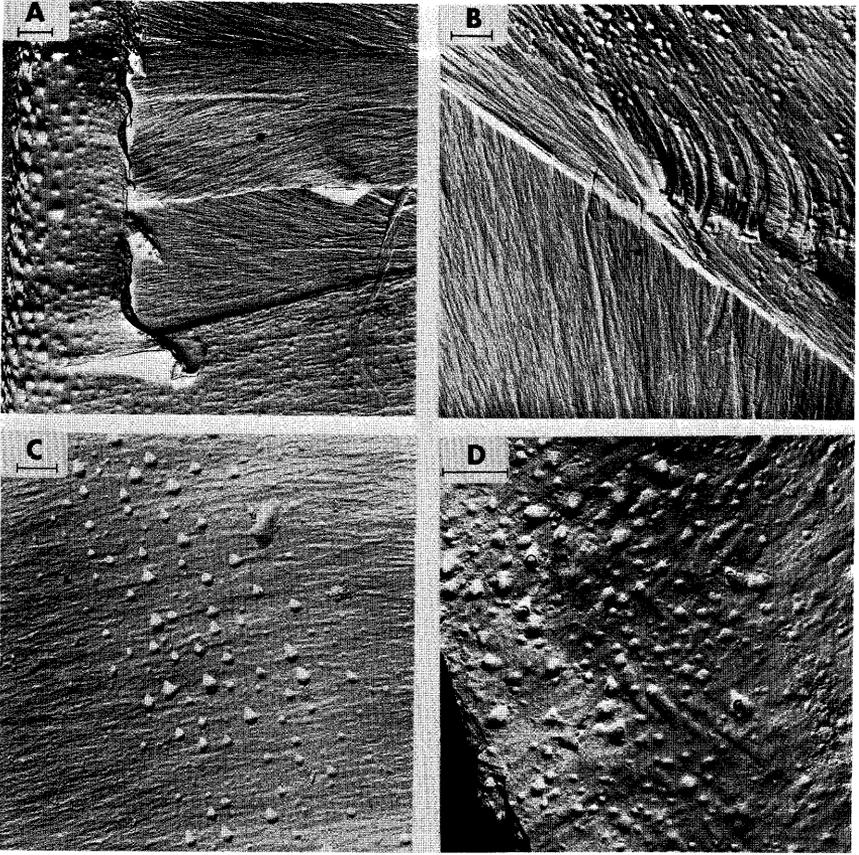


Figure 5-11.—Longitudinal tracheids viewed from lumen. (A) Warty layer on left obscures S_2 microfibrils which are visible through lighter warty layer at bottom. At upper right, removal of surface reveals varying fibril angles in three lamellae of S_2 layer. Virginia pine, earlywood, heartwood. (B) At upper right, microfibrils of S_3 layer, at unusually small fibril angle, are visible through warty layer. At lower left, typical fibril angle of S_2 layer is visible where S_3 has been removed. Table-Mountain pine, earlywood, sapwood. (C) Warty layer with moderate number of medium size warts. Clearly visible microfibrils of S_3 layer indicate absence of encrustation. Sand pine (Ocala), earlywood, heartwood. (D) Heavy encrustation, obscuring microfibrils and covering warts. Longleaf pine, latewood, sapwood. Scale marks show 1 μ m. (Photo from Côté and Day 1969.)

oleoresin into them. In longitudinal section these secretory cells vary in shape from more or less square to somewhat hexagonal (fig. 5-15). Resin canals in heartwood frequently are obstructed by tylosoids resulting from proliferation of epithelial cells.

PARENCHYMA

In southern pines, longitudinal parenchyma partially surrounds most longitudinal resin canals (Howard and Manwiller 1969). The parenchyma lies in strands just outside the sheath of epithelial cells, and in vertical

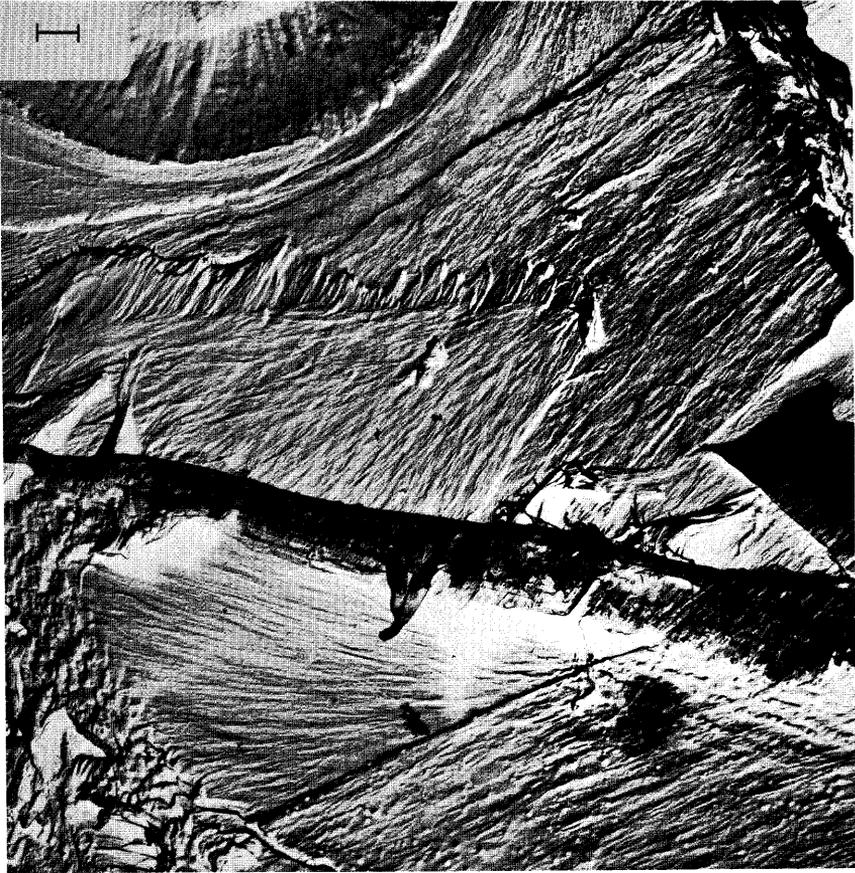
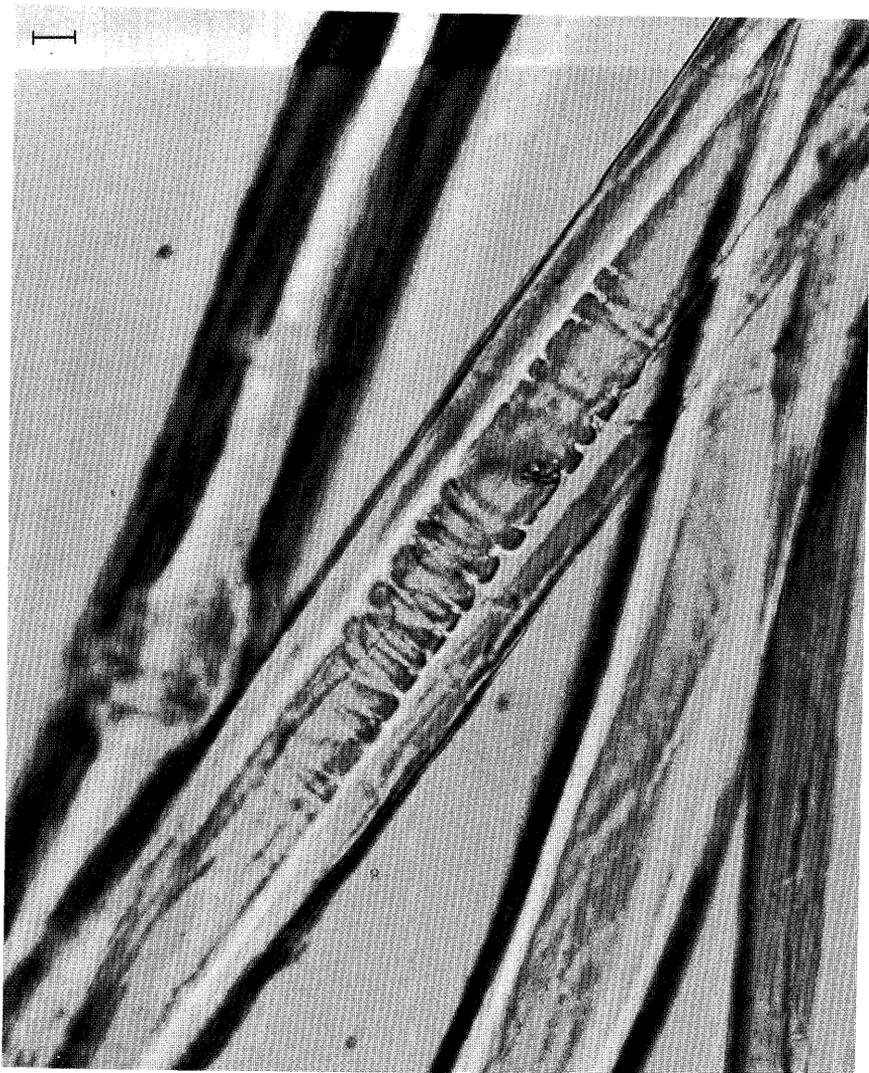


Figure 5-12.—Radial surface of latewood longitudinal tracheid viewed from lumen, showing various microfibril angles in cell-wall layers. At lower right, S_2 layer is visible through warty layer; lower left, transition lamellae. At upper left is part of a bordered pit, with S_1 microfibrils streamlined around it. Between are exposed segments of S_2 and transition lamellae. Pitch pine, heartwood. Scale mark shows $1 \mu\text{m}$. (Photo from Côté and Day 1969.)

section is distinguishable from them by longer, narrow dimensions and more rectangular shape (figs. 5-6 (8-8a, C), 5-15). When more than one layer is present, cells of the innermost strand are slightly longer than the epithelial cells; those of the outermost layer are $1\frac{1}{2}$ to three times as long.

Most longitudinal parenchyma cells are thin-walled; thick-walled specimens are occasionally found. These have conspicuous simple pits that give a nodular appearance to cell walls (fig. 5-6 DT).

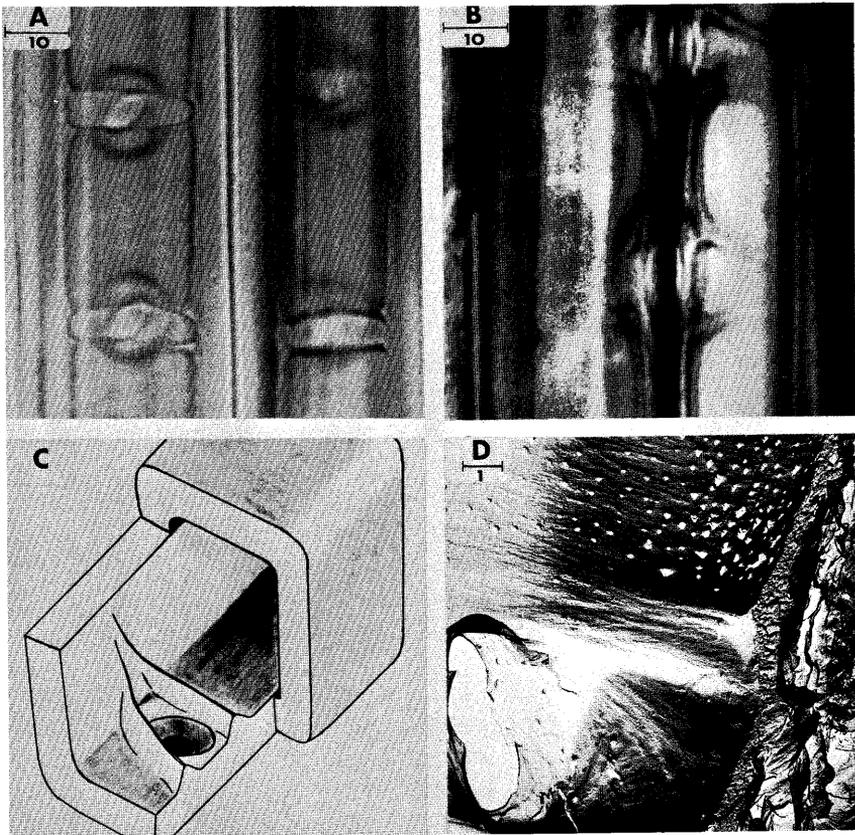
Dry wood, when sectioned may show a variety of contents within parenchyma cells. Côté and Day (1969) have published micrographs of crystalline inclusions as well as substances presumed to be starch.



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Figure 5-13.—Spiral thickening in macerated longitudinal tracheid of mature latewood. Loblolly pine sapwood. Scale mark shows 10 μm . (Photo from Howard and Manwiller 1969.)

5-4 STRUCTURE OF HORIZONTAL ELEMENTS

The rays contain all the horizontal elements of the xylem: ray tracheids, ray parenchyma, and epithelial cells (figs. 5-6, 5-16). A southern pine ray may be either homogeneous (composed of only one cell type), or heterogeneous (containing both ray tracheids and parenchyma). Most rays are uniseriate, i.e., one cell wide. Multiseriation is found only in the central portion of **fusiform rays**, which contain horizontal resin canals.



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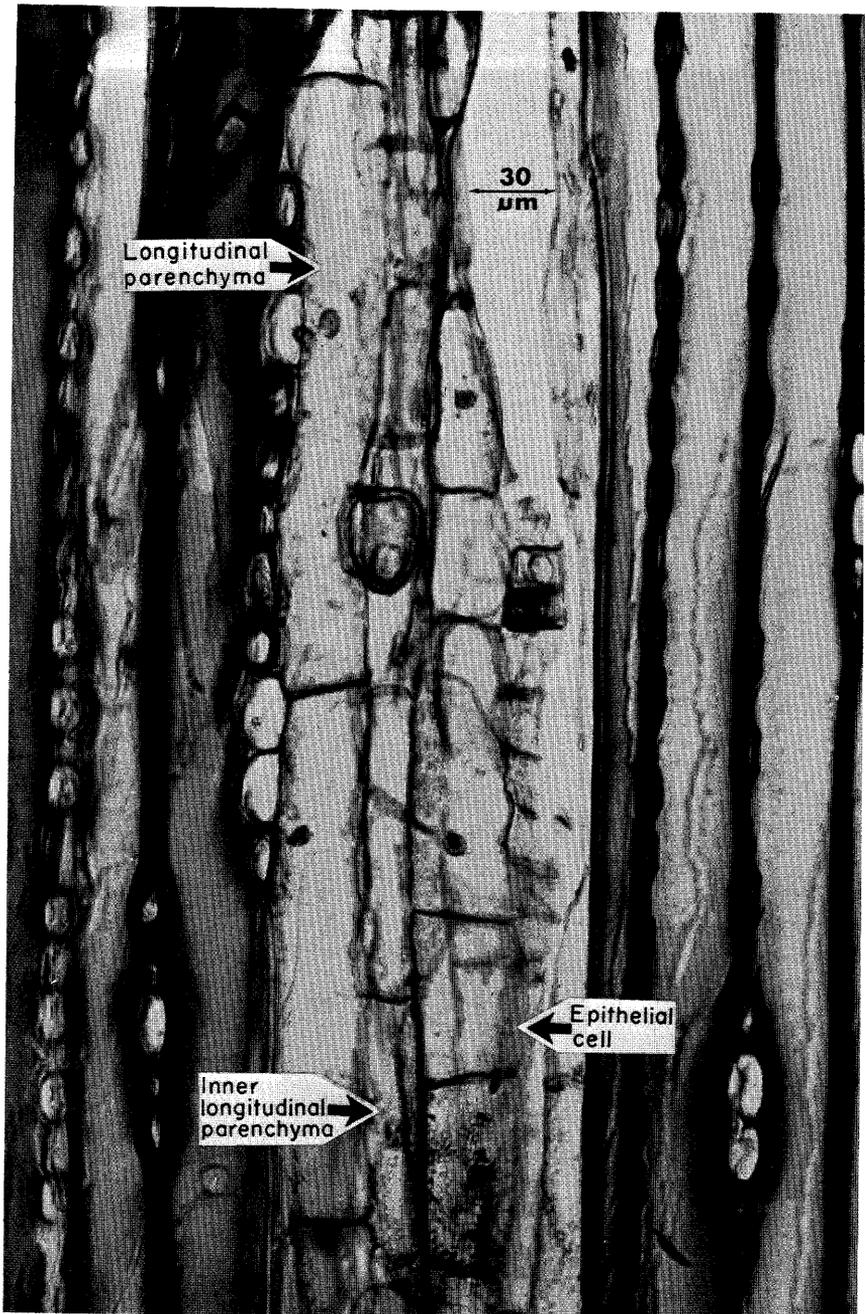
Figure 5-14.—Callitroid thickenings in longitudinal tracheids. (A) Radial section. Pond pine, latewood, sapwood. (B) Tangential section. Slash pine, latewood, sapwood. (C) Interpretive diagram of thickenings at radial pit in latewood. (D) Thickening above and below pit aperture (only part of lower thickening visible at lower left). Occurrence of these structures varied widely with species. Pond pine, latewood, heartwood. Scale marks show μm . (Photos A and B, and drawing C, from Howard and Manwiller 1969; photo D from Côté and Day 1969.)

According to Panshin et al. (1964, p. 112), rays occupy about 9 percent of the volume in wood of the major southern pines.

Pine species	Average ray volume	Variation in samples examined
	----- Percent -----	
Loblolly	7.6	1.6
Shortleaf	8.0	3.3
Longleaf	8.3	3.7
Slash	11.7	1.8

RAY TRACHEIDS

The ray tracheids are called “dentate” because of their prominent and complicated wall thickenings with jagged or “toothlike” appearance in



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Figure 5-15.—Longitudinal parenchyma and epithelial cells of resin canal in earlywood of Virginia pine sapwood. Longitudinal section. (Photo from Howard and Manwiller 1969.)

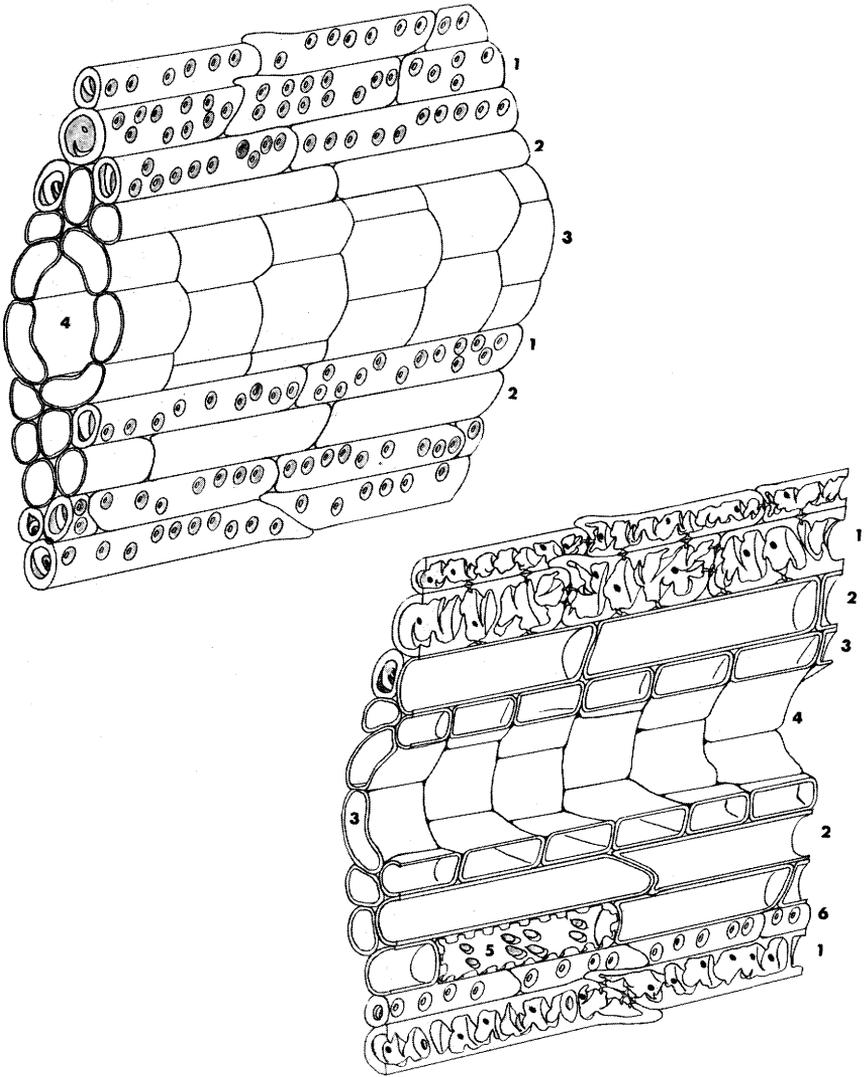


Figure 5-16.—Fusiform ray. (Top) Unsectioned. (Bottom) Sectioned longitudinally. 1, ray tracheids; 2, ray parenchyma; 3, epithelial cells; 4, resin canal; 5, thick-walled parenchyma with simple pits; 6, unsectioned ray tracheids with bordered pits. (Drawing after Howard and Manwiller 1969.)

radial and transverse section (figs. 5-17, 5-18). In tangential view (fig. 5-18 right) the sculpturings are seen as irregular, circular, or semicircular ridges extending partially around the interior but not completely closing the lumen.

In heterogeneous rays, ray tracheids form the margins and may be interspersed among the central parenchyma rows. Small bordered pits connect the ray tracheids with each other and with longitudinal tracheids. Walls adjacent to ray parenchyma have half-bordered pits.

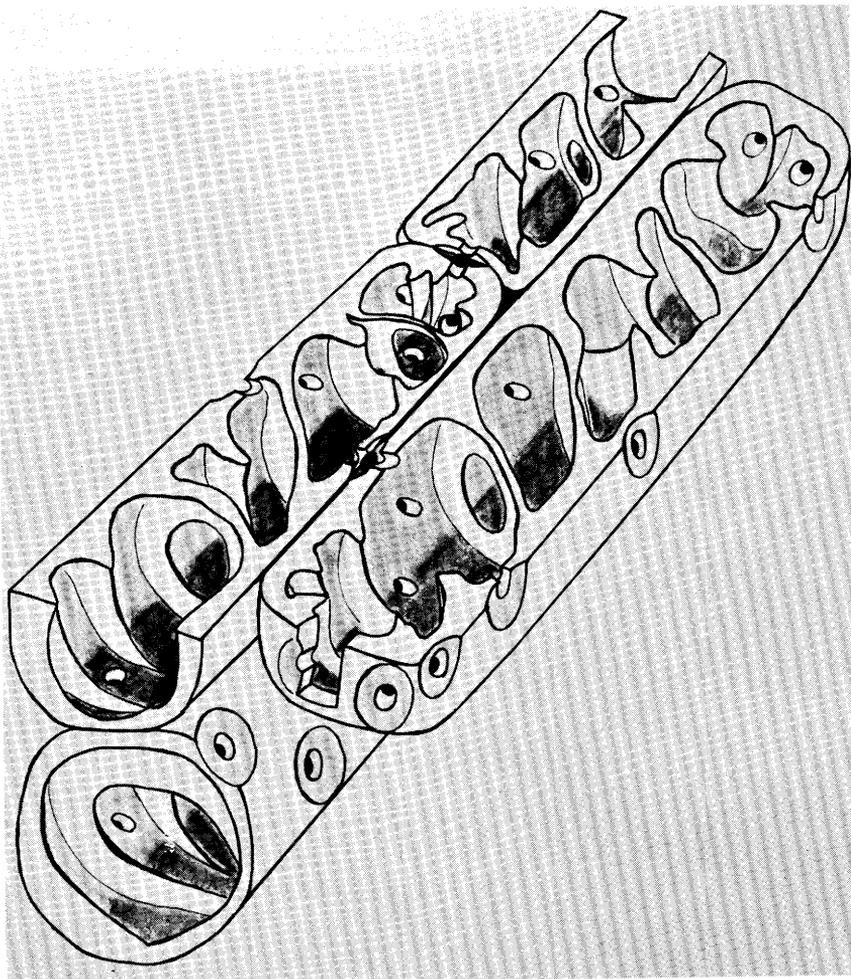
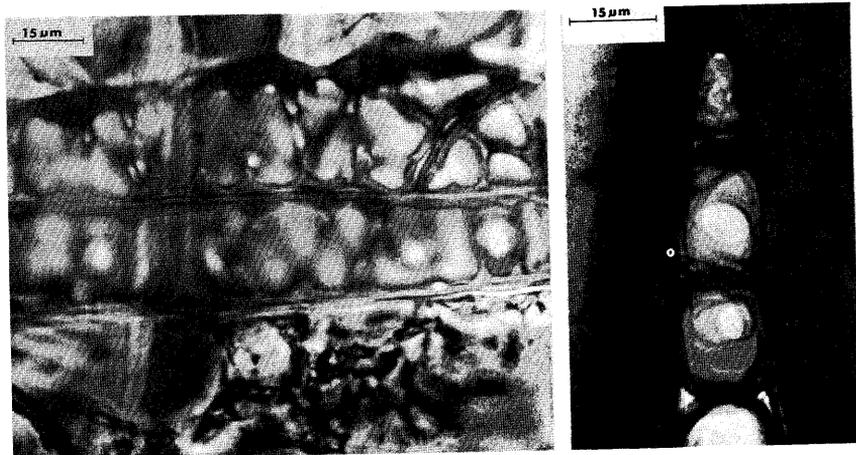


Figure 5-17.—Sectioned dentate ray tracheids. (Drawing after Howard and Manwiller 1969.)

The degree of dentation varies between individual rows of ray tracheids; those nearer the center of the ray are more dentate. The outermost row varies most between specimens. Dentation (or reticulation) is most pronounced in latewood and first-formed rows of earlywood.

Enlarged marginal ray tracheids of highly irregular shape are occasionally found; they extend vertically into the longitudinal tissues and may join with cells of other rays. Such "erect" structures are considered abnormal and are not of diagnostic value.

Organization of ray tracheid wall layers.—Côté and Day (1969) conclude that one cannot safely label the secondary wall layers of ray tracheids with S_1 , S_2 , and S_3 to compare directly with longitudinal tracheids. Orientation of microfibrils ranges from axial up to an angle of 45° (fig. 5-19).



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Figure 5-18.—Dentate ray tracheids. (Left) In radial section, dentations show as sharply defined membranes and as gray areas of varying intensity in two ray tracheids. Cell below them is living parenchyma. Earlywood of slash pine sapwood. (Right) In tangential section, dentations show as light gray areas, obscuring all but a small central part of the lumen in the three upper tracheids. Shortleaf pine, latewood, sapwood. (Photos from Howard and Manwiller 1969.)

In radial view, the streamline pattern of microfibrils around the many pits makes identification of wall layers difficult.

The tangential view of figure 5-19B shows that there is a thin outer layer—presumably just inside the primary wall; this section was chlorite treated to remove some lignin. The additional thickenings vary greatly in different portions of the tracheid.

Cell wall sculpturing.—The secondary walls of ray tracheids are sculptured externally and internally by pitting. Thickenings or dentations project into the cell lumens.

Figure 5-17 approximates the **dentations** in three dimensions. The light microscope shows them in radial and tangential section (fig. 5-18). They have also been viewed with the electron microscope in tangential, transverse, and radial section (fig. 5-19). Obviously the shapes and variations are complex.

Electron micrographs of pit structures in ray tracheids will be found in figures 5-27 and 5-28.

In ray tracheids, pit chambers are smaller than in longitudinal tracheids; in other respects the cavities are structurally similar.

RAY PARENCHYMA

Ray parenchyma cells are located in the central portion of heterogeneous rays. Most are thin-walled and unpitted. Scarce in southern pine, but more frequent in heartwood than sapwood, are thick-walled, heavily pitted parenchyma cells (figs. 5-20, 5-21). They have a nodular appearance in section and appear lignified. In hard pines having pinoid pits, including

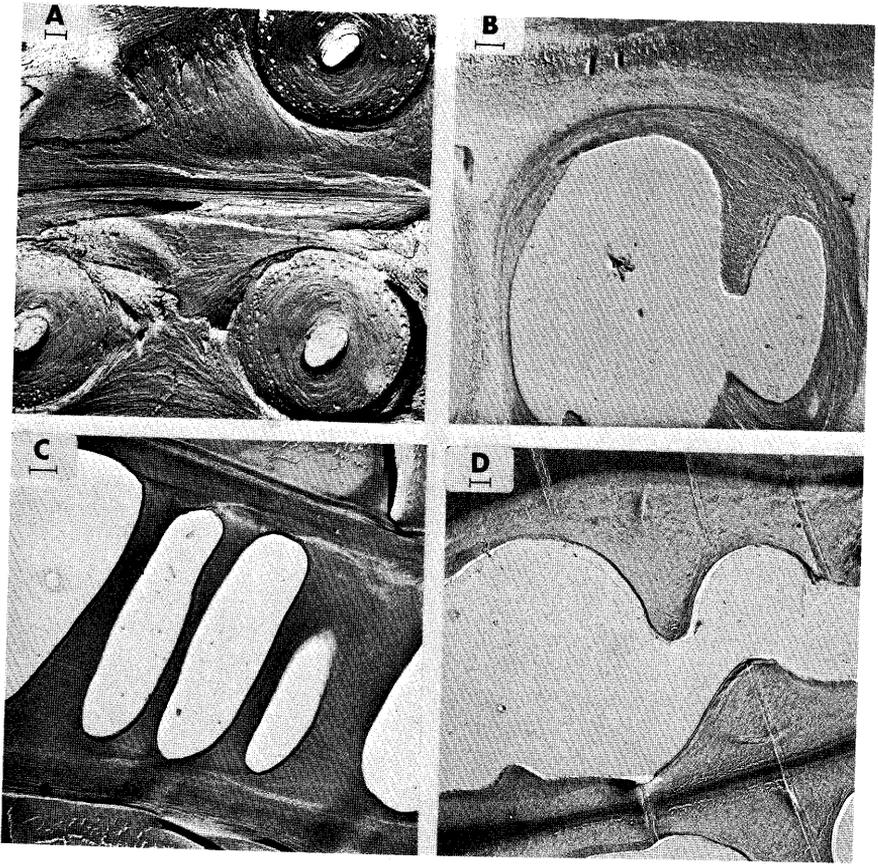


Figure 5-19.—Structure of dentate ray tracheids. (A) Ray tracheid walls are lamellated, with varied microfibril orientation, here partly obscured by streamlining around pits; no consistent layers have been identified. View is from outside, in split radial section, and appears to show two adjacent ray tracheids. Sand pine (*Ocala*), earlywood, sapwood. (B) Tangential section, with part of lignin removed by chlorite treatment; lamellae of ray tracheid wall extend into dentations. Slash pine (var. *elliottii*), latewood, heartwood. (C) Transverse section, showing dentation. The three oval openings are interconnected, because dentations do not completely occlude the cell lumen. Shortleaf pine, latewood, heartwood. (D) Radial section. Interior surfaces of ray tracheids assume diverse shapes, due to the varying patterns of dentation. Longleaf pine, latewood, heartwood. Scale marks show 1 μ m. (Photos from Côté and Day 1969.)

the southern pines, numbers of thick-walled cells increase as the sapwood-heartwood border is approached (Balatinecz and Kennedy 1967). Wall thickening thus seems to be associated with heartwood formation. Both thick- and thin-walled forms may be found in the same ray, the thick-walled cells being nearer the ray margins, usually adjacent to ray tracheids. Pitting is simple (see sec. 5-5). With the exception of spruce pine, all trees examined by Howard and Manwiller (1969) contained occasional thick-walled parenchyma cells.

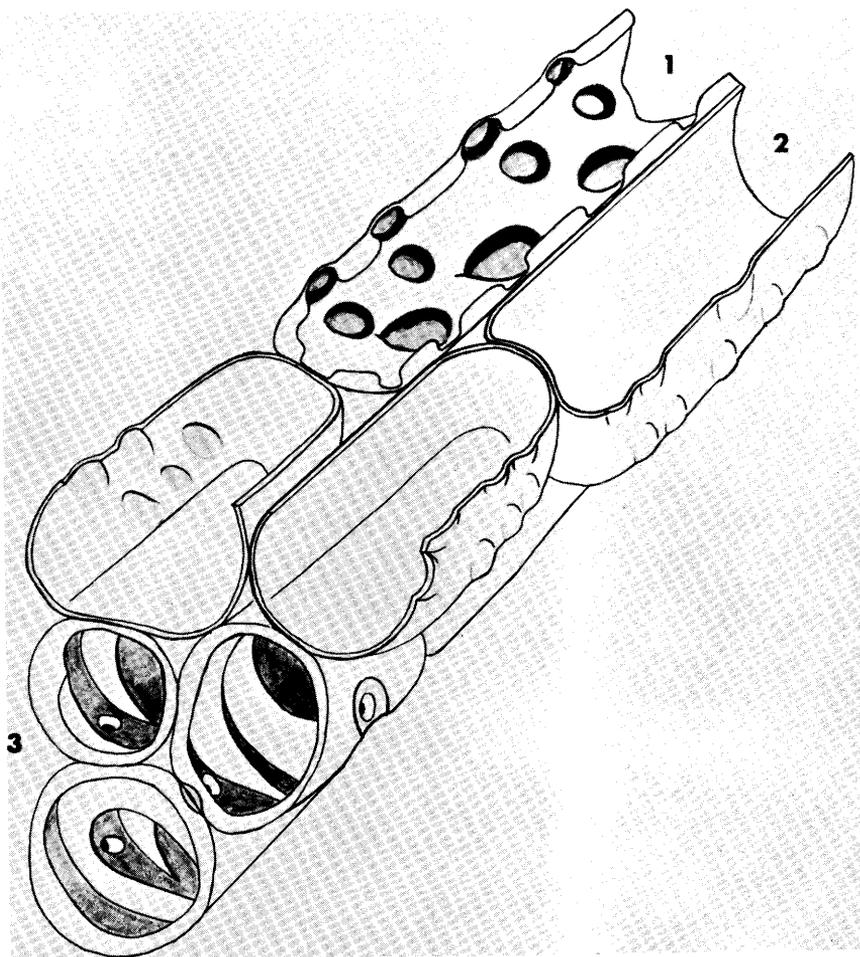


Figure 5-20.—Sectioned ray parenchyma. 1, thick-walled parenchyma with simple pitting; 2, thin-walled parenchyma. Note bulges where wall conforms to tracheid bordered pit chamber at crossfield; 3, dentate ray tracheids. (Drawing after Howard and Manwiller 1969.)

Côté and Day (1969) observed that parenchyma cells have an outer primary wall with random distribution of microfibrils (fig. 5-22A). The secondary walls are lamellated; microfibrils have distinctly different orientation in various layers (fig. 5-22B). Intercellular spaces and lamellation of walls are seen in tangential section (fig. 5-22CD). Radial sections permit comparison of thick- and thin-walled cells (fig. 5-23). Typical pitting is seen in figures 5-31, 5-32.

End walls of adjoining ray parenchyma sometimes display fine channels or openings that accommodated **plasmodesmata** connecting their protoplasm (Thomas and Nicholas 1968, p. 88; fig. 5-23CD).

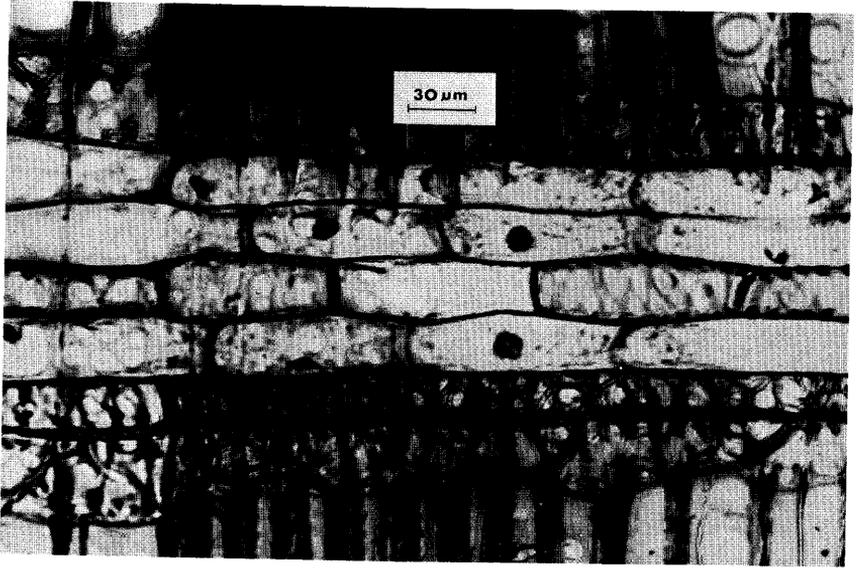


Figure 5-21.—Ray with both thin- and thick-walled parenchyma. Radial view of pitch pine sapwood. (Photo from Howard and Manwiller 1969.)

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EPITHELIAL CELLS

Horizontal epithelial cells are found only in rays (figs. 5-6LW, 5-16). They are similar to, but smaller than, epithelial cells of the vertical resin canals. Transverse views, exposed in tangential sections of fusiform rays, show lamellated walls whose thicknesses vary more or less randomly (fig. 5-24).

5-5 PIT PAIRS

A pit is defined as a gap or recess—open to the lumen—in the secondary wall together with an external closing membrane which usually is common to a pit in an adjoining cell. Pit pairs create passageways (more or less obstructed) through which liquids and gases can move from cell to cell in the living tree and in wood during conversion processes such as seasoning, preservation, and pulping (fig. 5-6F 0 0' Z Z'). Because the permeability of these passageways is of great importance during processing for utilization, they have been examined in great detail. There are six possible combinations of pit pairs in southern pine wood.

TRACHEID TO TRACHEID—BORDERED

Pit pairs between longitudinal tracheids have a full border in each cell, and a centrally thickened **membrane** stretched across the pit chamber (fig. 5-25). Surrounding the central thickened portion, or **torus**, is a ring of thinner, perforated membrane, called the **margo**. During normal

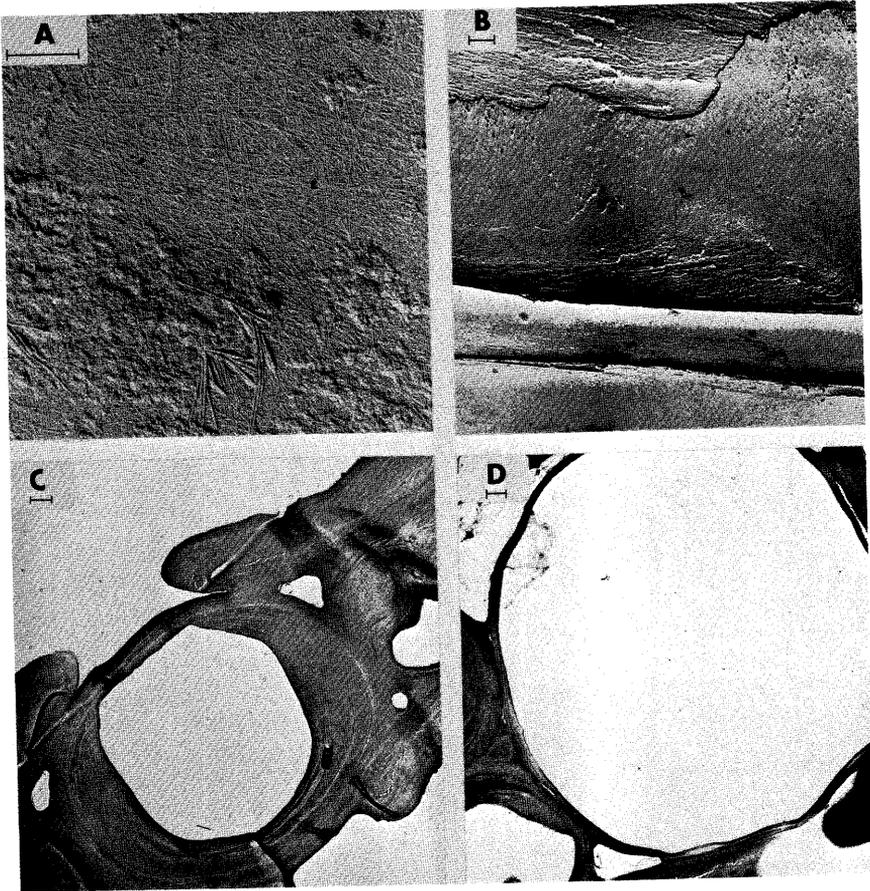


Figure 5-22.—Structure of ray parenchyma cells. (A) Radial section, replica of surface, showing randomly oriented microfibrils of primary cell wall. Slash pine (var. *elliottii*), earlywood, sapwood. (B) Replica of split radial section, showing layered structure of secondary cell wall; the cell axis is parallel with top of page. Pond pine, earlywood, sapwood. (C) Tangential section across thick-walled parenchyma cell with half-bordered pit to prosenchymatous (conducting) cell, upper left. Note intercellular spaces and cell-wall lamellation. Table-Mountain pine, earlywood, heartwood. (D) Tangential section across thin-walled cell. Most parenchyma cells are of this type; there is little or no thickening of the secondary cell wall. Slash pine (var. *densa*), earlywood, heartwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

seasoning the torus is usually drawn to one of the pit apertures (aspirated), creating a seal (fig. 5-9).

In earlywood tracheids, pits are large, have round apertures, and are often marked by **domes** (fig. 5-25C), where the pit borders protrude into the lumen. **Crassulae** (thickenings of the middle lamella and cell wall) frequently bound the upper and lower edges of radial pits in earlywood (fig. 5-25F). In the thick walls of latewood tracheids, prominent domes rarely form and apertures are generally more slit like than circular (fig. 5-25D);

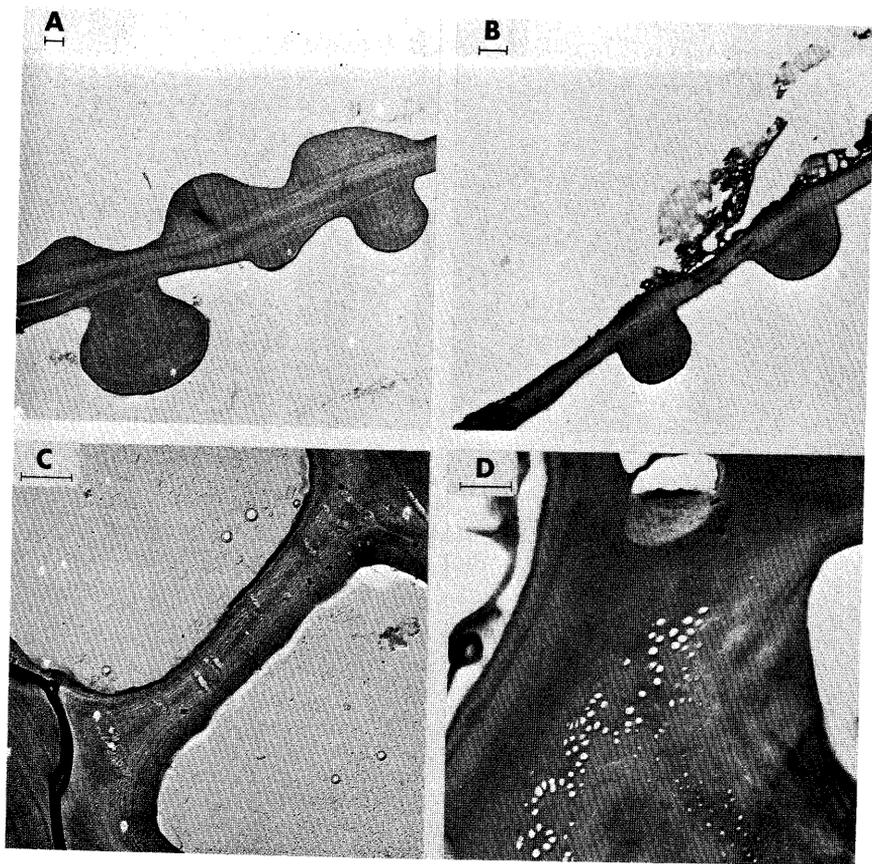


Figure 5-23.—Walls of adjacent parenchyma cells. (A) Radial section, thick-walled cells. Table-Mountain pine, earlywood, heartwood. (B) Radial section, thin-walled parenchyma cell at upper left, thick-walled at lower right. Pits in thick wall have no overhang and there are no opposite gaps in the thin wall. Virginia pine, earlywood, heartwood. (C) Transverse section showing end wall between ray parenchyma cells, with traces of fine intercellular openings. Pitch pine, latewood, sapwood. (D) Tangential section through end wall between two ray parenchyma cells, showing distribution of plasmodesmata openings, affording interchange of cell protoplasm. Slash pine (var. *elliottii*), latewood, heartwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

in cross section, channels, called **pit canals** (fig. 5-25E), extend through the thick cell wall to connect the pit chamber with the lumen.

In both earlywood and latewood, warts occur on both the lumen and the pit-chamber face of pit borders, often in concentrations that obscure the underlying structure (figs. 5-25, 5-26). In slash pine (only one tree examined) warts are infrequent in pit chambers, but a few occurred (fig. 5-26C). Microfibrils on the lumen face of pit borders appear continuous with those in the adjacent cell walls; they are deflected around the aperture in a streamline pattern (fig. 5-25C). On the pit-chamber face the microfibril pattern, when visible, is circular (fig. 5-26C).

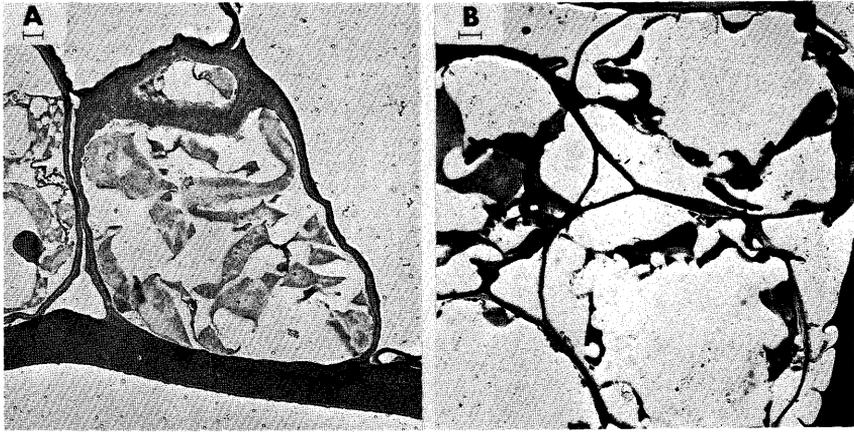


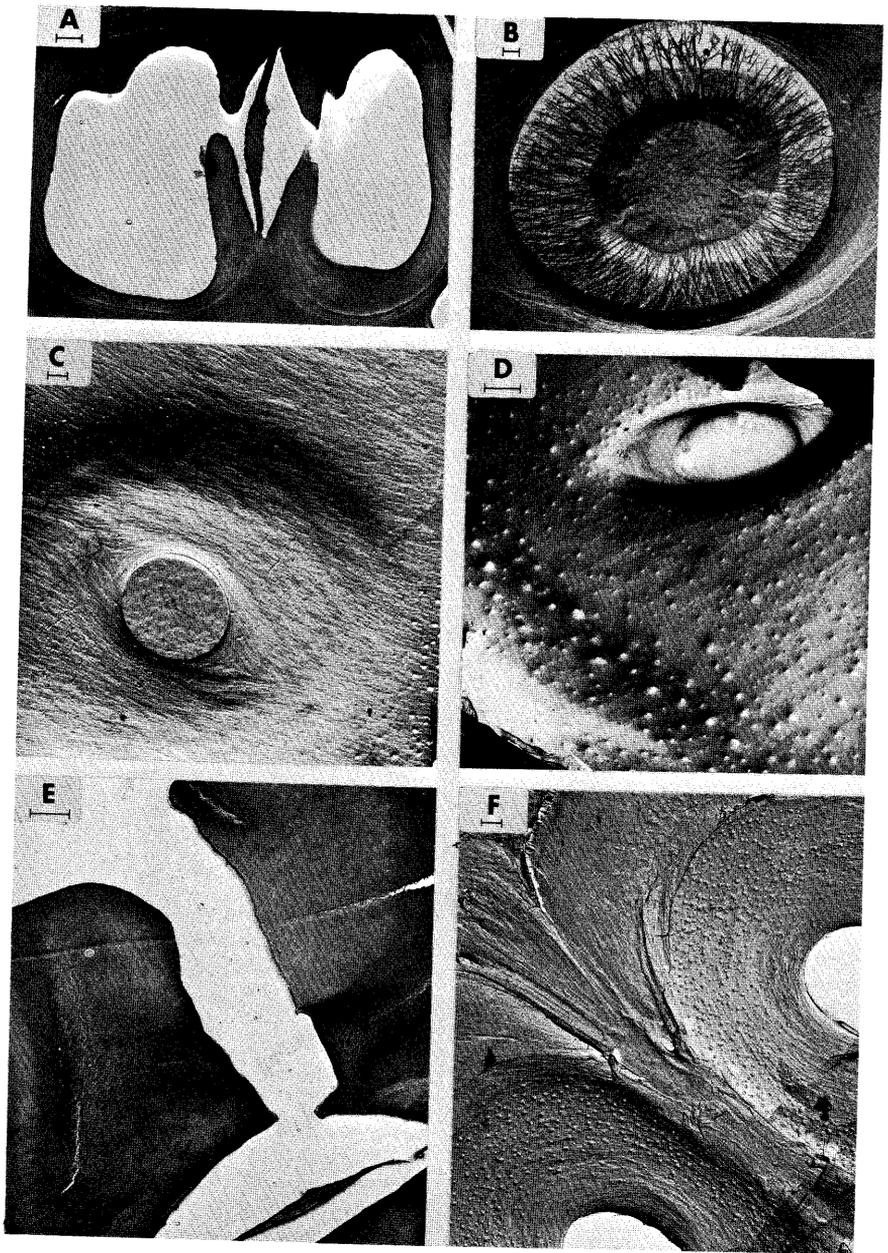
Figure 5-24.—Tangential sections through fusiform rays show transverse views of epithelial cells surrounding resin canals. Broken remnants of cell contents are visible within the cells. (A) Thickness of cell walls varies between cells, and within individual cells; lamellations are evident in thickened cell wall in upper part of central cell. Area at upper right is probably part of resin canal. Broad dark band below central cell appears to be a thick-walled ray parenchyma cell. Pitch pine, earlywood, sapwood. (B) Extremely thin-walled epithelial cells. Thickness of walls in these cells varies widely in all pine species. Slash pine (var. *elliottii*), earlywood, sapwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

Encrustations of resins and other deposited materials may occur around pit apertures which have been closed by aspiration of the torus. Such encrustations are rare in earlywood, more common in latewood, and may completely mask the structure in latewood of heartwood (fig. 5-26B).

Pits between longitudinal tracheids are chiefly on the radial walls and tend to be concentrated near the ends (fig. 5-7A). Tangential pits connecting tracheids, though not as frequent as radial pits, are fairly common in the southern pines; they are found throughout the growth ring but more frequently in earlywood than latewood. They are equal in size to adjacent radial pits (Howard and Manwiller 1969, fig. 5).

Radial pitting between tracheids may be uniseriate (pits in a single row), biseriate, or rarely triseriate. Virginia pine tracheids typically have uniseriate radial pitting in earlywood. Care should be taken, however, in identification by this feature alone, for Table-Mountain, spruce, Ocala sand, Choctawhatchee sand, and pitch pines also have one-row pitting with few biseriate pits.

Thomas (1967) showed that pit membrane structures vary widely in earlywood and latewood of both heartwood and sapwood. Within-tree variation appears to be as great as between-species variation. Some membranes have fine supporting strands, especially in the earlywood of sap-



wood, while in latewood the microfibrillar bundles are often much coarser. The levels of encrustation are not completely predictable, but sapwood membranes are generally less encrusted than heartwood (Thomas 1969; Côté and Day 1969).

Thomas (1969) has studied nonaspirated pit membranes of longleaf,

pond, and loblolly pine; his conclusions are given in the following three paragraphs.

There is a definite circular orientation of microfibrils in the margo around the periphery of the torus (fig. 5-26D). The density variation in the margo appears to be controlled by the number of randomly oriented, small-diameter microfibrils present. The number of margo microfibrils is negatively correlated with age of the wood. Study of trees from several age classes showed the deterioration of the margo to be related to the number of years since the wood was formed rather than the age of the tree at the time the wood was produced (fig. 5-26F).

Encrustations sufficient to alter margo porosity were not found on earlywood bordered pit membranes in sapwood; heavy encrustations were observed on latewood bordered pit membranes regardless of location (fig. 5-26B).

Aspiration of pit membranes in the heartwood region occurs in the standing tree. Extremely tight aspiration can be observed throughout the discolored heartwood zone.

In transverse section, the cell wall layers of the bordered pit are difficult to identify. Murmanis and Sachs (1969) have diagrammed their concept of the structure as it occurs in eastern white pine (*Pinus strobus* L.), and compared this concept with diagrams made by Wardrop and Davies (1961), Jutte and Spit (1963), and Harada and Côté (1967).

TRACHEID TO RAY TRACHEID—BORDERED

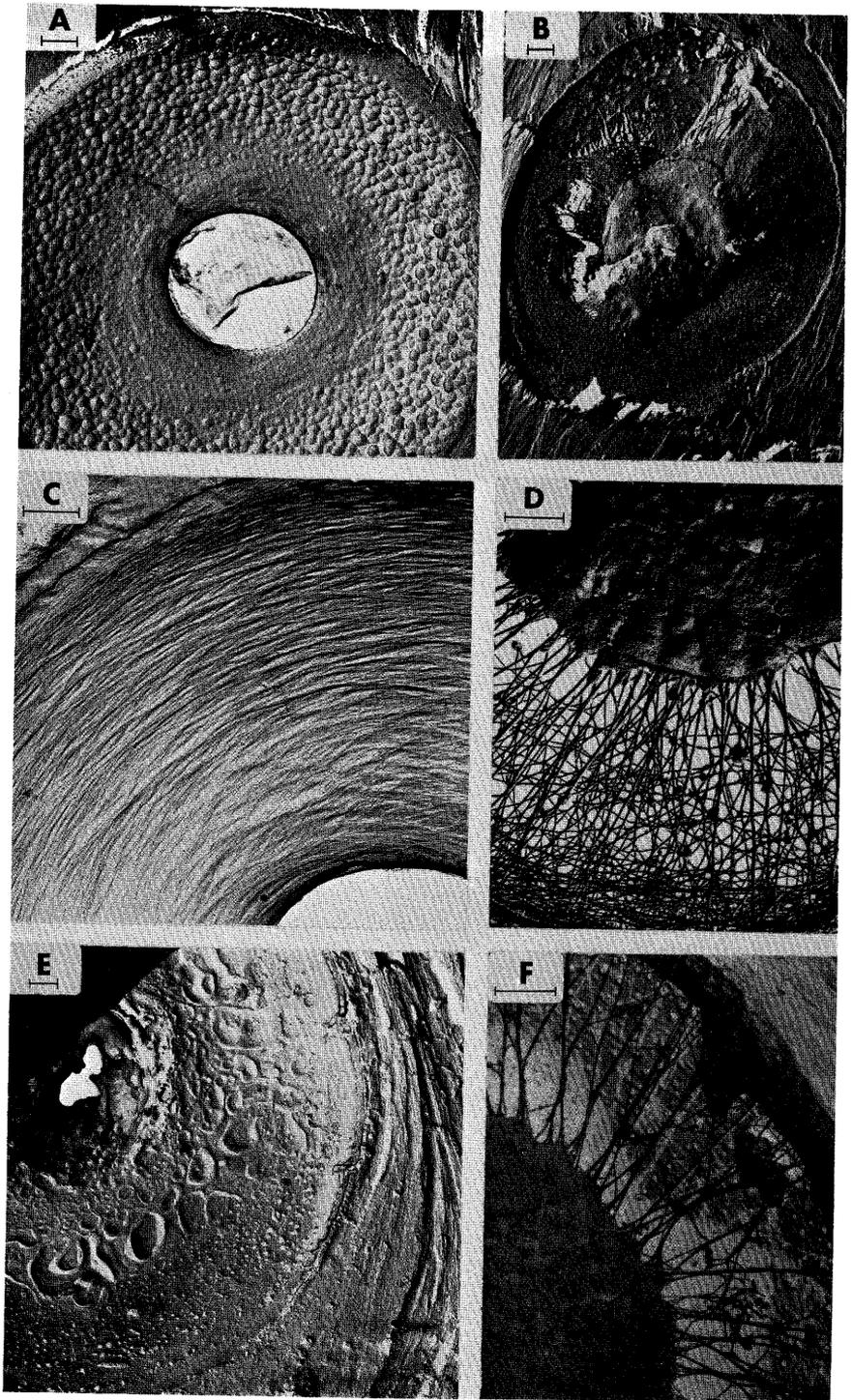
Pit pairs between tracheids and ray tracheids have small cavities, averaging a little over half the diameter of cavities in pits between longitudinal



Figure 5-25.—Bordered pits in tracheids of southern pines.

- (A) Section showing pit borders. Pit membrane in unspirated position, as shown, is normal in living portions of tree. (Pit pair shown is between ray tracheids.) Spruce pine, latewood, heartwood.
- (B) Bordered pit membrane (not aspirated) in pit pair between longitudinal tracheids. Central torus is thickened, primarily with lignin, though microfibrils are sometimes visible on surface. Surrounding margo is thin, permeable, consists mainly of microfibrils. Longleaf pine, earlywood, sapwood.
- (C) Replica of bordered pit, viewed from lumen. Central circle is aperture, surrounded by raised dome; microfibrils in streamline pattern around aperture; minute spots are warts. Sand pine (Ocala), earlywood, sapwood.
- (D) Slit-like pit canals and apertures are common in latewood; abundant warts may occur in either earlywood or latewood. Replica, viewed from lumen. Table-Mountain pine, latewood, heartwood.
- (E) Pit canal, connecting aperture with lumen, upper left, typical of thick-walled latewood tracheids. Pitch pine, latewood, sapwood.
- (F) Barlike structure between two bordered pits which may correspond to crassulae, i.e., thickenings of the middle lamella and cell wall. Replica, viewed from outside tracheid. Shottleaf pine, earlywood, sapwood.

Scale marks show 1 μ m. (Photos from Côté and Day 1969, except B, which is from Thomas 1969.)



←
Figure 5-26.—Details of bordered pit structure in longitudinal tracheids of southern pine.

- (A) Replica of pit chamber, with membrane removed, showing warts on chamber face of pit border. There is also some encrustation. Table-Mountain pine, earlywood, heartwood.
- (B) Pit membrane (non-aspirated) with heavy encrustations. These encrustations are rare in earlywood, common in latewood, more common in heartwood than sapwood. Longleaf pine, latewood, sapwood.
- (C) Pit chambers free of warts are rare, but were common in the tree illustrated. Microfibrils show circular orientation. Slash pine (var. *elliottii*), latewood, heartwood.
- (D) Low-density margo, in which radial, circular, and random microfibrils are visible. Torus surface encrusted, probably with lignin. Pond pine, earlywood, sapwood.
- (E) In some tracheids, especially in heartwood, encrustations may completely obscure the pit structure; replica of chamber face of pit border. Note, however, that pit in C is free of encrustations. Longleaf pine, earlywood, heartwood.
- (F) Deteriorated margo; circular and random microfibrils reduced. Deterioration increases with time since wood was formed. Membrane not aspirated. Twentieth ring of 60-year-old tree. Longleaf pine, earlywood.

Scale marks show 1 μm . (Photos A, C, E, from Côté and Day 1969; B from R. J.

Thomas—presentation at a Symposium, "Utilization of the Southern Pines", Alexandria, Louisiana, November 6-8, 1968; D and F from Thomas 1969.)

tracheids of earlywood (fig. 5-27). Since they are nearly equal in size to longitudinal tracheid-tracheid pit pairs in latewood, in electron microscopy (but not light microscopy) they can be confused with the latter. Both Thomas (1967) and Côté and Day (1969) observed, however, that

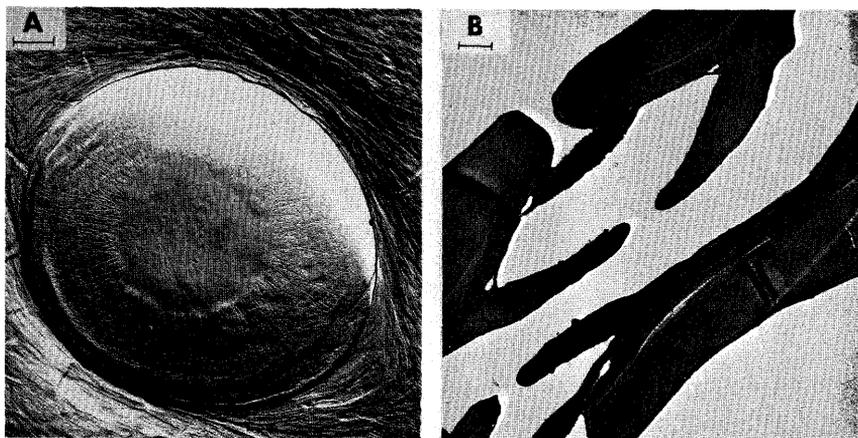


Figure 5-27.—Tracheid to ray tracheid pit pairs. Membranes are denser than those in tracheid-to-tracheid pits, and pit diameters are smaller.

- (A) Replica of split surface, showing pit membrane. Note streamlining of cell-wall microfibrils around pit. Table-Mountain pine, earlywood, sapwood.
- (B) Cross section with longitudinal tracheid on upper left and ray tracheid in center. Part of a pit in opposite wall of ray tracheid at lower left. Shortleaf pine, earlywood, sapwood.

Scale marks show 1 μm . (Photos from Côté and Day 1969.)

when a ray tracheid is involved, the margo is often more densely packed with microfibrils (fig. 5-27).

In a total of 11 trees, Thomas and Nicholas (1969) examined the membrane structure of tracheid to ray tracheid bordered pits in longleaf, pond, shortleaf, and loblolly pines. They observed a torus, a dense multilayered margo composed of microfibrils, and a considerable amount of surface encrustation which substantially reduced porosity of the margo. Removal of encrustants showed two types of membrane structure. In the first, margo microfibrils were continuous over the torus surface, while in the second the microfibrils had a circular orientation around the periphery of the torus. On rare occasions, pit membranes from specimens treated with sodium chlorite were found to lack a distinct torus.

RAY TRACHEID TO RAY TRACHEID—BORDERED

The pits connecting ray tracheids (fig. 5-28) are much smaller, and are more variable than those joining longitudinal tracheids. The margo may have visible microfibrils or be heavily encrusted. The torus is not always circular.

When viewed in section, pronounced variability is observable. A thickened torus and thin margo is common, but uniformly thickened (possibly encrusted) membranes are also present (fig. 5-28). Spruce pine has fully developed tori on many membranes of ray tracheids; however, it alone was observed to lack a torus thickening in some membranes.

In pit chambers of ray tracheids, there is a spectrum of wart sizes and numbers in all species. Encrustation is generally greatest in latewood of heartwood, but heavy deposits have appeared in pit chambers of earlywood in sapwood.

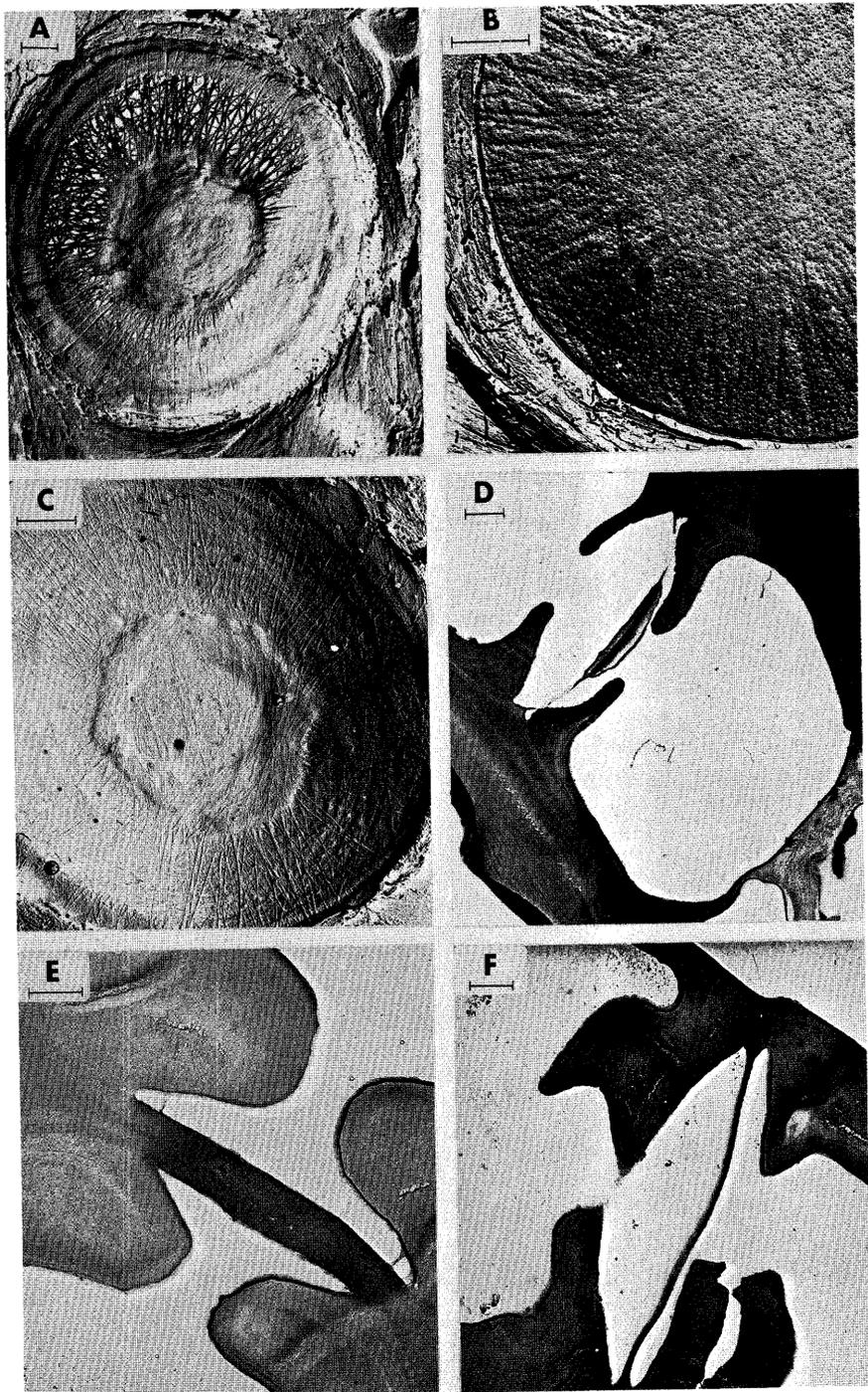
TRACHEID TO RAY PARENCHYMA—HALF-BORDERED PINOID

Pinoid pits, the distinctive feature of the hard pines, occur where longitudinal tracheids and ray parenchyma are in contact (figs. 5-29, 5-30). These pits are bordered on the tracheid side and have a characteristic egg shape in earlywood but more nearly a lens shape in latewood. The

Figure 5-28.—Pits connecting ray tracheids are smaller and more varied than those between longitudinal tracheids. A, B, C, replicas of pit membranes; D, E, F, sections.

- (A) Thin, relatively unencrusted margo; in many samples the mat of microfibrils is much denser. Table-Mountain pine, earlywood, sapwood.
- (B) Heavily encrusted margo; torus obscured. Loblolly pine, latewood, heartwood.
- (C) Irregular torus. Virginia pine, earlywood, sapwood.
- (D) Membrane in ray tracheid pits is often similar to that between longitudinal tracheids, with thin margo and thickened torus. Shortleaf pine, latewood, sapwood.
- (E) Membrane is sometimes greatly thickened, without distinguishable torus and margo. Slash pine (var. *densa*), earlywood, heartwood.
- (F) In spruce pine, only, some pit membranes between ray tracheids are unthickened, with no evidence of a central torus. Spruce pine, latewood, sapwood.

Scale marks show 1 μ m. (Photos from Côté and Day 1969.)

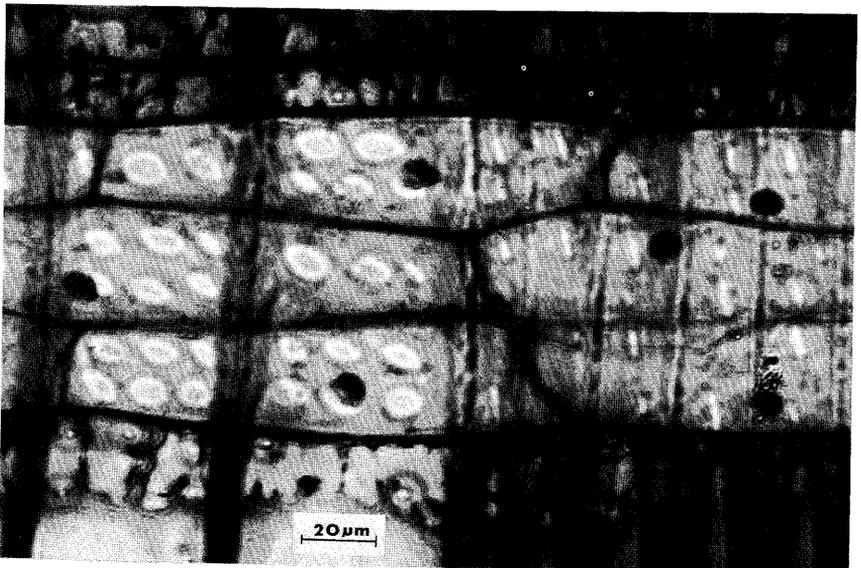


corresponding area in thick-walled parenchyma contains a simple pit, but in thin-walled parenchyma a pit is not formed, as secondary wall thickening has not occurred. Therefore, the crossfield (longitudinal to radial) pitting seen in radial section (figs. 5-29, 5-31) actually exists on the tracheid wall only and is visible through the translucent parenchyma. The thin parenchyma wall may sometimes (particularly on the larger pits) bulge outward slightly to conform with the tracheid pit chamber (fig. 5-31B). Number, shape, and size of crossfield pits vary considerably within a single ray and from ray to ray.

The structure can be clearly seen with an electron microscope (fig. 5-31); detectable openings in the pit membrane do not appear in electron micrographs (Thomas and Nicholas 1968; Côté and Day 1969).

RAY TRACHEID TO RAY PARENCHYMA—HALF BORDERED

While figure 5-32AB shows only sapwood, heartwood has similar structures. Côté and Day (1969) observed, as did Balatinecz and Kennedy (1967), that little or no lignification takes place in most ray parenchyma walls, causing them to show as light bands in photographs. Thick-walled parenchyma cells show a gap in the secondary wall, whereas thin-walled parenchyma do not (fig. 5-32AB).



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Figure 5-29.—Crossfield (longitudinal tracheid to ray parenchyma) pinoid pitting, earlywood, and latewood. Radial section of Virginia pine sapwood. (Photo from Howard and Manwiller 1969.)

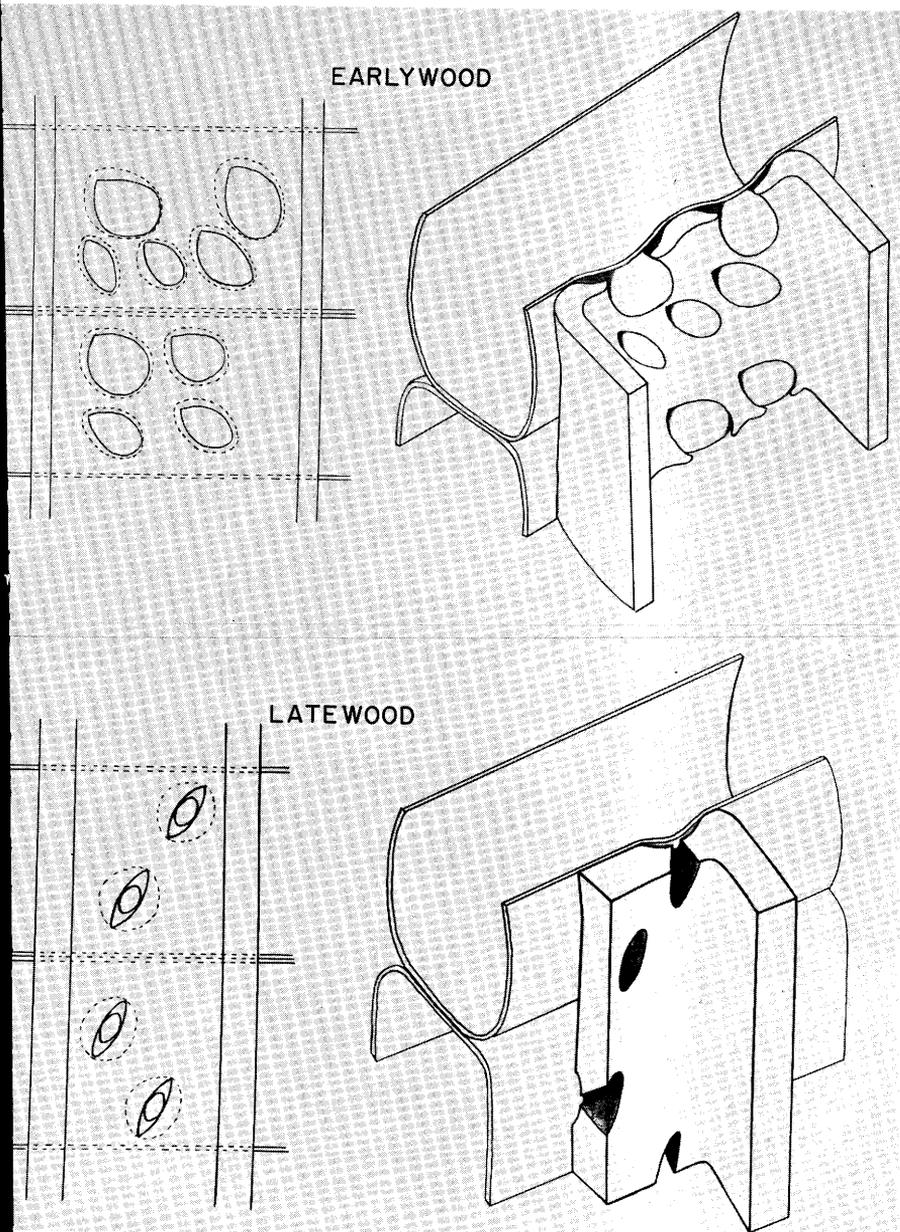


Figure 5-30.—Pinoid pits between longitudinal tracheids and ray parenchyma; earlywood and latewood. (Drawings from Howard and Manwiller 1969.)

RAY PARENCHYMA TO RAY PARENCHYMA—SIMPLE

The pit membrane of figure 5-32C is part of the simple pit pair formed by gaps in the secondary wall of adjoining cells. It is comprised of the primary wall of each cell together with the intercellular layer between

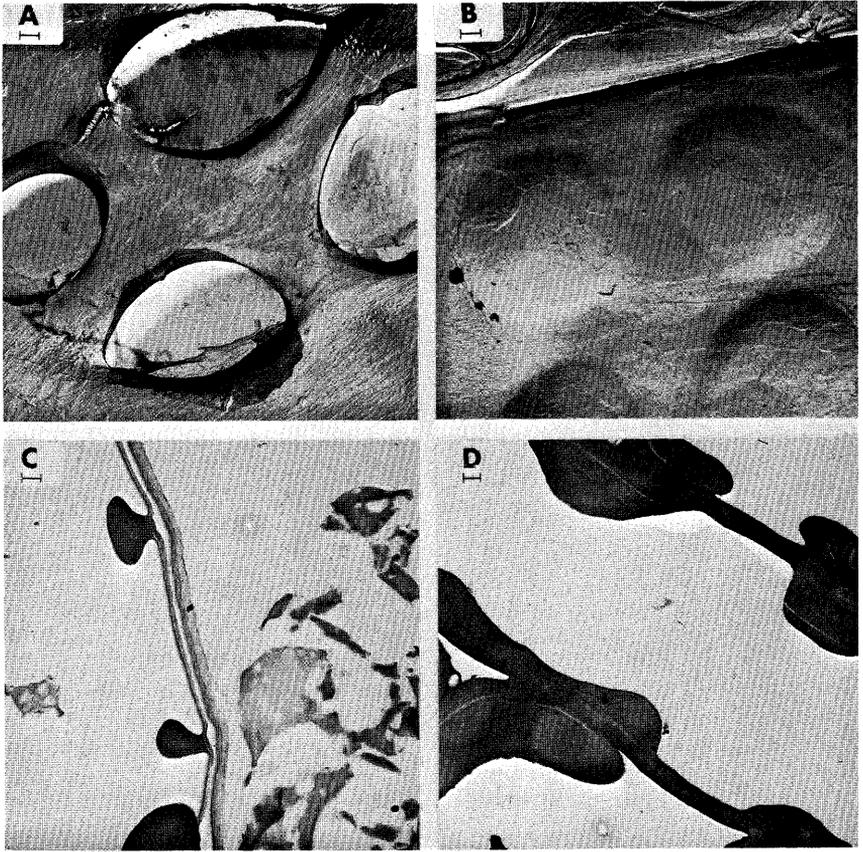


Figure 5-31.—Half-bordered *pinoid pits* connect longitudinal tracheids with ray parenchyma cells. (A) Viewed from tracheid side, surface replica exhibits characteristic pinoid shape. Many samples show warts on lumen face of pit borders. Shortleaf pine, earlywood, sapwood. (B) Surface replica, viewed from parenchyma cell lumen. Thin wall of parenchyma cell is continuous over pit cavity; often, as here, it is somewhat sunken into cavity. Either face of pinoid pits may be encrusted. Virginia pine, earlywood, heartwood. (C) Transverse section; longitudinal tracheid on left; thin-walled parenchyma on right. Parts of three adjacent pits show slightly overhanging pit borders on tracheid side; parenchyma wall is continuous. Broken cell contents on right. Shortleaf pine, earlywood, sapwood. (D) Transverse section; thick-walled parenchyma cell, bordered above and below by longitudinal tracheids. Note simple pits (without overhanging borders) in secondary wall of parenchyma cell. Table-Mountain pine, earlywood, heartwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

them. Since most ray parenchyma cells are thin-walled, walls between them commonly lack pits; fine plasmodesmata openings connecting thin-walled ray parenchyma cells are sometimes observable (fig. 5-23CD). Similar channels are shown in figure 5-32C, where they occur in a true pit membrane (Thomas and Nicholas 1968).

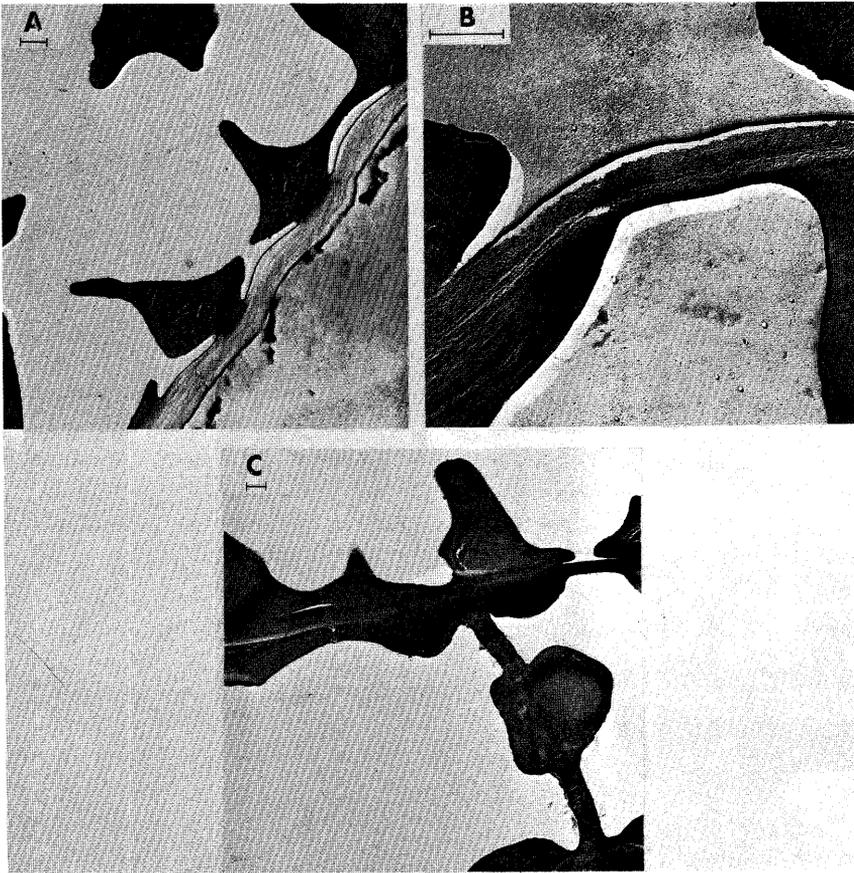
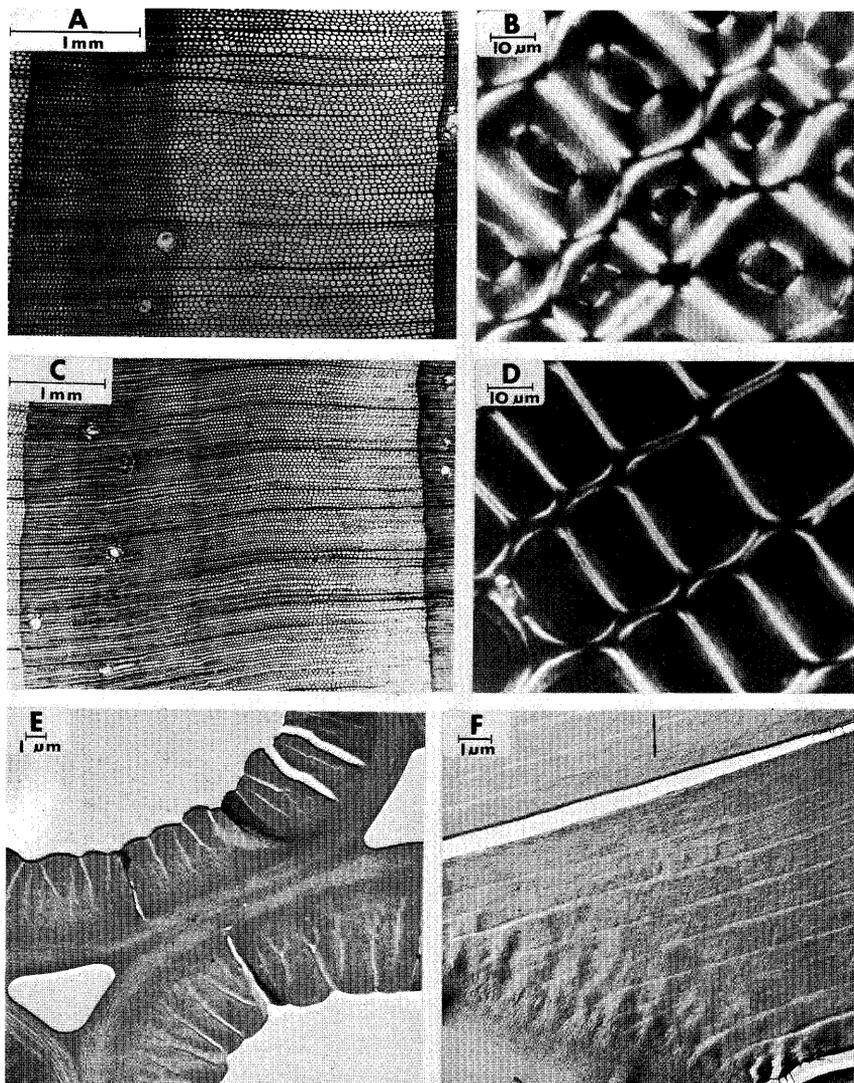


Figure 5-32.—Pits between ray tracheids and ray parenchyma are half-bordered; those between parenchyma cells are simple. (A) Tangential section through half-bordered pits between thin-walled parenchyma, lower right, and ray tracheid, left; parenchyma cell wall showing as light band because it contains little lignin, is continuous across pits. Dentations distort tracheid lumen. Virginia pine, earlywood, sapwood. (B) Cross section through pit between ray tracheid, above, and thick-walled parenchyma, below; there is no overhanging pit border in the parenchyma cell. Virginia pine, earlywood, sapwood. (C) Radial section through two simple pit pairs between thick-walled ray parenchyma cells. Fine light lines across cell walls are probably perforations accommodating plasmodesmata. Upper cell, with bordered pit, is dentate ray tracheid. Table-Mountain pine, earlywood, heartwood. Scale marks show 1 μm . (Photos from Côté and Day 1969.)

5-6 COMPRESSION WOOD

Southern pines, in common with other conifers, may develop **compression wood**. This abnormal wood is relatively weak in bending (Perem 1958) and has a low modulus of elasticity if compared to normal wood of the same specific gravity; it shrinks excessively (commonly 1 percent or more) in the longitudinal direction when dried. Products containing com-



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Figure 5-33.—(A) Annual ring of normal mature southern pine tissues in cross section. (B) Normal cell-wall layering is revealed in transverse section by polarized light; the thin primary wall and S_1 layer of secondary wall show as a single bright layer on the outside of each cell, the dominant S_2 layer shows next as a dark area, and the thin S_3 layer is bright. (C) Compression wood tissues in cross section show gradual transition from thin-walled earlywood cells to thick-walled latewood cells. (D) In compression wood, polarized light shows no S_3 layer (compare with B above). (E) More or less round cells with intercellular spaces are typical in compression wood. Helical cavities in S_2 layer are shown in transverse section of spruce pine. (F) Microfibrils of S_2 layer in compression wood cell walls make an abnormally large angle with the cell axis. Helical cavities visible in near-radial section through the S_2 layer of spruce pine. Arrow aligned with tracheid longitudinal axis. Portion of S_1 layer visible at bottom. (Photos A, B, C, and D from Manwiller 1966, species of southern pine not reported; photos E and F by W. A. Côté, Jr.)

pression wood—whether dimension lumber, plywood, or fiber—may be distorted by this excessive longitudinal movement. Because it is low in alpha-cellulose and high in lignin content, compression wood, when chemically pulped, has a lower yield than normal wood.

<u>Pine species and components</u>	<u>Normal wood</u>	<u>Compression wood</u>
	- - - - - <i>Percent</i> - - - - -	
Loblolly		
Lignin	28.3	35.2
Alpha-cellulose	45.7	34.6
Pitch		
Lignin	28.1	37.6
Alpha-cellulose	43.9	32.7

The foregoing data on loblolly pine are from Pillow and Bray (1935); those for pitch pine are from Côté et al. (1966). Analysis by Shelbourne and Ritchie (1968) showed no significant differences in extractive content between normal wood and compression wood of loblolly pine.

With the unaided eye, compression wood is distinguished from normal wood by its lifeless reddish color, abnormally wide and usually eccentric annual rings, and wide bands of apparent latewood. By transmitted light, compression wood in thin cross section is darker than normal wood.

Compression wood tissues show gradual transition from thin-walled earlywood cells to thick-walled latewood cells (fig. 5-33C). Although parenchyma appears to be the same in normal and compression wood, the tracheids are quite different. Tracheid length in both earlywood and latewood is 0.25 to 0.50 mm. less in compression wood than in normal loblolly pine wood (Shelbourne and Ritchie 1968).

In transverse section, tracheids in compression wood are distinguished by roundness of cells, checks, or cavities in the inner portion of the secondary wall, and by intercellular spaces (fig. 5-33E). In radial section, helical checks or cavities are seen to follow the microfibril alignment (Côté et al. 1968). Electron micrographs show that the microfibrils in the S_2 layer of compression wood make an abnormally large angle—sometimes more than 45° —with the longitudinal axis of the cell (fig. 5-33F).

With a polarizing light microscope, it can be observed that the S_3 layer is missing from compression wood and that the S_1 layer is thicker than in normal wood (fig. 5-33D).

Shelbourne and Ritchie (1968) found that on a total ring basis, the specific gravity of a limited sample of loblolly pine compression wood was the same as that of normal wood; specific gravity of latewood compression wood, however, was significantly lower than that of normal latewood.

Compression wood is prone to develop on the underside of leaning trees. For this reason, plantation managers remove leaning trees in early thinnings when possible. It has been shown, however, that loblolly pines with no lean also develop important amounts of compression wood (Zobel and Haught 1962).

<u>Amount of lean</u>	<u>Compression wood portion of merchantable volume</u>
	<i>Percent</i>
Essentially straight	6
Intermediate, i.e., average	9
Crooked	16
Excessively crooked (one-tree sample)	67

In a study of eight 11-year-old loblolly pines, von Wedel et al. (1968) found that knots are surrounded by compression wood to the extent that the compression wood associated with knot wood averaged 7.1 percent of tree volume inside bark. The top 5-foot merchantable bolt (to 4-inch top diameter) in these 11-year-old pines averaged 9.5-percent compression-wood volume, with 5-foot bolts immediately above and below this having 11.5- and 8.9-percent compression wood associated with knots.

North Carolina State College (1957, p. 14) observed that juvenile wood of loblolly pine contained 42 percent compression wood, while mature wood contained only 7 percent.

Wahlenberg (1946, p. 33) reported that fast-growing longleaf and loblolly pines developed more compression wood than slow-growing trees of the same species.

5-7 RESIN CANALS

These ducts are interconnecting longitudinal and horizontal systems. The tangential section of figure 5-6 illustrates a fusiform ray and its included horizontal resin canal intersecting a vertical canal. Vertical canals are commonly three or four times larger in diameter than horizontal canals.

The canals are not structural elements, but are void spaces surrounded by specialized parenchyma (epithelial cells) that secrete resin into the cavity (figs. 5-3, 5-6, 5-15, 5-16). These secretions, comprising the major extractives in southern pine wood, provide the basis for the United States naval stores industry (ch. 28).

Vertical resin canals occur throughout both earlywood and latewood in the first eight to 12 growth rings (fig. 5-34E). In mature normal wood and in compression wood the canals are most prominent in the latewood (fig. 5-33AC). In a limited sample of slash pine, Hobert (1932) found that 60 percent of the vertical resin canals were in latewood.

Wounding—e.g., by working for naval stores—increases the number of vertical resin canals as much as tenfold in the new earlywood laid down 2 or 3 feet above the wound.

The number of resin canals present per unit area in normal longleaf (Roth 1897) and slash (Hobert 1932) pine has been measured in limited samples. Only a fraction (less than one in 20) of the rays present in pine are fusiform, i.e., contain resin canals.

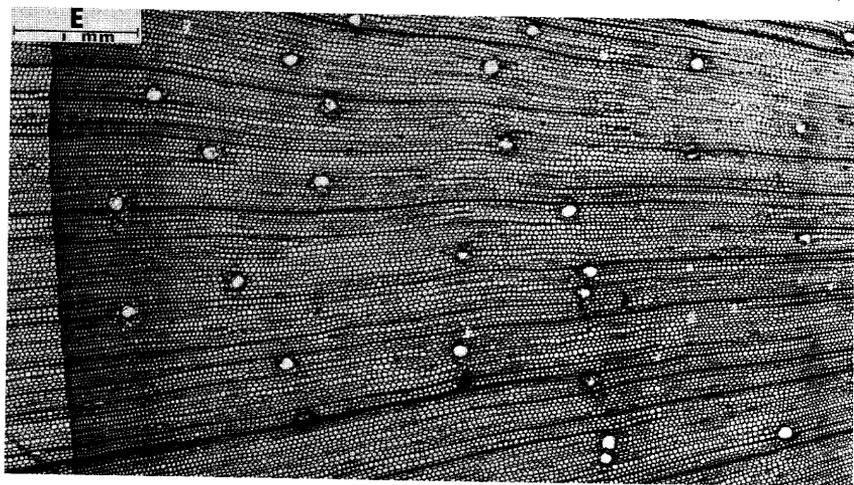
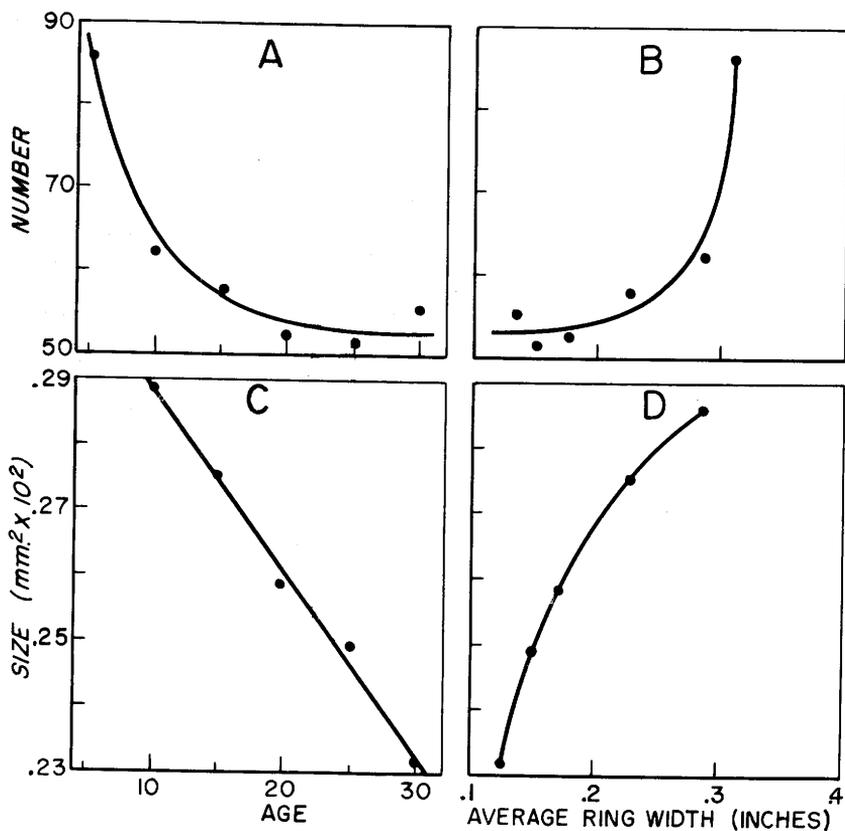


Figure 5-34.—Relationship of number and size of radial resin canals in slash pine to tree age when ring was formed (A, C) and to average ring width (B, D). The number of resin canals is given per square millimeter of tangential section. (E) Distribution of longitudinal resin canals throughout the annual ring is typical of juvenile wood in southern pine. (Drawings A, B, C, and D after Mergen and Echols 1955; photo E from Manwiller 1966, species not reported.)

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Pine species	Vertical resin canals in cross section	Horizontal resin canals in tangential section	Uniseriate rays in tangential section
	----- <i>Number/sq. in.</i> -----		
Longleaf.....	—	300-400	15,000
Slash.....	219	458	20,000

Hobert reported that frequency of vertical canals in slash pine increased with ring width; he found 200 canals per square inch in rings 0.22 inch wide and 300 canals per square inch when rings were twice as wide (0.44 inch). He found no correlation between frequency of horizontal canals and ring width.

A later study of 10 slash pine trees sampled at breast height (Mergen and Echols 1955) did show a correlation between ring width and frequency of horizontal resin canals; conclusions were as follows:

- The number of radial resin canals formed per unit area was highest during early age (i.e., in rings near pith) and decreased rapidly until about the 20th year, at which age the number became relatively constant (fig. 5-34A).

- Average number and size of radial resin canals increased with increasing ring width (fig. 5-34BD). As rings near the pith were widest, it was not clear whether this effect was independent of radial position.

- Average size of resin canals decreased linearly with age of ring (fig. 5-34C).

Readers interested in morphological and anatomical changes related to resin stimulation in pine will find reports by Fahn² and Zamski (1970) useful; the latter publication describes the effect of microclimatic conditions on resin duct formation and resin secretion.

5-8 VARIATIONS IN ANATOMY

Because of within-species and within-tree variability, small wood samples from all 10 southern pines cannot as yet be positively identified. It is probable, however, that among species there are valid, observable, statistical differences in cellular dimensions. Because it is difficult to get a representative sample of a species population, and measurement of cellular dimensions is very time consuming, statistically valid comparisons among southern pine species are not available; the data at hand are incomplete, but summarization is useful.

To simplify this presentation on variability, only longitudinal tracheids will be considered. Comparisons of cellular dimensions will be restricted to length, fibril angle in the S₂ layer, radial diameter, tangential diameter, and wall thickness.

² Fahn, A. Morphological and anatomical changes related to resin stimulation. USDA Forest Service, Southeastern Forest Experiment Station, Olustee, Fla. Final Report A10-FS-15, Grant No. FG-Is-209, dated July 30, 1970.

TRACHEID LENGTH

Tracheid length affects the strength, surface, and bonding properties of fiber products and is therefore of interest. Long tracheids shrink less longitudinally in drying than short tracheids (Dadswell and Nicholls 1959). For many purposes, long tracheids are more desirable than short. Some industries, however, are interested in pine wood with short tracheids to supplement hardwood in a mixture of pulp fibers.

Among-species variation.—Table 5-3 lists selected published data pertinent to tree-average values for tracheid length in each of the southern pine species. Data are listed by species, and in order of reported tracheid length. Where available, age is reported, since comparisons are meaningful only between trees of similar age. Table 5-4 summarizes available data to provide estimates of tracheid length for 30-year-old trees. Since southern pine tree breeders are genetically manipulating tracheid length, as well as other wood properties, plantation-grown pines of the future may have tracheid lengths different than those shown in table 5-4.

Except for the spruce pine values, tracheid lengths shown in table 5-4 are not based on sound statistical sampling procedure; they are simply estimates of tree-average values for the present population of 30-year-old trees based on the data arrayed in table 5-3. From table 5-4, loblolly, longleaf, shortleaf, and slash pines appear to have the longest tracheids (average 4 mm.); the remaining six species have tracheids that probably average about $3\frac{1}{2}$ mm. in length.

When trees of different species are grown to the same age on the same site, it is possible that some of these apparent differences change or disappear. Cole et al. (1966) found that among 16- to 21-year-old slash, loblolly, longleaf, and pond pines growing on a single Georgia site, only longleaf had outer-wood, breast-height tracheid lengths differing significantly from the others; longleaf tracheids were 0.3 mm. longer than those of the other three species. Snyder and Hamaker (1970) compared tracheid lengths in breast-height samples of loblolly and spruce pines 40 to 70 years old growing in the same stands in south Mississippi; they found no significant difference between species.

Within-species variation.—Tracheid length varies greatly from tree to tree. Tree-average values are positively correlated with tree age (see spruce pine data in table 5-3). Furthermore, in the 30th annual ring, one loblolly pine may have tracheids averaging only 2.6 mm. long, while those in the same ring of another loblolly may average 6.1 mm. (Zobel et al. 1961). Jurbergs (1963) observed that in a 15-tree sample of slash pine, average fiber lengths in the eighth and ninth growth rings (breast height) varied from 2 mm. in one tree to 4.1 mm. in another.

Data from the Department of Wood and Paper Science of North Carolina State University (1969, p. 33) provide some indication of variability of tree-average tracheid length among 16 specially selected loblolly pine

TABLE 5-3.—*Selected data pertinent to tree-average values for tracheid length in southern pines*

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
LOBLOLLY PINE				
3.	-----	-----	-----	Grabow (1923)
3.10	0.31	6	Whole-tree average, North Carolina	¹
3.2	-----	2	Average for two lowest bolts in 16-year-old stem	Cole et al. (1966)
3.2	-----	3	Rings 24 to 30, breast height	Jackson and Morse (1965a)
3.23	-----	16	Tree average for rings 0-10 in 16 specially selected trees from Va., N.C., S.C. and Ga. Tree averages for corewood ranged from 2.93 to 3.50 mm.	Barefoot et al. (1970, p. 11)
3.45	-----	50	Tree outer wood, rings 8-16	Cole et al. (1966)
3.5	-----	6	Average for trees approximately 40 years old; estimated from graph	Bethel (1941, fig. 3)
3.7	-----	2	Earlywood, rings 10-30, breast height, Georgia	Greene (1966)
3.81	-----	50	Earlywood only in Louisiana logs showing at least 40 rings	McMillin (1968)
4.0	-----	12	Tree average	Wheeler et al. (1966)
4.04	-----	50	Latewood only in Louisiana logs showing at least 40 rings	McMillin (1968)
4.2	-----	88	Rings 15 to 30, latewood, breast height	McElwee and Zobel (1963)
4.26	.42	12	Ring 20 at breast height, latewood, Texas	Kramer (1957)
4.28	-----	16	Tree average for rings 10-35 in 16 specially selected trees from Va., N.C., S.C., and Ga. Tree averages for mature wood ranged from 3.76 to 4.77	Barefoot et al. (1970, p. 11)

TABLE 5-3.—*Selected data pertinent to tree-average values for tracheid length in southern pines—Continued*

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
LOBLOLLY PINE—Continued				
4.33	.91	-----		Panshin et al. (1964, p. 99)
4.46	1.4-6	4	Tree average	Barefoot et al. (1964)
4.5	-----	308	Average of ring 15 and ring 30, latewood, breast height	Zobel et al. (1960)
4.5	-----	149	Latewood from ring 30, breast height, Maryland and Delaware	Whitesell et al. (1966)
4.7	-----	10	Average for breast-height increment cores taken from 40- to 70-year old trees in south Mississippi	Snyder and Hamaker (1970)
4.79	-----	128	Rings 19 to 22, 10 seed sources, breast height, Georgia	Jackson and Strickland (1962)
4.82	.63	1	Average for single Louisiana tree 78 years old; range was from 3.2 to 7.4 mm.	2
LONGLEAF PINE				
3.7	-----	-----		Grabow (1923)
3.7	-----	2	Average for two lowest bolts in 17-year-old stems	Cole et al. (1966)
3.81	-----	50	Tree outerwood, rings 8 to 21	Cole et al. (1966)
4.29	1.8-6.3	1	Ring 10 through ring 230, 1 foot off ground	Shepard and Bailey (1914)
4.77	.69	1	Average for single Louisiana tree 60 years old; range was from 3.2 to 6.3 mm.	2
4.90	.83	-----		Panshin et al. (1964, p. 99)
4.9	1.6-6.9	-----		Browning (1963, table II)
PITCH PINE				
2.30	1.36-3.48	-----	Breast height, 7 years old; loblolly of same age on same site averaged 2.63 with range from 1.56 to 3.68	Koo and Hong (1967, pp. 86-90)

TABLE 5-3.—Selected data pertinent to tree-average values for tracheid length in southern pines—Continued

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
PITCH PINE—Continued				
2.95	-----	2	Rings 24 to 30, breast height	Hamilton (1963)
3.40	.59	1	Average for single New Jersey tree 65 years old; range was from 2.1 to 5.1 mm.	²
3.57	.74	-----	-----	Panshin et al. (1964, p. 99)
3.75	.83	-----	-----	Panshin et al. (1964, p. 99)
POND PINE				
2.6	-----	9	Rings 1 to 7, breast height	Cole et al. (1966)
2.73	.36	-----	-----	Panshin et al. (1964, p. 99) ²
3.22	1.34	1	Average for single Florida tree 67 years old; range was from 1.0 to 7.0 mm.	
3.50	-----	9	Rings 8 to 21, breast height	Cole et al. (1966)
3.6	2.6-4.6	180	Rings 20 to 30, latewood, breast height	McElwee and Zobel (1963)
SAND PINE				
2.85	-----	-----	-----	USDA Forest Products Laboratory (1953) ²
3.64	.67	1	Tree average for 57-year-old Choctawatchee sand pine; range was from 2.2 to 5.1 mm.	
4.40	.76	1	Tree average for 58-year-old Ocala sand pine; range was from 2.8 to 6.5 mm.	²
SHORTLEAF PINE				
2.48	-----	10	Earlywood in rings 13 to 20, breast height	Hamilton (1963)
2.63	-----	10	Latewood in rings 13 to 20, breast height	Hamilton (1963)
2.8	-----	2	Rings 24 to 30, breast height	Jackson and Morse (1965a)

TABLE 5-3.—Selected data pertinent to tree-average values for tracheid length in southern pines—Continued

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
SHORTLEAF PINE—Continued				
3.3	-----	1	Average for rings 10 through 25, all fibers, breast height, in Arkansas tree	McGinnes (1963)
3.7	-----	1	Average for rings 25 through 35, all fibers, breast height, in Arkansas tree	McGinnes (1963)
3.7	-----	-----	-----	Grabow (1923)
3.76	.79	1	Average for single Louisiana tree 68 years old; range was from 2.8 to 5.8 mm.	²
4.34	-----	190	Latewood in ring 20, breast height; Tennessee; at this sample point, tree averages for latewood ranged from 3.0 to 5.3 mm.	Thor and Bates (1970)
4.46	.91	-----	-----	Panshin et al. (1964, p. 99)
4.64	.92	-----	-----	Panshin et al. (1964, p. 99)
4.85	.76	-----	-----	Panshin et al. (1964, p. 99)
SLASH PINE				
3.08	1.22	1	Average for single Louisiana tree 39 years old; range was from 1.0 to 6.8 mm.	²
3.1	-----	2	Rings 24 to 30, breast height	Jackson and Morse (1965a)
3.2	1.0-5.5	6	21- to 23-year-old trees in Florida; latewood	Echols (1955)
3.3	-----	15	Rings 8 and 9, breast height	Jurbergs (1963)
3.55	-----	50	Rings 8 to 17	Cole et al. (1966)
3.8	-----	2	Average from two lowest bolts in 17-year-old stem	Cole et al. (1966)
3.8	-----	3	Entire annual increment sheath 17 rings in from bark of trees about 37 years old, Georgia	Taras (1965)

TABLE 5-3.—Selected data pertinent to tree-average values for tracheid length in southern pines—Continued

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
SLASH PINE—Continued				
3.9	-----	38	Ring 15, latewood, breast height	Zobel et al. (1963)
4.1	3.1-5.0	271	Rings 19, 20, and 21 at breast height. Trees from 15 geographic areas	Strickland and Goddard (1966)
4.4	3.1-5.4	109	Earlywood in rings from 10th to cambium in trees 15 to 45 years old, breast height; range shown is for core averages not individual fibers	Wangaard ³
4.58	.87	-----	-----	Panshin et al. (1964, p. 99)
4.6	3.9-5.9	109	Latewood in rings from 10th to cambium in trees 15 to 45 years old, breast height; range shown is for core average not individual fibers	Wangaard ³
4.6	-----	13	Ring 19, 24-30 inches off ground	Dadswell and Nicholls (1959)
4.6	-----	38	Ring 30, latewood, breast height	Zobel et al. (1963)
SPRUCE PINE				
3.24	.62	12	15-year old, slow growing ⁴	Manwiller ⁵
3.37	.66	12	15-year-old, fast growing ⁴	Manwiller ⁵
3.44	.66	12	30-year-old, slow growing ⁴	Manwiller ⁵
3.72	.75	12	30-year-old, fast growing ⁴	Manwiller ⁵
3.86	.76	12	45-year-old, slow growing ⁴	Manwiller ⁵
4.04	.81	12	45-year-old, fast growing ⁴	Manwiller ⁵
4.6	-----	10	Average for breast- height increment cores taken from 40- to 70-year-old trees in south Mississippi	Snyder and Hamaker (1970)

TABLE 5-3.—Selected data pertinent to tree-average values for tracheid length in southern pines—Continued

Fiber length (millimeters)	Range or standard deviation	Trees sampled	Comment	Reference
	<i>Millimeters</i>	<i>Number</i>		
TABLE-MOUNTAIN PINE				
3.46	.59	1	Average for single Virginia tree 50 years old; range was from 1.7 to 5.7 mm.	²
VIRGINIA PINE				
2.1	-----	-----	-----	Isenberg (1951, p. 11-12 and 16-31)
2.80	-----	-----	-----	USDA Forest Products Laboratory (1953) ²
3.06	.69	1	Average for single Virginia tree 51 years old; range was from 1.4 to 5.3 mm.	²
3.41	-----	195	Ring 10, breast height, Kentucky and Tennessee	Thor (1964)
3.85	-----	195	Ring 25, breast height, Kentucky and Tennessee	Thor (1964)

¹ Einspahr, D. W., Thode, E. F., Peckham, J. R., and Van Horn, W. M. Wood and pulp properties as determined from loblolly pine increment cores and whole tree measurements. Inst. Pap. Chem., Project 2057, Rep. 5, 40 pp. 1961. Appleton, Wis.

² Single tree collected for USDA Forest Service anatomy study FS-SO-3201-1.2.

³ Wangaard, F. F. Unpublished data for 112 slash pine trees gathered throughout major range of the species. Trees were 15 to 45 years old and were evaluated in 1962 at Yale University, New Haven, Conn.

⁴ Tree-average values. Trees sampled over major commercial range. Slow-growing trees had more than 6 rings per inch at 1-foot level, whereas fast-growing showed less than 6 rings per inch.

⁵ Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La. Final Report FS-SO-3201-1.1 dated May 1, 1972.

cut in Virginia, North Carolina, South Carolina, and Georgia, as follows:

<u>Wood location and statistic</u>	<u>Earlywood</u>	<u>Latewood</u>
	----- <i>Mm.</i> -----	
Core wood, 0 to 10th ring		
Low	2.86	3.15
Average	3.15	3.44
High	3.33	3.87
Outer wood, 11th to 35th ring		
Low	3.69	3.87
Average	4.23	4.37
High	4.70	4.89

The foregoing data suggests that length is strongly dependent on hereditary factors as well as environmental conditions.

Zobel et al. (1961) observed that loblolly pine trees of high specific gravity have slightly shorter tracheids than less dense trees. McMillin's (1968) data on loblolly support this observation (fig. 5-35). In Manwiller's³ study of 72 spruce pine trees, a negative correlation ($r = -0.196$) was observed between specific gravity and earlywood (but not latewood) tracheid length; his data were based on a total of 648 pieces of earlywood and 648 pieces of latewood drawn from three heights and three radial positions in each tree. Kramer (1957), in a study of 12 loblolly pines, found no correlation between tracheid length (latewood, breast height) and specific gravity. Whitesell et al. (1966) also failed to find a correlation in their study of 149 loblolly pines from Maryland and Delaware.

Zobel et al. (1961, p. 162) found that tracheid lengths were similar in fast- and slow-growing loblolly dominants and codominants. Kramer (1957) found no correlation between growth rate and tracheid length in breast height latewood of loblolly pine. Manwiller's data (see table 5-3)

³ Manwiller, F. G. Variation of transverse cellular dimensions and specific gravity in stems of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.8 dated May 1, 1972.

TABLE 5-4.—*Tracheid lengths in 30-year-old southern pines—tree averages*¹

<u>Pine species</u>	<u>Length</u>
	<i>Mm.</i>
Loblolly -----	4
Longleaf -----	4
Pitch -----	3½
Pond -----	3½
Sand -----	3½
Shortleaf -----	4
Slash -----	4
Spruce -----	3½
Table-Mountain ----	3½
Virginia -----	3½

¹ Approximations based on survey of the literature.

show that spruce pines of equal age have longer tracheids if fast grown.

Thor (1964) showed that Virginia pine trees from three stands in Kentucky had longer tracheids (4.2 mm. in one stand) than trees further south in Tennessee (3.5 mm. in one stand). For Atlantic Coastal Plain loblolly pine, however, both Zobel et al. (1960) and Whitesell et al. (1966) found that tracheid length increased considerably from north to south; also, longer tracheids were found inland in Tennessee. For the other eight species, data on geographic variation in tracheid length are not at hand.

Little quantitative and statistically sound data are available relating tree-average fiber length to elevation, site, rainfall, or silvicultural practice. The physiological factors affecting fiber length were discussed in Section 4-3.

Following is a summary of references on fiber-length variations from tree to tree within species:

<u>Pine species</u>	<u>Reference</u>
Loblolly	Kramer (1957)
	Jackson and Greene (1958)
	Zobel et al. (1960, 1961)
	Jackson and Strickland (1962)
	Barefoot et al. (1964, fig. 2)
	Goggans (1964)
	Posey (1964)
	Cole et al. (1966)
	Greene (1966)
	Wheeler et al. (1966)
	Whitesell et al. (1966)
	Department of Wood and Paper Science of North Carolina State University (1969)
	Barefoot et al. (1970, p. 11)
Snyder and Hamaker (1970)	
Longleaf	Cole et al. (1966)
Pond	McElwee and Zobel (1963)
	Cole et al. (1966)
Shortleaf	Greene and Carmon (1962)
	McGinnes (1963)
	Thor and Bates (1970)
Slash	Echols (1955)
	Jackson and Greene (1958)
	Dadswell and Nicholls (1959)
	Jurbergs (1963)
	Zobel et al. (1963)
	Taras (1965)
	Cole et al. (1966)
Strickland and Goddard (1966)	
Spruce	Snyder and Hamaker (1970)
	Manwiller (see text footnotes 1, 3.
Virginia	Thor (1964)

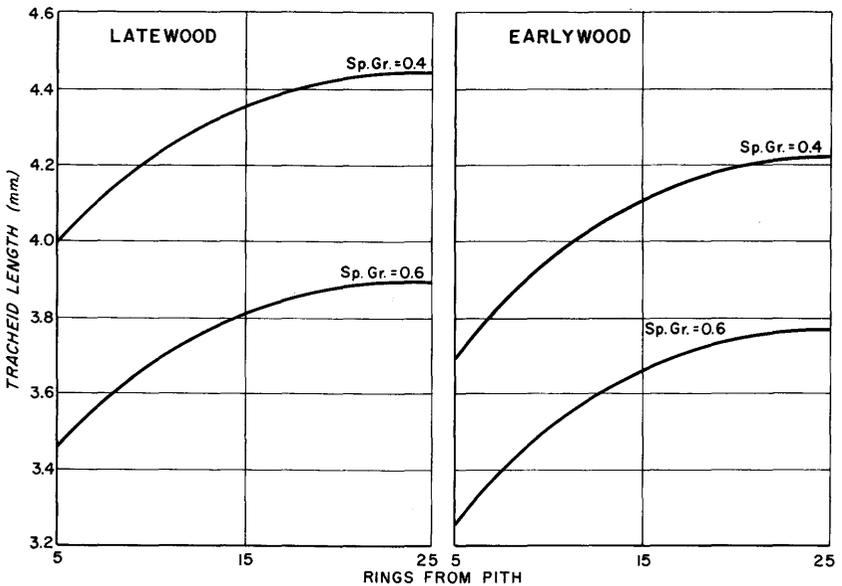


Figure 5-35.—Tracheid length in loblolly pine as related to number of rings from pith and unextracted specific gravity of wood, oven-dry weight and green volume basis. (Drawings after McMillin 1968.)

No references are available on tree-to-tree variation of fiber length in pitch, sand, or Table-Mountain pine.

Within-tree variation.—Some generalizations on tracheid length were stated in section 4-3: (1) bolewood tracheids, on the average, are longer than those of branches (Jackson 1959) but may be shorter than those in roots⁴; (2) in the stem, tracheid length increases from the pith outward until it reaches a maximum level at age 20 to 60 years, after which it varies somewhat at random; (3) tracheid length increases from the base of the stem upward until it reaches a maximum length and then decreases toward the top.

Much of the tracheid length variation associated with diameter and height results from differences between **juvenile** or corewood found in the first four to 10 rings from the pith and **mature** or outer wood (Zobel 1961). In stem cross sections, the juvenile wood can be distinguished from mature wood by its lifeless appearance, relatively small amount of latewood, and generally gradual transition from earlywood to latewood (fig. 5-34). Juvenile wood has shorter tracheids, thinner cell walls, higher librill angles, and lower specific gravity than mature wood found further

⁴ Examination of 20 southern pine trees uprooted in 1969 by high winds in the vicinity of Alexandria, La., showed that the bulk of the rootwood had a tracheid length of 3.99 mm. with standard deviation of 0.89; the stemwood in the zone 1 to 2 feet from ground level had tracheids averaging 2.97 mm. in length and standard deviation of 0.64 (See sec. 13-3 and fig. 13-22.).

from the pith. When dried, corewood may shrink more longitudinally and less transversely than outer wood.

Hallock (1968) measured the diameter of juvenile cores in 206 butt logs and 192 upper logs of "old-field" loblolly pine cut near Macon, Ga. He found that the mean diameter of the juvenile core was smaller in butts (1.9 inches) than in uppers (2.2 inches). In butt logs, the number of annual rings in the juvenile core averaged 6.14 with standard deviation of 1.94; the uppers showed 4.79 rings with standard deviation of 1.49.

In a study of 14 loblolly pine trees, Zobel et al. (1959) observed that the juvenile wood core was approximately cylindrical but had a tendency to decrease in diameter toward the top (3.8 inches at breast height and 3.4 inches at 45 feet). The juvenile core was found to extend about seven annual rings outward from the pith; transition wood extended to the 10th ring in some trees. Volume of juvenile wood ranged from 7 to 47 percent of the merchantable bole.

Variation in tracheid length with position in southern pine trees has been studied and some data specific to loblolly, longleaf, shortleaf, slash, and spruce pines are at hand.

Data are most plentiful for loblolly. McMillan (1968) made an analysis of tracheid length of loblolly pine wood (as distinct from the tracheid length of stems) in relation to three gross wood characteristics that can readily be measured. The characteristics, or factors, were rings from the pith, growth rate, and specific gravity.

The wood in a large second-growth southern pine stem characteristically increases in specific gravity with increasing rings from the pith, while the growth rate slows. For a given number of rings from the pith, however, the range of variation in specific gravity and growth rate between stems is remarkably large. For example, it is possible to isolate corewood of low density and slow growth from one stem while corewood from a second stem may also be of low density but of fast growth. As another example, the outer wood of one stem and the corewood of a second stem may both contain fast-grown wood of low density.

By removing wood from many stems and stratifying it by two densities (less than 0.49 and more than 0.49) and two growth rates (less than 6 and more than 6 rings per inch) at each of three radial positions in the stem (0 to 10, 11 to 20, and 21 to 30 rings from the pith), McMillin was able to isolate the independent relationship of each of these wood characteristics with tracheid length.

This approach is quite different from studies where it is desired to determine the radial variation of tracheid length in stems. In these cases, the variation is usually measured along sections, wedges, or increment cores removed from the stem. Since the typical change in specific gravity and growth rate along such sections precludes stratification by specific gravity and growth rate at all radial positions, the independent relationship of each factor with tracheid length is confounded.

McMillin found that tracheid lengths, averaged over all specific gravities and growth rates, increased with increasing number of rings from the pith.

<u>Number of rings from the pith</u>	<u>Latewood</u>	<u>Earlywood</u>
	- - - -	<i>Mm.</i> - - - -
0 to 10 (core).....	3.79	3.52
11 to 20 (middle).....	4.13	3.91
21 to 30 (outer).....	4.21	4.00

When averaged over all positions and growth rates, tracheids were longer in wood of low specific gravity than in wood of high specific gravity.

<u>Unextracted specific gravity</u>	<u>Latewood</u>	<u>Earlywood</u>
	- - - -	<i>Mm.</i> - - - -
Less than 0.49 (avg. 0.45).....	4.16	3.93
More than 0.49 (avg. 0.52).....	3.92	3.69

Tracheid length was not related to rate of growth. The relationships between tracheid length and number of rings from the pith are plotted in figure 5-35 for wood of two specific gravities. Multiple regression analysis provided the following equations:

$$\begin{aligned} \text{Latewood tracheid length, mm.} &= 4.8016 + 0.0643 (\text{number of rings}) \\ &- 2.7281 (\text{unextracted specific gravity}) - 0.0014 (\text{number of rings})^2 \\ &\qquad\qquad\qquad (5-2) \end{aligned}$$

$$\begin{aligned} \text{Earlywood tracheid length, mm.} &= 4.2468 + 0.0737 (\text{number of rings}) \\ &- 2.2138 (\text{unextracted specific gravity}) - 0.0016 (\text{number of rings})^2 \\ &\qquad\qquad\qquad (5-3) \end{aligned}$$

The equation for latewood accounted for 47 percent of the total variation in tracheid length; the standard error of the estimate was 0.23. The corresponding statistics for earlywood were 51 percent and 0.23.

In a study of 12 loblolly pine sampled at breast height, Kramer (1957) showed that the annual rate of tracheid length increase is rapid near the pith. The rate of increase diminishes with distance from the pith, but in the 66-year-old trees sampled, tracheid length was still increasing slightly (fig. 5-36). Tracheid lengths in the 10th ring (but not earlier rings) were indicative of fiber lengths ultimately attained in mature wood of individual trees.

Greene (1966) measured earlywood tracheid length at breast height in two loblolly pines in Georgia and observed that length was shortest (1.5-2 mm.) in the first ring. Length increased rapidly to about 3.5 mm. by ring 15 and thereafter slowly increased to 4.2 in the 45th ring; no maximum was reached.

In 16 loblolly pines cut in Virginia, North Carolina, South Carolina, and Georgia, Barefoot et al. (1970) reported that average tracheid length

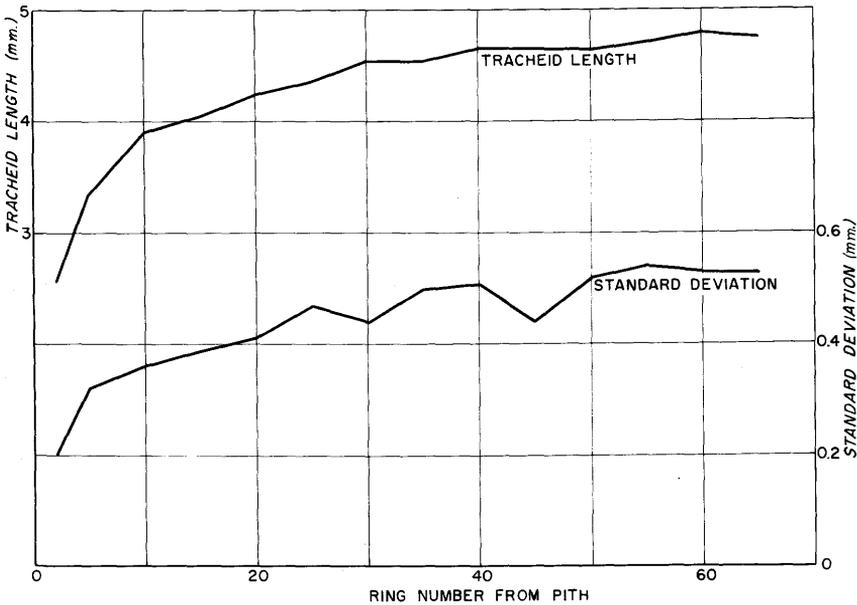


Figure 5-36.—Length of last-formed latewood tracheids, as related to number of rings from pith. Averages of breast height samples from 12 loblolly pine trees cut in Polk County, Tex. (Drawing after Kramer 1957.)

in corewood (0-10 years) was 3.23 mm.; in outer wood (10-35 years) tracheid length averaged 4.28 mm.

The combined effects of height and radial position on tracheid length in six loblolly pines were observed by Bethel (1941) as shown in figure 5-37. The six trees included dominants, codominants, and suppressed specimens growing on dry upland and wet bottom-land sites. He concluded that maximum fiber lengths occur at 44 percent of tree height.

Jackson (1959) sampled two 24-year-old loblolly pines near Athens, Ga., and observed that at all heights tracheid length was maximum in the outermost rings. In each annual increment, tracheid length increased up to a certain height in the tree and then decreased; in general, this region of maximum tracheid length in each increment was at greater height in the outer rings but never exceeded the 10-foot level (fig. 5-38).

Wheeler et al. (1966) separated corewood (i.e., first to 10th rings) from mature wood in 12 dominant and codominant loblolly pines cut in southern South California. Tracheids in both juvenile and mature wood were significantly shorter at the 5-foot level than at 10 feet above ground level; the difference was about $\frac{1}{2}$ -mm. for corewood and $\frac{1}{4}$ -mm for outer wood. In juvenile wood the lengths remained constant above 10 feet; in mature wood, lengths remained nearly constant, but there was a small reduction in tracheid length at the 15-foot height level compared to the 20- and 25-foot levels.

Greene (1966) studied tracheid length variation with height in the first, fifth, and 10th ring from the pith of a single loblolly pine cut in Georgia.

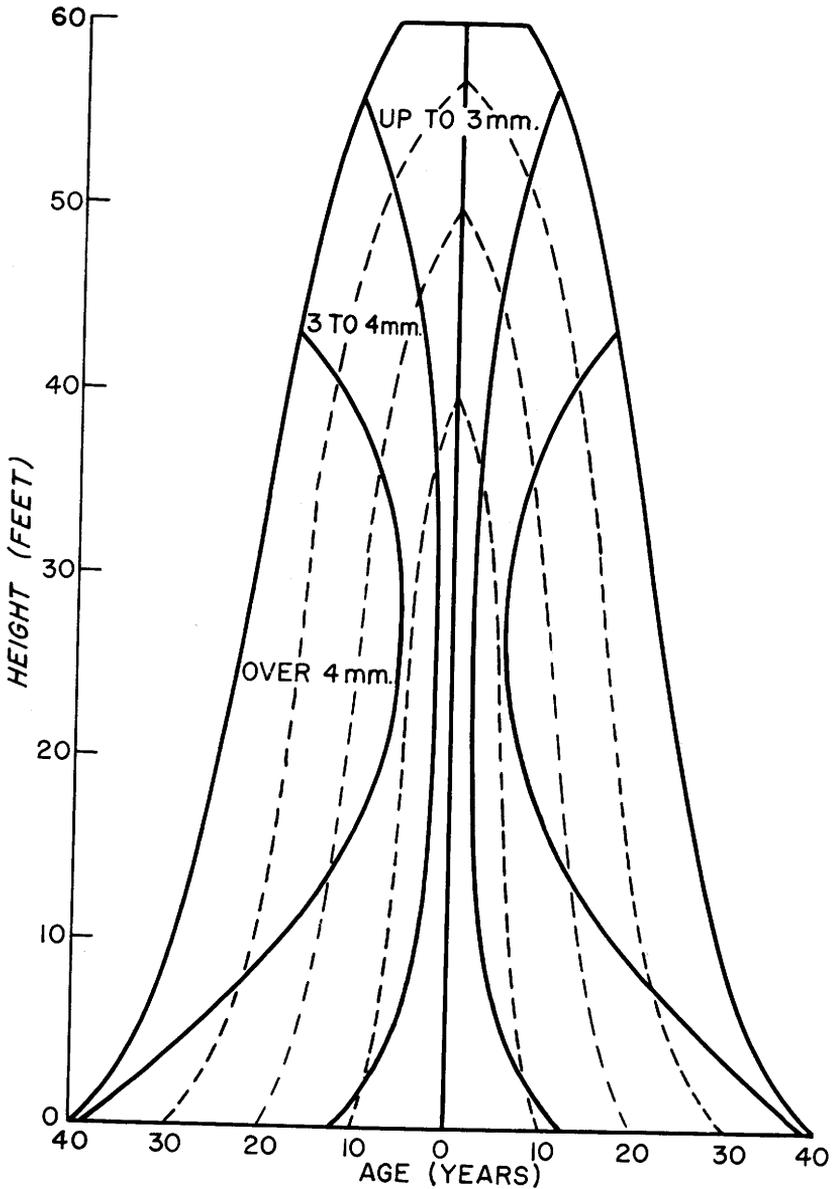


Figure 5-37.—Tracheid lengths in loblolly pine. (Drawing after Bethel 1941.)

He found that length did not vary with height in the first ring (1.9 mm.). In the fifth ring, maximum length (4.2 mm.) was reached at 20 feet above the ground. In the 10th ring, length was maximum (5.1 mm.) 15 feet above ground level.

For longleaf, data on tracheid length variation are meager. Shepard and Bailey (1914) measured one specimen at the 1-foot level. Average

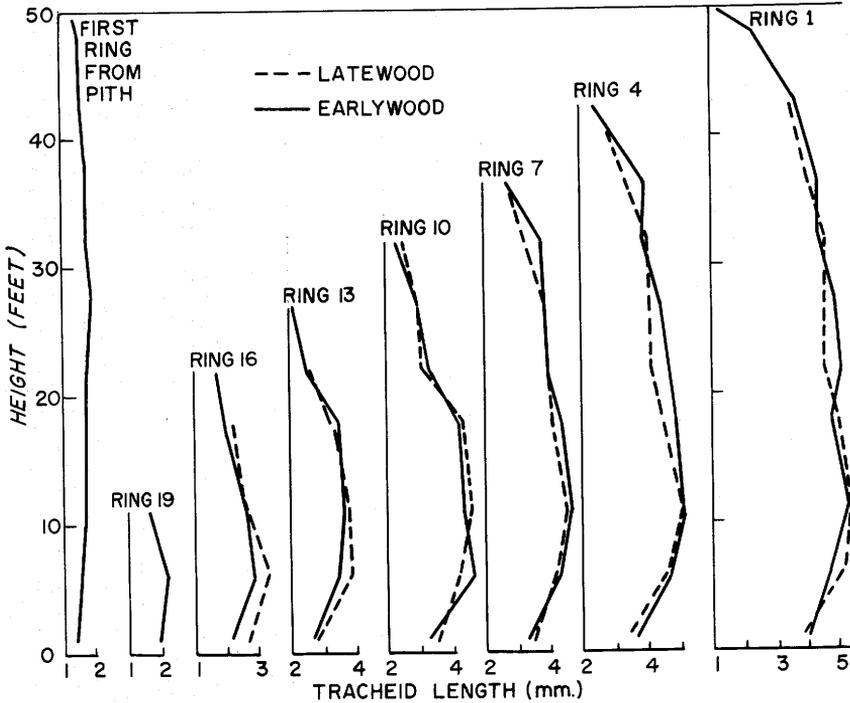


Figure 5-38.—Tracheid lengths observed in a single loblolly pine as related to height in the stem and number of annual increments from cambium. (Drawing after Jackson 1959.)

tracheid length reached a maximum of 5.08 mm. at age 160. The overall average of every 10th increment up to 230 years was 4.3 mm.

Years from pith	Tracheid lengths		
	Maximum	Minimum	Average
	----- Mm. -----		
10	3.00	1.80	2.42
20	3.85	2.40	3.06
30	4.50	2.80	3.70
40	4.95	2.80	4.06
60	6.05	3.05	4.33
80	5.70	3.05	4.41
100	6.30	3.45	4.88
160	6.20	4.00	5.08
230	5.20	2.85	4.00

McGinnes (1963) sampled a single 36-year-old Arkansas shortleaf pine tree at breast height. Lengths of pooled earlywood and latewood tracheids 1 to 10 years old averaged 2.04 mm.; fibers in wood 10 to 25 years old averaged 3.3 mm. long, and in 25- to 35-year wood averaged 3.7. Latewood tracheids were about 0.25 mm. longer than those of earlywood.

Taras (1965) examined three slash pine trees cut in Georgia; they averaged 37 years in age and 13.4 inches d.b.h. Neither earlywood nor latewood tracheids differed in length with cardinal direction in the tree. Latewood tracheids were about 0.25 mm. longer than earlywood tracheids (fig. 5-39).

Tracheid lengths in both earlywood and latewood at all levels above 1 foot were short near the pith (1 to 3 mm.) and increased in length rapidly for the first 10 to 15 years (to about 4 or 5 mm.); lengths continued to increase with age but at a slower rate and never reached a maximum. In any increment sheath, the shortest tracheids were near ground level and near the top of the tree; maximum lengths were near the 10- to 20-foot level. In any one sheath, the change in length with height in the tree was about 1 mm. (fig. 5-39).

In Australia, Dadswell and Nicholls (1959) measured the length of slash pine tracheids in 13 trees sampled 24 to 30 inches above ground level; tracheid length increased in a smooth curve from 2 mm. at age 2 (range $1\frac{1}{4}$ to $2\frac{3}{4}$) to 5 mm. at age 25 (range $4\frac{1}{2}$ to $5\frac{1}{4}$). Maximum tracheid length was reached after 15 to 20 growth rings. When average tracheid length was shorter than normal in the first few rings, length was also shorter than normal in succeeding rings.

Good data are available for tracheid length of spruce pine in its major commercial range (Manwiller³). Earlywood and latewood have significantly different patterns of variation with height above ground (feet) and number of rings to the specimen as shown by the following equations and by figure 5-40.

$$\begin{aligned} \text{Earlywood tracheid length, mm.} &= 2.14 & (5-4) \\ &+ 0.0899 & (\text{number of rings}) \\ &- 0.001268 & (\text{number of rings})^2 \\ &+ 0.003129 & (\text{height}) \\ &+ 0.004484 & (\text{number of rings}) (\text{height}) \\ &- 0.00003445 & (\text{number of rings}) (\text{height})^2 \\ &- 0.0001183 & (\text{number of rings})^2 (\text{height}) \end{aligned}$$

Equation 5-4 accounted for 49 percent of the observed variation; standard error of the estimate was 0.50 mm.

$$\begin{aligned} \text{Latewood tracheid length, mm} &= 2.560 & (5-5) \\ &+ 0.08651 & (\text{number of rings}) \\ &- 0.001375 & (\text{number of rings})^2 \\ &+ 0.003154 & (\text{number of rings}) (\text{height}) \\ &- 0.000003 & (\text{number of rings})^2 (\text{height})^2 \end{aligned}$$

Equation 5-5 accounted for 42 percent of the observed variation with standard error of the estimate of 0.56 mm.

Latewood tracheids at middle and upper heights in spruce pine stems averaged about 4 mm. in length by the 10th annual ring; near ground level, however, it was not until the 25th ring that tracheids averaged

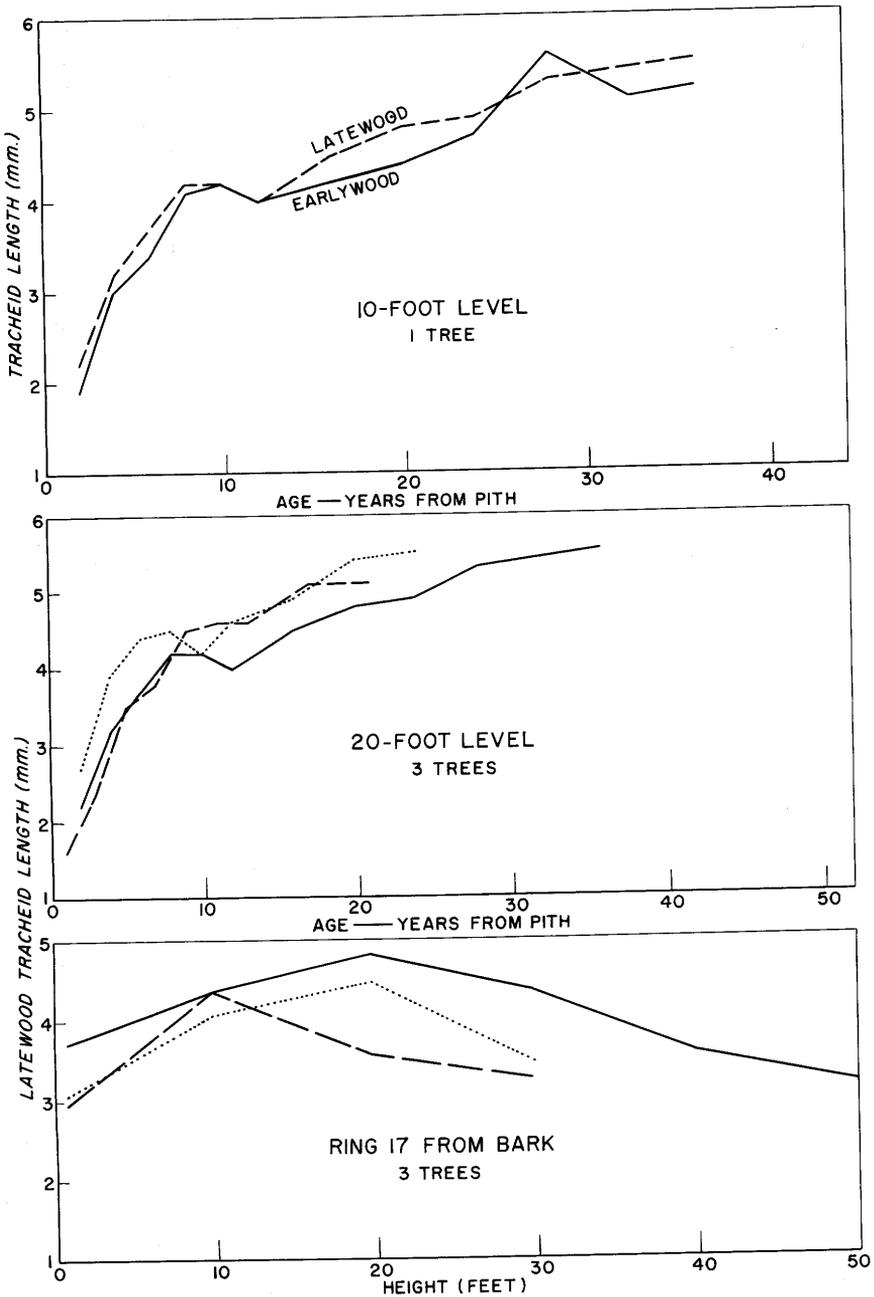


Figure 5-39.—Tracheid lengths in three Georgia slash pines (average d.b.h. 13.4 inches, average age 37 years). (Top) Comparison of earlywood and latewood variation with radial position at 10-foot level (one tree only). (Middle) Variation of latewood with radial position at 20-foot level (three trees). (Bottom) Variation with height in the 17th latewood sheath from the bark, i.e., the latewood sheath laid down in the year when trees averaged 20 years old. (Drawing after Taras 1965.)

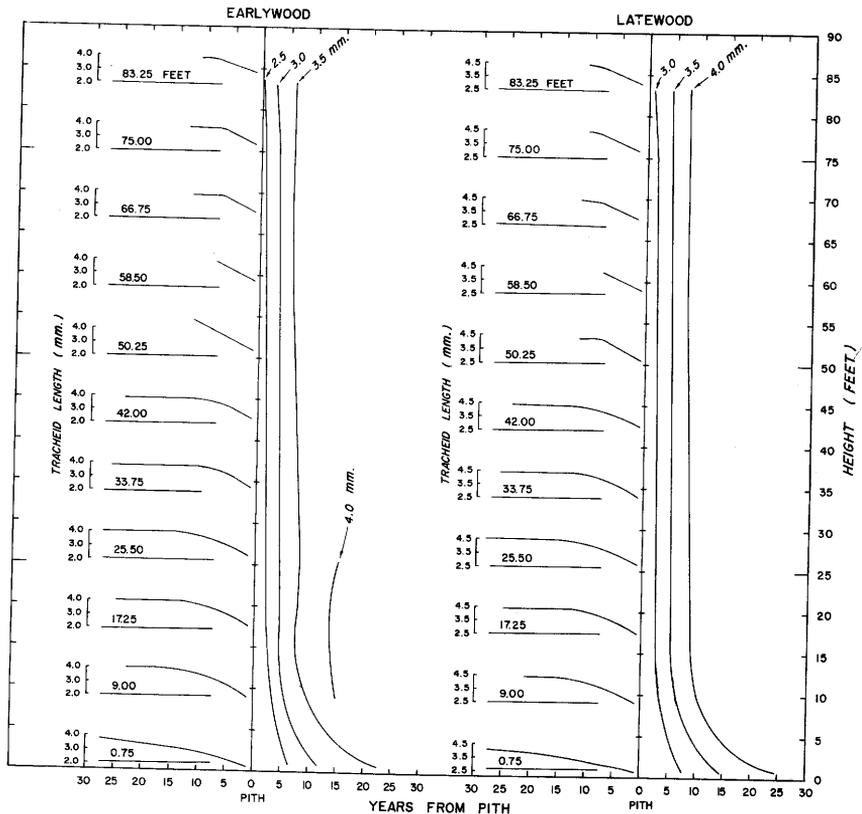


Figure 5-40.—Tracheid length variation in earlywood (left) and latewood (right) with number of years from the pith and vertical position in stemwood of spruce pine. Data are based on observations of 72 trees cut throughout major commercial range. Vertical curves to the right of pith are tracheid-length contour lines; horizontal curves to left of pith show positive correlation between tracheid length and years from pith at indicated sample heights. No data were extrapolated to make these curves. (Drawing after Manwiller².)

4 mm. in length. Earlywood tracheids were shorter but a similar trend was evident (fig. 5-40).

Tracheid length also varies across individual growth increments. Jackson and Morse (1965a) observed that the length of loblolly pine fibers increases through the earlywood to a maximum at about 55-percent of ring width and then decreases to the end of the latewood (fig. 5-41); they found no significant difference between length of earlywood and latewood fibers. However, McMillin (1968) observed in a 50-tree sample that loblolly earlywood fibers are significantly shorter than those of latewood (3.81 compared to 4.04 mm.). Kramer (1957), in a 12-tree, breast-height sample of Texas loblolly found a linear increase in fiber length across the growth ring, e.g., from 3 mm. for first-formed earlywood to 3.6 for last-formed latewood.

North Carolina State University (1969, p. 33) found that latewood tracheids in corewood of 16 loblolly pines averaged 0.29 mm. longer than earlywood tracheids; in outer wood (11th to 35th rings) latewood tracheids averaged 0.14 mm. longer than earlywood tracheids.

Jackson and Morse (1965a) found patterns for shortleaf and slash pines (fig. 5-41) that were similar to their findings for loblolly. In shortleaf the maximum length was at about 57 percent of ring width and in slash pine at 62 percent.

Taras (1965), in a one-tree sample of slash pine found that latewood tracheids were a little longer than earlywood tracheids at all ages and heights (fig. 5-39). In a 112-tree sample of breast-height slash pine wood (older than 10 years, Wangaard⁵ found the median length for earlywood to be 4.4 mm. while the latewood median was 4.6 mm.

For longleaf pine, Gerry (1915, 1916) observed from 5,000 measurements on an unspecified number of trees that latewood fibers were shorter

⁵ Wangaard, F. F. Unpublished data for 112 slash pine trees gathered throughout major range of the species. Trees were 15 to 45 years old and were evaluated in 1962 at Yale University, New Haven, Conn.

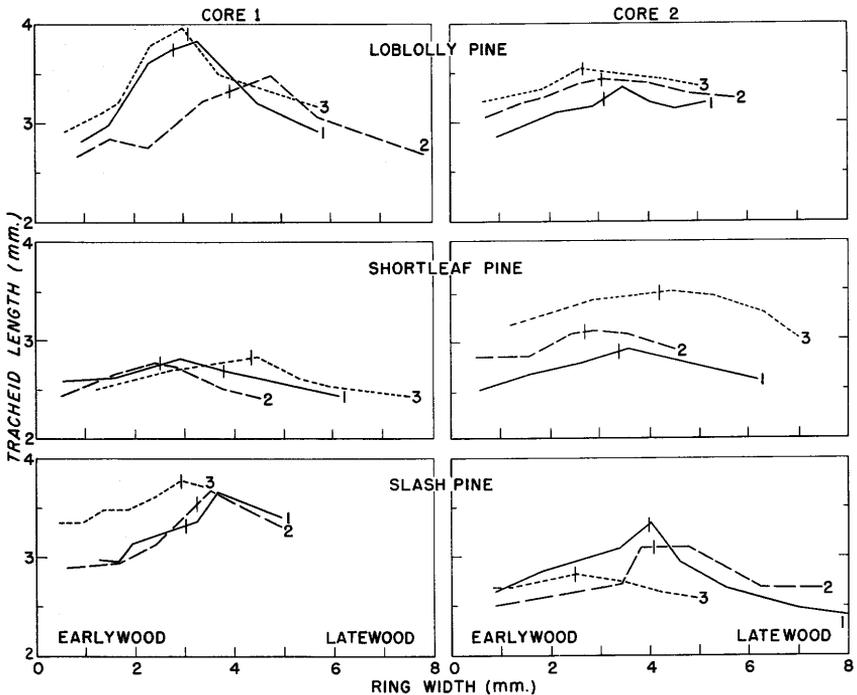


Figure 5-41.—Variation in tracheid lengths across single growth rings. Vertical bars indicate the transition from earlywood to latewood. The sequence of rings (three widest of outermost six rings in 30-year-old trees at breast height) is shown by numbers to the right of each curve; three is closest to bark. (Drawings after Jackson and Morse 1965a.)

than those of earlywood. This finding is contrary to observations on other species.

Manwiller³, in a 1,296-point sample of 72 spruce pine trees, found that latewood tracheids averaged 3.5 mm. long; earlywood fibers measured 3.2 mm. In this study, samples of latewood and earlywood were taken at three heights in each tree and three radial positions at each height; the averages do not, however, represent species average values because they are not weighted by volume.

For loblolly pine, Wheeler et al. (1966) have provided equations to predict average tracheid lengths of whole trees from average tracheid lengths at the 5-foot level (fig. 5-42), which facilitate assessments from increment borings. Tracheid length of mature wood at the 5-foot level was the best predictor (i.e., $r = 0.903$).

Correlation of tracheid length with other factors.—In later sections of this chapter, reported correlations of various anatomical dimensions with tracheid length are noted. Following are correlations found by Manwiller³ in his study of 1,296 sample points in 72 spruce pine trees.

Factor correlated with tracheid length	r	
	Earlywood	Latewood
Fibril angle -----	-0.31	-0.31
Tracheid radial diameter -----	.53	.26
Tracheid tangential diameter -----	.57	.56
Tangential wall thickness -----	.22	.33
Lumen radial diameter -----	.50	.91
Lumen tangential diameter -----	.52	.38
Specific gravity of earlywood (or latewood) -----	.20	.06
Number of rings to specimen -----	.50	.46
Distance to specimen -----	.50	.48
Height above ground -----	.14	.12

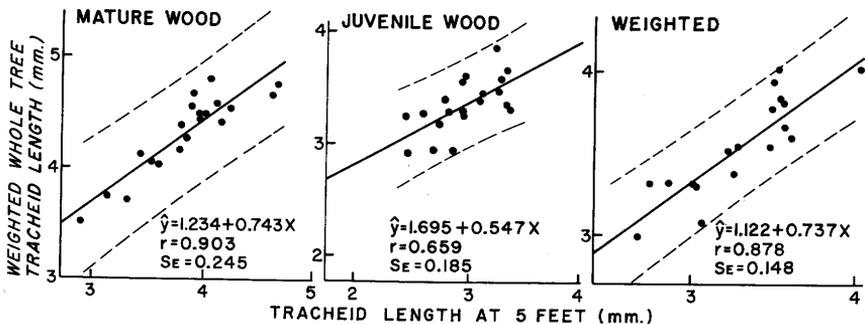


Figure 5-42.—Regression of weighted whole-tree tracheid lengths on tracheid lengths at 5-foot level in loblolly stems. Dashed lines indicate 95-percent confidence limits. (Drawings after Wheeler et al. 1966.)

Manwiller³ observed poor correlation between width of annual ring and tracheid length; also, specific gravity of earlywood and latewood had low correlation with tracheid length in these tissues.

FIBRIL ANGLE

Fibril angle—as used in this discussion—refers to the average angle between fibrils in the S_2 layer and the tracheid longitudinal axis (fig. 5-43). Wood with high fibril angles may have more than normal longitudinal shrinkage, but evidence is not entirely conclusive. Both tracheid length and wall thickness have been observed negatively correlated with fibril angle. It follows, then, that trees with low fibril angles probably will yield relatively dense wood with long fibers. Minute checks in the S_2 layer—associated with high fibril angles—adversely affect tear and burst strength of sulfate and sulfite pulps (Pillow et al. 1941). For most purposes, therefore, southern pine wood with low fibril angles is preferable to wood with high angles.

Measurement of fibril angle.—The physical concept of fibril angle in the S_2 layer of the secondary wall is well illustrated by electron micrographs (e.g., figs. 5-11B, 5-12, 5-33F). Equipment for electron microscopy is too expensive, and techniques too exacting for routine measurement of fibril angles. Four methods are in current use, two of them applicable only to latewood tracheids.

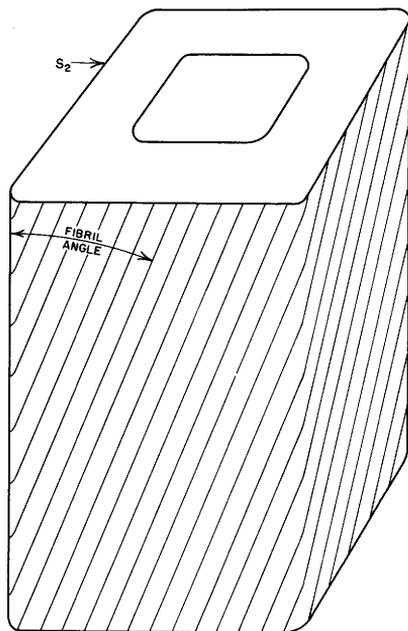


Figure 5-43.—Fibril angle in the S_2 layer of the cell wall.

Marts (1955) described the technique of fluorescence microscopy. Heat is used to induce checks in pine latewood tracheids. These checks are assumed to be parallel to the fibrils and are visible at ray crossings in radial split sections when the wood is treated with fluorochromes and viewed under ultraviolet light. The technique does not work as well with earlywood tracheids; Hiller and Brown (1967, p. 454) have described a modification of the procedure to improve its applicability to earlywood.

For latewood tracheids only, it is possible to measure the inclination of the apertures of bordered pits in longitudinal tracheids (figs. 5-7 right, b; 5-25E). This observation can be made with a light microscope. It is assumed that each slit-like aperture is aligned with the fibrils in the S_2 layer (Bailey and Vestal 1937).

A technique suitable for both earlywood and latewood calls for microscopic examination of single walls of macerated tracheids under polarized light. The procedure is described by Preston (1952, p. 116). More recently, Page (1969) described a technique for measuring fibril angles of intact tracheids in situ.

Also applicable to both earlywood and latewood (in situ) is the X-ray diffraction technique described by Hermans (1949, p. 248).

Fluorescence microscopy, polarized light, and X-ray diffraction have the advantage of applicability to solid wood. Observation of pit apertures requires preparation of either radial sections or macerated tracheids.

The various methods do not yield identical data. Macerated tracheids may shorten (and their fibril angles increase slightly) when released from the solid wood. Jurbergs (1963) has published data comparing the method of pit apertures with X-ray diffraction; his data on slash pine show a correlation coefficient of 0.766 between the two methods, with measurement of pit apertures giving slightly lower values. McGinnes (1963, p. 19) has compared estimates of fibril angle in shortleaf by the methods of cell wall checks and polarized light; generally, the methods agreed within a degree or two. The wall check method yielded slightly lower values. Preparatory to his extensive work on spruce pine with the polarized light method, Manwiller³ observed that the polarized light technique applied to macerated latewood tissues indicated fibril angles about 8° larger than those indicated by pit apertures observed in radial sections; regression analysis showed that values obtained by the two methods were closely correlated ($r^2 = 0.86$). The polarized light method also indicated 4 to 5° larger fibril angles than the wall check method applied to macerated tissue ($r^2 = 0.71$).

Measurement technique should be specified in any comparative tabulation of fibril angles.

Among-species variation.—There are insufficient published data to permit valid statistical comparisons of fibril angles in the various species.

Within-species variation.—Data are available for slash, spruce, and loblolly pines. As with tracheid length, fibril angle varies considerably

between individual trees of the same species. Because fibril angles are larger in juvenile wood than in mature wood, young trees have larger tree-average values than older trees.

In a study of slash pine latewood sampled at breast height and evaluated for fibril angle by checks in the cell wall, Hiller (1954) found that fast-grown trees showed a negative linear correlation between fibril angle and rings from pith; slow grown trees also had higher angles near the pith but the relationship was curvilinear (fig. 5-44). While these relationships may not be true for slash pine trees in general, the curves illustrate differences between trees.

By X-ray diffraction, Dadswell and Nicholls (1959) measured breast-height fibril angles in wood from 13 slash pine trees ranging from 15 to 30 years of age. In some trees fibril angle was as great as 45° near the pith. In many trees it did not fall below 20° by the 20th annual increment, but in some it was nearer 10° at this age.

By observing pit apertures, Jackson and Morse (1965b) measured fibril angles in progeny from three loblolly and 10 slash pine parents. They concluded that parents having wood of large fibril angle produced

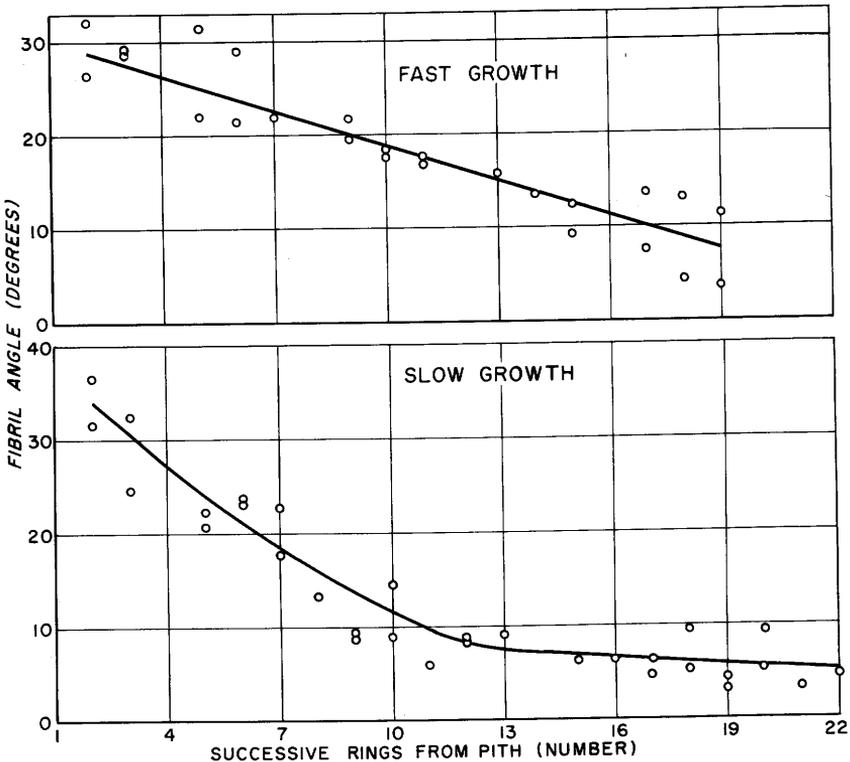


Figure 5-44.—Fibril angles in breast-height latewood from four slash pines cut near Olustee, Fla. The two fast-grown trees averaged 11.4 inches d.b.h. at 19 years; the two slow-grown trees averaged 8.5 inches d.b.h. at 21 years. (Drawings after Hiller 1954.)

progeny having large fibril angles; parents with low angles produced progeny with low angles.

In an extensive study of 72 spruce pine trees drawn from the major commercial range, Manwiller^{1,3} measured fibril angles of macerated fibers by the polarized light method. He found that tree-average fibril angle was negatively correlated with tree age, but not with rings per inch growth rate measured 1 foot above ground level. No effects of latitude and longitude were observed. The overall average was 35.9°.

Tree age	Tree-average fibril angle	Standard deviation
<i>Years</i>	<i>----- Degrees -----</i>	
15	38.1	9.2
30	35.9	8.9
45	33.6	8.4

Within-tree variation.—Fibril angles vary within the cell wall, within each annual growth increment, with number of rings from the pith, and with height in the tree. Data are most plentiful for loblolly, slash, and spruce pines; some information on shortleaf and longleaf is also at hand. The following discussions are arranged in alphabetical order by species.

Pillow and Bray (1935) and Pillow et al. (1941) observed fibril angles in normal and compression wood of loblolly pine; they used the wall-check method.

Cell type in loblolly	Fibril angle	
	Range (1941)	Average (1935)
	<i>----- Degrees -----</i>	
Earlywood		
Normal.....	20-50	23
Compression wood.....	—	35
Latewood		
Normal.....	5-10	5
Compression wood.....	30-45	29

In a study of fibril angles by the polarized light technique, McMillin⁶ removed loblolly pine wood from 50 trees in Louisiana and stratified samples by two densities and two growth rates in the 0 to 10, 11 to 20, and 21 to 30 growth-ring zones. Selected logs were from various heights, but all showed at least 40 annual rings. This factorial design permitted isolation of the independent relationships to fibril angle of wood specific gravity, growth rate, and number of rings from the pith. From 4,800

⁶ McMillan, C. W. Fibril angle of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201.1-23 dated September 7, 1969.

observations, he found that fibril angles were substantially greater for earlywood (33.4°) than for latewood (26.9°).

Earlywood (but not latewood) fibril angles were greater in wood of fast growth (less than 6 rings per inch) than in wood of slow growth (more than 6 rings per inch). When averaged over all levels of specific gravity and numbers of rings from the pith, earlywood fibril angles were 34.2° for fast growth and 32.6° for slow.

He observed a significant interaction between specific gravity and growth rate; in earlywood of high specific gravity, fibril angle was 35.1° when growth rate was fast and 32.0° when growth rate was slow. No difference was detected when specific gravity was low.

Specific gravity	Earlywood fibril angles at two growth rates	
	Less than 6 rings per inch	More than 6 rings per inch
	----- Degrees -----	
Less than 0.49.....	33.3	33.3
More than 0.49.....	35.1	32.0

Averaged over high and low densities and fast and slow growths, McMillin's factorial design showed significant but modest variation in latewood fibril angles with increasing distance from the pith. The fibril angle of outer wood did not differ significantly from middle wood. Fibril angles of latewood in rings 0 to 10 averaged 28.0° , as compared with 26.3° in rings 11 to 30.

Number of rings from the pith	Latewood fibril angle
	----- Degrees -----
0 to 10 (corewood) -----	28.0
11 to 20 (middle wood) -----	25.6
21 to 30 (outer wood) -----	27.1

For whole wood of loblolly pine (weighted average of earlywood plus latewood), McMillin found that fibril angle averaged 30.7° and was greater in corewood (av. 32.2°) than in middle or outer wood (29.9°).

By observing wall checks in twelve 30- to 35-year-old dominant and codominant loblolly pines cut near Crossett, Ark., Pillow et al. (1953) plotted the correlation between latewood fibril angle (range 2° to 51°) and distance to the pith (negative), height in the tree (negative), and width of annual ring (positive). Results are summarized in figure 5-45.

Variation of the fibril angle with height in the tree in two successive sheaths of latewood was measured in a single loblolly tree near Crossett, Ark. (Hiller 1964a). As determined from pit apertures, the fibril angle was negatively correlated with number of internodes from the apex (fig. 5-46); angles were low (3° to 9°) near ground level and high (20° to 25°) near the tree top.

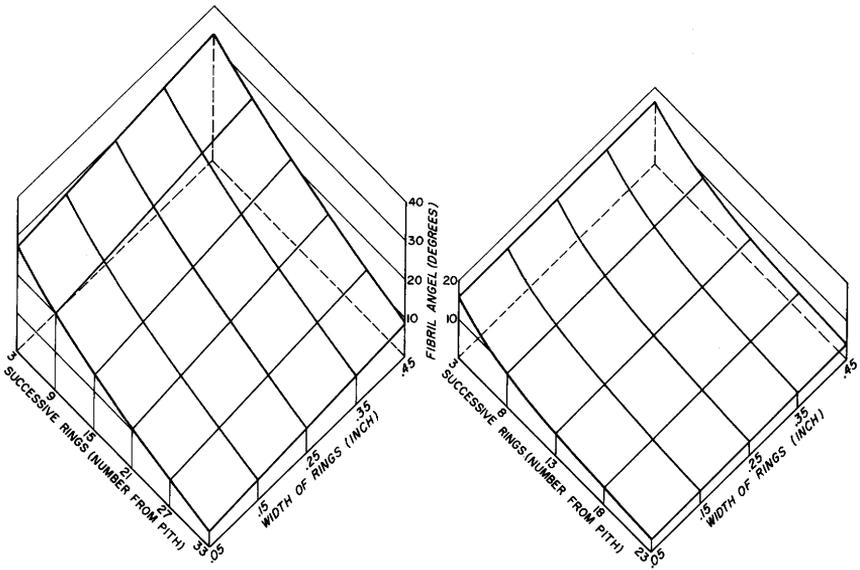


Figure 5-45.—Relationship of fibril angle in loblolly pine latewood (determined by wall-check method) to radial position and width of annual ring. (Left) Breast height. (Right) Intermediate height and also height at base of crown. (Drawings after Pillow et al. 1953.)

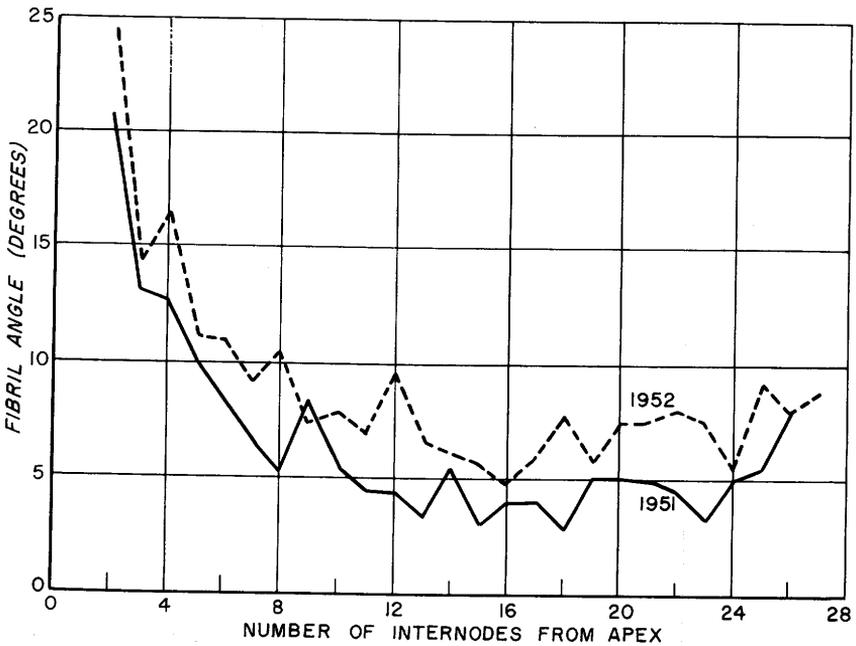


Figure 5-46.—Variation of fibril angle in the 1951 and 1952 latewood sheaths of a loblolly pine as observed from pit apertures. (Drawing after Hiller 1964a.)

Variation across an entire increment (at various heights) in relation to moisture availability during the growing season has been studied (Hiller and Brown 1967). Lack of soil moisture increased the earlywood (but not the latewood) fibril angle as measured by fluorescence microscopy (fig. 5-47). The trend from high fibril angle in earlywood (20° to 40°) to low angle in latewood (5° to 25°) is evident.

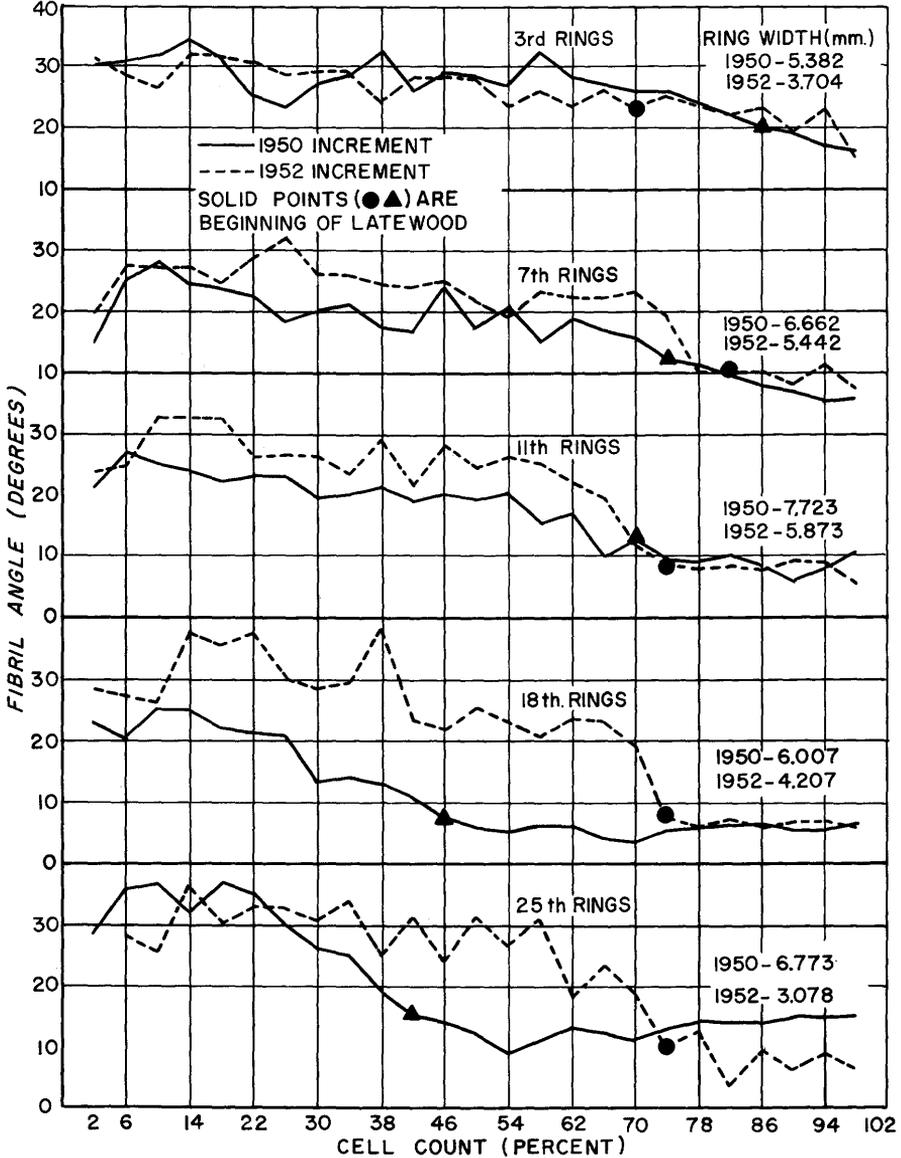


Figure 5-47.—Fibril angle variation (as measured by fluorescence microscopy) across two annual increment sheaths at five different heights in a 37-year-old loblolly pine tree. Solid points mark transition from earlywood to latewood. Soil moisture was adequate in 1950; 1952 was a year of drought. (Drawing after Hiller and Brown 1967.)

The only published data specific to fibril angle in longleaf pine were taken by Dunning (1968); in the one tree sampled he found that the S_2 layer of latewood was comprised of fibrils deposited in a Z helix with an angle to the axis of approximately 15° (fig. 5-8).

McGinnes (1963), using polarized light, studied the variation in fibril angles at breast height in a single shortleaf pine cut in Missouri. At age 30, earlywood had a fibril angle of about 35° ; latewood at this age had an angle of about 10° (fig. 5-48).

For slash pine, four sources of data are at hand. Wangaard⁵ in a 1962 study (results not published) of 112 slash pine trees aged 15 to 45, measured fibril angles at breast height in rings from the 10th year to the cambium; he found that earlywood fibril angle ranged from 26° to 55° (median 41) and latewood angle ranged from 6° to 31° (median 17).

By X-ray diffraction, Dadswell and Nicholls (1959) measured fibril angles at the 28-inch level in 13 slash pine trees grown in Australia. From age 1 to 4 the angle was more or less constant at 40° (range 35° to 45°); thereafter it decreased steadily to about 15° at age 24 (range 10° to 25°).

By observation of wall checks, Hiller (1954) measured fibril angles in the breast-height latewood of four slash pine trees; she found that fibril angle diminished from about 30° at age 1 to about 5° at age 20 (fig. 5-44).

Within-tree fibril angle variation in spruce pine was studied by Man-

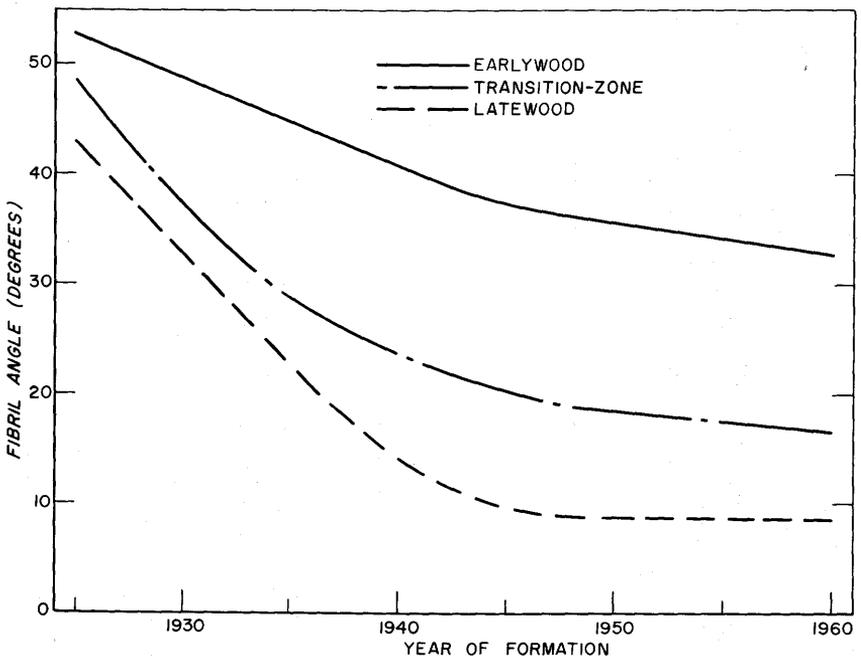


Figure 5-48.—Single-tree values for fibril angle at breast height in annual rings formed during a range of years. Angles were measured in tracheid radial walls. The shortleaf pine was 36 years old in 1960. (Drawing after McGinnes 1963.)

willer³. In a polarized light analysis, he measured 1,296 specimens excised from 72 trees comprising three age classes and two growth rates; the trees were selected from throughout the major commercial range of the species. Fibril angle in earlywood averaged 38.3°; latewood averaged 34.7°. Since his data were not weighted by wood volume, these values do not represent true species averages even though each tree was sampled at three heights and three radial positions at each height.

Manwiller's best prediction equations for fibril angle that reflect only position in the tree (height above ground in feet and number of rings from the pith to the specimen) were different for earlywood and latewood as follows:

$$\begin{aligned} \text{Earlywood fibril angle, degrees} &= 44.03 && (5-6) \\ &- 0.08788 \quad (\text{number of rings}) \\ &- 0.3058 \quad (\text{height}) \\ &+ 0.002805 \quad (\text{height})^2 \\ &- 0.02326 \quad (\text{number of rings}) (\text{height}) \\ &+ 0.0003174 \quad (\text{number of rings}) (\text{height})^2 \\ &+ 0.0004478 \quad (\text{number of rings})^2 (\text{height}) \end{aligned}$$

Equation 5-6 accounted for 24.6 percent of the observed variation with standard error of the estimate of 6.3°.

$$\begin{aligned} \text{Latewood fibril angle, degrees} &= 40.02 && (5-7) \\ &- 0.141 \quad (\text{number of rings}) \\ &- 0.3593 \quad (\text{height}) \\ &+ 0.004136 \quad (\text{height})^2 \end{aligned}$$

Equation 5-7 accounted for 17.7 percent of the observed variation with standard error of the estimate of 6.2°.

Correlation of fibril angle with other factors.—In several studies, a strong negative correlation between fibril angle and tracheid length has been observed; Jurbergs' (1963) observation of slash pine is a notable exception.

Pine species	Reference	Correlation coefficient, r	Remarks
Slash.....	Dadswell and Nicholls (1959)	-0.902	
Slash.....	Echols (1955)	-.956	See fig. 5-49
Slash.....	Hiller (1964b)	-.927	This is multiple r for an equation including wall thickness as well as tracheid length
Spruce.....	Manwiller ³	-.312	

For loblolly and slash pines, Hiller (1964a) has shown that fibril angle is negatively correlated with thickness of the radial cell wall (fig. 5-50); correlation coefficients were -0.82 and -0.89.

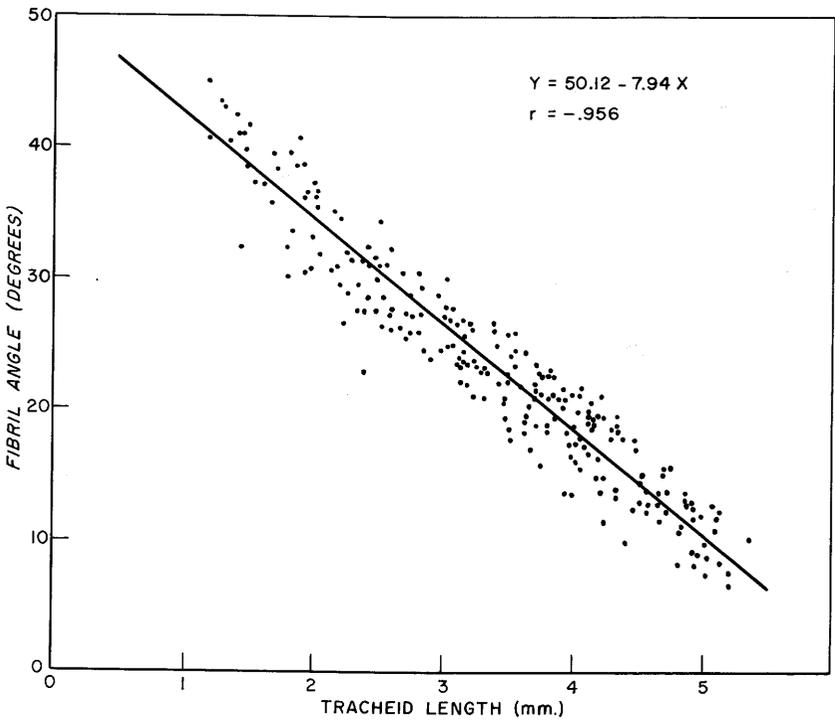


Figure 5-49.—Regression of fibril angle (determined from pit apertures) on tracheid length; the equation is based on 2,240 pairs of measurements of slash pine latewood. (Drawing after Echols 1955.)

In a study of slash pine latewood taken at breast height, Hiller (1964b) determined coefficients of determination (R^2) for correlations between fibril angle and a number of factors.

Factors correlated with fibril angle	R^2
Radial wall thickness + fiber length	.86
Radial wall thickness	.80
Rings from pith	.72
Percent latewood	.70
Inches from pith	.58
Ring width	.42

Hiller's studies (1964a b) were based on observation of pit apertures in latewood.

For shortleaf pine, data from McGinnes (1963 p. 46) also indicate a negative correlation between fibril angle and cell wall thickness. His plots (fig. 5-51) show that the slope and level of the regression lines are different for earlywood and latewood and for juvenile and mature wood.

For spruce pine throughout its major commercial range, Manwiller³ has provided a number of simple coefficients of correlation for fibril angle determined by examination under polarized light.

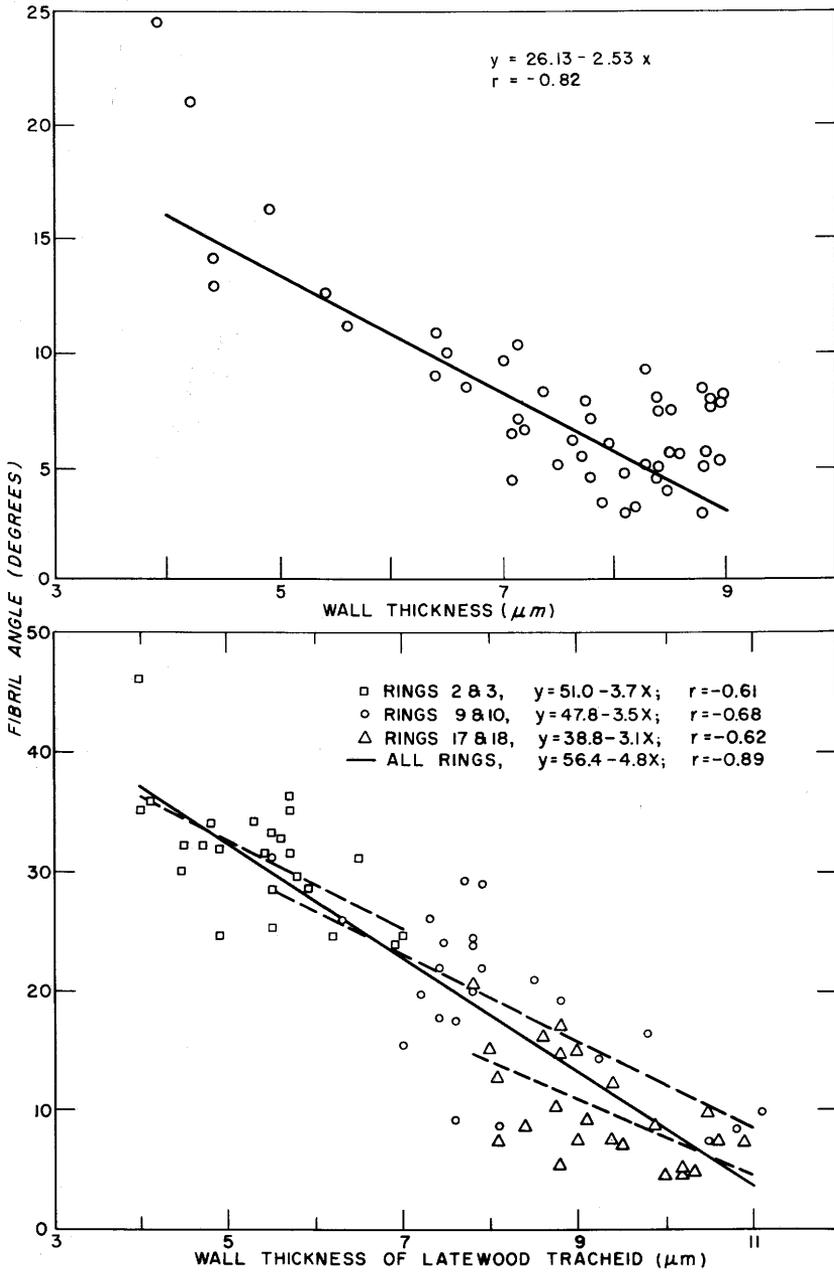


Figure 5-50.—Regression of fibril angle on radial wall thickness of cell. (Top) Based on observations of two increment sheaths of latewood in a single loblolly tree from Crossett, Ark. (Bottom) Based on observations of breast-high latewood from 12 slash pine trees cut near Olustee, Fla. (Drawings after Hiller 1964a.)

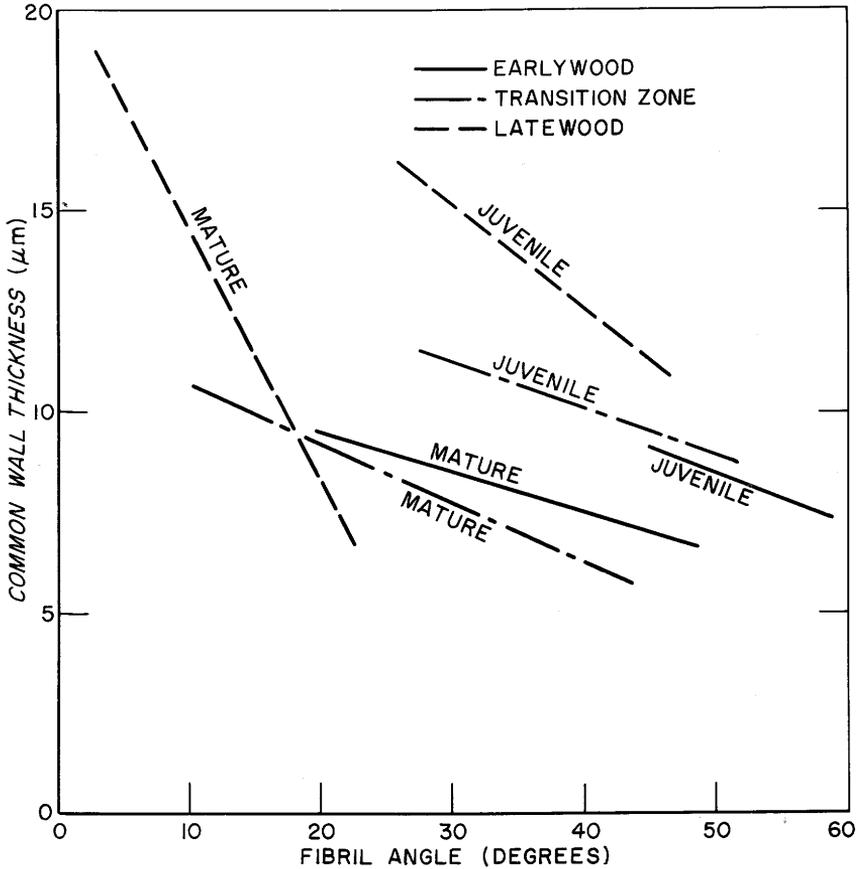


Figure 5-51.—Tangential common (double) wall thickness between tracheids versus fibril angle as measured with polarized light in wood taken at breast height in a single 36-year-old shortleaf pine cut in Missouri. (Drawing after McGinnes 1963.)

Factor correlated with fibril angle	r	
	Earlywood	Latewood
Tracheid length	—0.31	—0.31
Tracheid radial diameter	— .17	— .01
Tracheid tangential diameter	— .14	— .21
Tangential wall thickness	.05	— .08
Lumen radial diameter	— .19	.05
Lumen tangential diameter	— .16	— .17
Number of rings from pith	.04	— .03
Radial distance from pith to specimen	.10	.03
Ring width	.26	.16
Percent of latewood	.23	.24
Height above ground	— .36	— .26
Specific gravity of earlywood (or latewood)	.18	— .01
Width of earlywood (or latewood)	.08	.30

TRANSVERSE DIMENSIONS

Because southern pine fibers are thick-walled, they are strong and relatively stiff. For most products, this high strength is a desirable characteristic. For some paper products, the lack of conformability of individual fibers is disadvantageous. Conformability, and response to pulp refining procedures, is strongly influenced by cell diameter and wall thickness.

To clarify the following discussion, **radial wall thickness** is the thickness of the radially aligned wall, and **radial tracheid diameter** is the diameter measured in the radial direction; **tangential wall thickness** is the thickness of the tangentially aligned wall, and **tangential tracheid diameter** is the diameter measured in the tangential direction.

Among-species variation.—There are insufficient published data to permit statistically valid species comparisons of transverse cellular dimensions; however, table 5-5 presents some single-tree-average values with standard deviations. In these observations, radial walls of latewood cells were consistently thicker than tangential walls. All measurements were made on transverse surfaces of water-swollen solid wood using a dual-linear micrometer.

Within-species variation.—It is obvious that trees of high specific gravity have transverse cellular dimensions different than trees of low specific gravity; progeny of dense trees tend to also be dense (Brown and Klein 1961; Goggans 1962). Young trees have cells of smaller tangential diameter than old trees; latewood wall thickness is less in young than in old trees. Because there are discernible trends in the specific gravity of some species as a function of latitude or longitude, it follows that trends also exist for transverse cellular dimensions (see ch. 7). In short, within species, there are pronounced differences between trees.

Barefoot et al. (1970, p. 11) have published some transverse cellular dimensions for 16 loblolly pines cut in Virginia, North Carolina, South Carolina, and Georgia; their 16-tree averages are tabulated below with ranges in tree averages shown in parentheses.

Rings from pith	Cell wall thickness, radial	Lumen diameter, tangential	Cell diameter, tangential
	----- μ m>-----		
0-10	6.6 (5.9 to 7.4)	32.1 (28.8 to 36.4)	45.3 (43.0 to 49.1)
11-35	8.0 (7.1 to 9.1)	32.8 (27.4 to 38.3)	48.8 (44.0 to 53.0)

McMillin (1968) determined the relationships to transverse cellular dimensions measured in the radial direction, of growth rate (number of rings per inch), unextracted wood specific gravity, and radial position in the tree (rings from pith), in the study of samples from 50 Louisiana loblolly pines described in the subsection TRACHEID LENGTH. Radial

TABLE 5-5.—*Transverse tracheid dimensions in single specimens of the southern pines—tree averages*

Pine species	Comments ¹	Earlywood ²			Latewood ²			All wood ²								
		Single-wall thickness		Tracheid diameter	Single-wall thickness		Tracheid diameter	Single-wall thickness		Tracheid diameter	Cells examined					
		Tan- gential	Radial	Tan- gential	Radial	Tan- gential	Radial	Tan- gential	Radial	Tan- gential	Radial	Cells ex- amined				
		<i>μm.</i>														
		<i>Number</i>														
Loblolly ²	La., 78 yrs., 25.5 in., 92.5 ft.	3.4	3.4	46.8	49.9	900	8.2	10.1	42.8	32.1	520	5.2	5.8	45.3	43.4	1,420
		(.7)	(.7)	(8.4)	(10.2)		(1.5)	(2.1)	(8.0)	(6.3)		(2.6)	(3.5)	(8.4)	(12.4)	
Longleaf ²	La., 60 yrs., 16.7 in., 91.5 ft.	4.0	3.8	47.7	49.2	384	9.9	12.0	38.8	31.1	300	6.6	7.4	41.0	41.3	684
		(1.1)	(1.1)	(7.2)	(7.9)		(1.9)	(2.7)	(7.0)	(5.3)		(3.3)	(4.5)	(7.4)	(11.3)	
Pitch ²	N.J., 65 yrs., 10.2 in., 50.0 ft.	3.0	3.0	33.0	38.1	48	8.3	9.8	30.5	26.3	52	5.8	6.5	31.7	32.0	100
		(.2)	(.3)	(6.4)	(6.6)		(1.3)	(1.7)	(6.3)	(3.5)		(2.9)	(3.7)	(6.5)	(7.9)	
Pond ²	Fla., 67 yrs., 16.2 in., 84.7 ft.	3.2	3.2	40.8	47.5	316	9.5	11.7	38.4	30.1	208	5.7	6.6	39.8	40.6	524
		(.3)	(.5)	(6.4)	(7.0)		(1.7)	(2.2)	(5.8)	(4.2)		(3.3)	(4.4)	(6.3)	(10.4)	

TABLE 5-5.—*Transverse tracheid dimensions in single specimens of the southern pines—tree averages*

Pine species	Comments ¹	Earlywood ²					Latewood ²					All wood ³				
		Single-wall thickness		Tracheid diameter		Cells examined	Single-wall thickness		Tracheid diameter		Cells examined	Single-wall thickness		Tracheid diameter		Cells examined
		Tan- gential	Radial	Tan- gential	Radial		Tan- gential	Radial	Tan- gential	Radial		Tan- gential	Radial	Tan- gential	Radial	
Sand ²																
Ocala.....	Fla., 58 yrs., 10.3 in., 58.0 ft.	3.7 (.8)	3.7 (.9)	36.9 (5.6)	39.4 (5.5)	104	9.8 (1.9)	11.7 (1.8)	34.7 (5.3)	28.8 (4.2)	52	5.7 (3.2)	6.3 (4.0)	36.2 (5.6)	35.8 (7.2)	156
Choctawhatchee...	Fla., 57 yrs., 18.2 in., 69.0 ft.	3.7 (.9)	3.6 (.8)	34.6 (5.8)	38.7 (6.2)	296	8.7 (1.5)	9.9 (1.8)	32.6 (5.2)	26.9 (4.3)	164	5.5 (2.7)	5.8 (3.3)	33.9 (5.7)	34.5 (8.0)	460
Shortleaf ²	La., 68 yrs., 19.2 in., 82.5 ft.	3.4 (1.2)	3.3 (.6)	40.2 (6.7)	47.0 (7.6)	488	9.2 (1.5)	11.5 (1.9)	36.8 (5.5)	28.8 (5.1)	228	5.2 (3.1)	5.9 (4.0)	39.1 (6.5)	41.2 (10.9)	716
Slash ²																
var. <i>elliottii</i>	La., 39 yrs., 14.8 in., 74.5 ft.	3.2 (.3)	3.2 (.3)	45.1 (8.4)	52.1 (9.3)	216	9.0 (1.4)	12.9 (2.8)	39.1 (7.0)	27.1 (3.9)	124	5.3 (2.9)	6.8 (5.0)	42.9 (8.4)	43.0 (14.3)	340
var. <i>densa</i>	Fla., 47 yrs., 13.3 in., 46.0 ft.	3.8 (1.4)	3.6 (.9)	42.1 (8.0)	48.0 (8.7)	136	9.7 (1.5)	12.6 (2.2)	37.2 (5.7)	27.3 (4.2)	88	6.1 (3.2)	7.1 (4.7)	40.2 (7.5)	40.0 (12.4)	224
Spruce ⁴		3.5 (0.6)	-----	30.0 (3.4)	37.4 (5.1)	249 ×10 ³	5.9 (1.1)	-----	28.5 (3.6)	24.3 (3.6)	107 ×10 ³	-----	-----	-----	-----	-----
Table-Mountain ²	Va., 50 yrs., 9.1 in., 33.0 ft.	3.3 (.2)	3.6 (2.4)	36.3 (6.1)	37.5 (4.4)	48	8.2 (1.2)	9.2 (1.4)	30.1 (3.8)	25.9 (3.5)	56	5.9 (2.6)	6.6 (3.4)	33.0 (5.9)	31.3 (7.0)	104
Virginia ²	Va., 51 yrs., 10.0 in., 53.5 ft.	3.1 (.3)	3.2 (.3)	31.7 (5.9)	37.1 (6.4)	84	9.0 (1.1)	9.3 (1.6)	30.2 (5.4)	26.6 (2.4)	44	5.2 (2.8)	5.3 (3.1)	31.2 (5.8)	33.4 (7.3)	128

¹ Tree location, age, d.b.h., height.

² Single trees collected in connection with USDA Forest Service Study FS-SO-3201-1.2. Data were drawn to yield true tree average values of transverse dimensions for earlywood, latewood, and total wood; standard deviations are given in parentheses below tree average values.

³ Radial wall thickness is the thickness of the radially aligned wall. Radial tracheid diameter is the diameter measured in the radial direction.

⁴ The values for spruce pine earlywood and latewood are not weighted tree averages, but are simple averages from nine sample points per tree, i.e., at $\frac{1}{6}$, $\frac{2}{6}$, and $\frac{3}{6}$ the radius (in rings) at three heights (1 foot, at a 4-inch top, and midway between). Averages are based on data from 72 trees comprised of three age classes (15, 30, and 45 years) and two growth rates (less than 6, and more than 6 rings per inch).

diameters of tracheids and their lumens, in latewood, decreased with increases in rings per inch; thus both were larger in fast-grown wood. In latewood, cell wall thickness tended to be greatest in slow-grown wood. In earlywood, growth rate was not related to the radial diameter of tracheids or lumens, or to cell wall thickness.

Specific gravity was negatively correlated with radial lumen diameter in both earlywood and latewood. Radial tracheid diameter in earlywood decreased, and in latewood increased with increasing unextracted specific gravity. In latewood (but not earlywood) wall thickness increased with increasing unextracted specific gravity.

All three radial dimensions increased with number of rings from the pith except lumen diameter in latewood, and cell wall thickness in earlywood, neither of which were related to number of rings from the pith.

These findings are presented in more detail in the following subsection; relationships are expressed quantitatively in figure 5-52 and in equations 5-8, 5-9, 5-10, 5-11, 5-12, and 5-13.

In his study of 72 spruce pines drawn from the major commercial range, Manwiller^{1,3} measured transverse cellular dimensions of latewood and earlywood. He found that cells from fast-grown trees had significantly thicker walls and were larger in diameter, as shown in the following tabulation. No significant relationships with tree age, latitude, or longitude were observed, however.

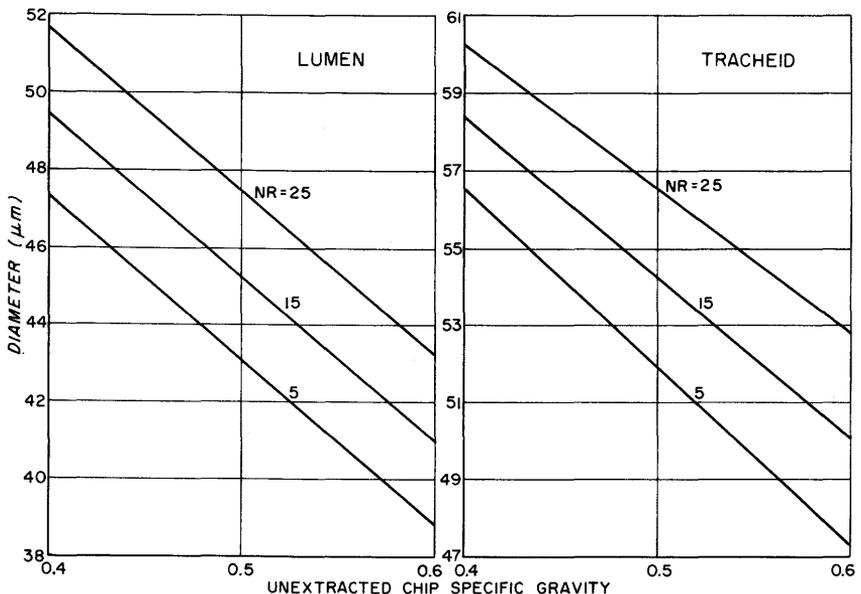


Figure 5-52.—Earlywood radial lumen diameter and tracheid diameter in loblolly pine as related to distance from the pith and unextracted chip specific gravity. NR is number of rings from the pith. (Drawings after McMillin 1968.)

Cell type and dimension	Tree growth rate 1 foot above ground level	
	Slow, i.e., more than 6 rings per inch	Fast, i.e., less than 6 rings per inch
	----- $\mu m.$ -----	
Earlywood		
Tangential wall thickness -----	3.4	3.6
Lumen radial diameter -----	29.5	31.2
Tracheid radial diameter -----	36.4	38.4
Lumen tangential diameter -----	22.3	23.6
Tracheid tangential diameter -----	29.2	30.7
Latewood		
Tangential wall thickness -----	5.8	6.0
Lumen radial diameter -----	11.7	13.2
Tracheid radial diameter -----	23.3	25.3
Lumen tangential diameter -----	16.0	17.3
Tracheid tangential diameter -----	27.5	29.4

The foregoing values are not weighted tree averages but are simple averages for nine sample points per tree, i.e., at 1/6, 3/6, and 5/6 the radius (in rings) at three heights (1 foot, at a 4-inch top, and midway between).

The following references document additional aspects of within-species variation in transverse cellular dimensions; further evidence is cited in chapter 7 (specific gravity).

Pine species	Reference
Loblolly -----	Pew and Knechtges (1939) Van Buijtenen (1958) Zobel et al. (1961) Barefoot et al. (1964) Posey (1964) Wheeler et al. (1966) McMillin (1968) Smith (1968) North Carolina State University (1969) Barefoot et al. (1970)
Slash -----	Taras (1965) Wangaard ⁵
Spruce -----	Manwiller ^{1 3}

Within-tree variation.—Transverse cellular dimensions vary within each annual growth increment, with number of rings from the pith, and with height in the tree. Differences between the north and south sides of southern pines may exist but were not evident in one major study of slash pine (Taras 1965). Detailed published data specific to the southern pines are meager and appear to be limited to loblolly, slash, and spruce pines. Goggans (1965) recently reviewed the data available. Since then some additional information has been published, notably Wheeler et al.

(1966), Smith (1968), McMillin (1968), Jurbergs (1968), and Manwiller³.

Although not yet published, the USDA Forest Products Laboratory has collected a wealth of data on transverse cellular dimensions in loblolly pine.

Figure 5-3 shows the abrupt transition from thin-walled earlywood cells to thick-walled latewood cells that normally occurs in each annual increment. Though cell dimensions vary with position in the tree, earlywood tracheids commonly have larger radial diameters, but only about half the cell wall thickness of tracheids in latewood. Published information on these dimensions is summarized in table 5-6.

There are substantial differences in tangential diameters of tracheids within the latewood of a single annual increment. To demonstrate this, Jurbergs (1968) measured 10 samples, each comprised of about 50 tracheids, from the tenth growth ring of a slash pine; the great variability is illustrated in figure 5-53.

Taras (1965) observed the variation in wall thickness and cell diameter with distance from the pith at breast height in slash pine (fig. 5-54). In earlywood, the wall thickness remained constant regardless of age; tangential tracheid and lumen diameter increased rapidly to about age 12 and more slowly thereafter. In latewood, wall thickness increased fairly rapidly for the first 10 years, then increased slowly, finally leveling off at about age 22. Tangential diameter increased more or less steadily to about age 28 and then became fairly constant. The tangential lumen diameter in latewood remained relatively constant from pith to bark. In latewood, the ratio of wall thickness to tangential tracheid diameter increased up to about age 10 and then remained relatively constant (0.5) with increasing age.

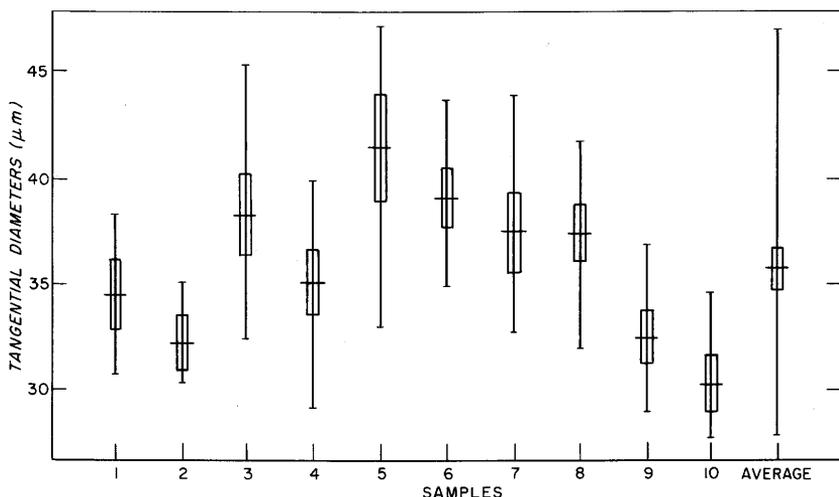


Figure 5-53.—Tangential diameters of slash pine latewood tracheids from different parts of an annual growth ring. Vertical line segments define the range found for each sample. Rectangular bars on line segments indicate two standard errors on each side of the mean. Short horizontal lines crossing bars show mean values. (Drawing after Jurbergs 1968.)

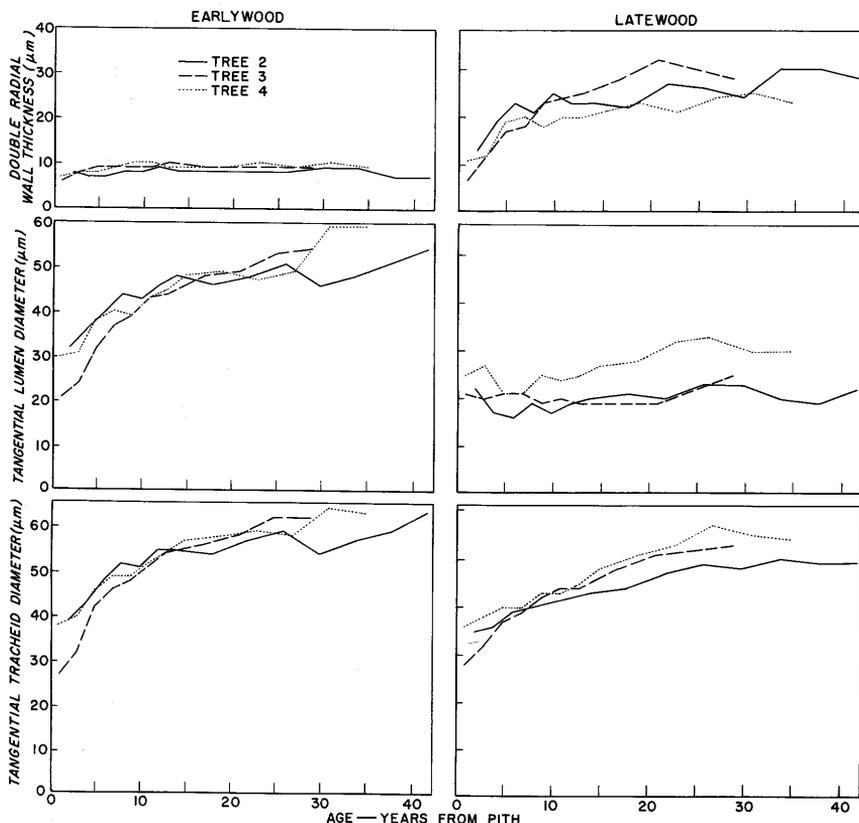


Figure 5-54.—Radial variation in transverse tracheid dimensions. Data are for three slash pines growing in Georgia and sampled at breast height. (Drawings after Taras 1965.)

Barefoot et al. have shown the variation in latewood wall thickness between core wood and outer wood in four 35- to 37-year-old loblolly trees; in core wood the wall thickness of latewood was about $2 \mu\text{m}$. less than in outer wood (fig. 5-55).

Radial tracheid diameter in earlywood and latewood was measured at breast height in two 13-year-old loblolly pines by Smith (1968). Between the tree ages of 7 and 13, there was no overall major trend in radial diameters (fig. 5-56). The observations were part of a thinning study; Smith concluded that thinning produced earlywood tracheids that were narrower and latewood tracheids that were wider than those found in unthinned stands.

For shortleaf, the only data at hand were observed by McGinnes (1963) in Missouri. He measured tracheid wall thickness at breast height in a single 36-year-old tree and found that latewood walls were about $6 \mu\text{m}$. thick near the pith and increased to a constant thickness of about $7 \mu\text{m}$. by age 15; earlywood walls were $3\frac{1}{2} \mu\text{m}$. thick near the pith and increased to a constant thickness of about $4 \mu\text{m}$. by age 8.

The foregoing observations of transverse cellular dimensions recorded

Longleaf.....	3.3	6.5	-----	-----	-----	-----	-----	Source not stated	Wahlenberg (1946, p. 26)
Pitch.....	3.7	-----	-----	³ 35	-----	-----	-----	2 trees, breast height	Hamilton (1963)
Pond.....	-----	-----	-----	See table 5-5	-----	-----	-----	-----	-----
Sand.....	-----	-----	-----	See table 5-5	-----	-----	-----	-----	-----
Shortleaf.....	3.0	7.4	-----	³ 39	-----	² 26	-----	-1 tree, breast height	Hamilton (1963)
	4.	7.	-----	-----	-----	-----	-----	1 tree, breast height	McGinnes (1963)
Slash.....	4.	11.	-----	55	-----	45	-----	3 trees, breast height	Taras (1965)
	-----	7.5	-----	-----	-----	-----	-----	12 trees, breast height	Hiller (1964a)
	-----	-----	-----	-----	-----	38	-----	10 trees, macerated tissue	Jurbergs (1968)
	-----	-----	-----	-----	22	30 to 38	-----	1 tree, cross section	Jurbergs (1968)
	-----	-----	48	³ 51	28	³ 33	-----	112 trees, breast height	Wangaard (text footnote ⁵)
	3.5	6.6	45	37	30	34	-----	1 tree, breast height, outer five rings	Quirk et al. (1968)
Spruce.....	3.5	5.9	37	30	24	29	-----	72 trees, three heights	Manwiller (text footnote ³)
Table-Mountain.....	-----	-----	-----	See table 5-5	-----	-----	-----	-----	-----
Virginia.....	-----	-----	-----	See table 5-5	-----	-----	-----	-----	-----

¹ The USDA Forest Products Laboratory has accumulated a very large amount of data on transverse dimensions of loblolly pine; publication in 1972 is scheduled.

² Average of radial and tangential diameters.

³ Macerated fibers; not clearly identified as tangential diameter.

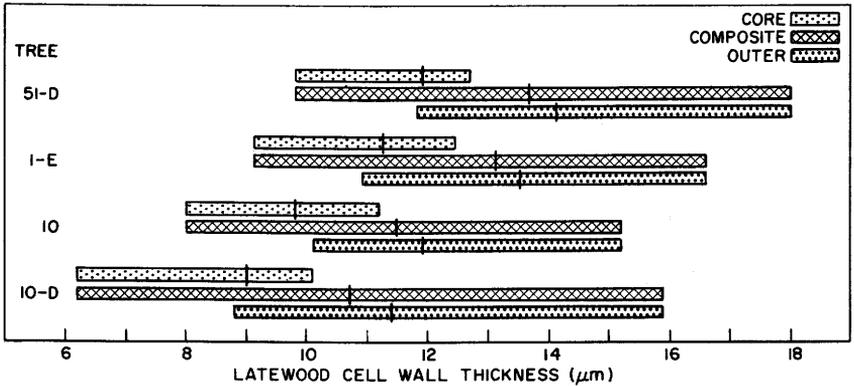


Figure 5-55.—Weighted means and ranges (whole tree) of latewood cell-wall thickness in four 35- to 37-year-old loblolly pines. Corewood and outer wood values are compared. (Drawing after Barefoot et al. 1964.)

averages as found within tree stems, and reflect the naturally occurring variation associated with radial position of samples, specific gravity of the wood, and its growth rate. To determine the independent relationships of these factors to cell dimensions, McMillin (1968) analyzed macerated samples of Louisiana loblolly pine wood stratified as described in the subsection in this chapter on tracheid length. He found that none of the factors were

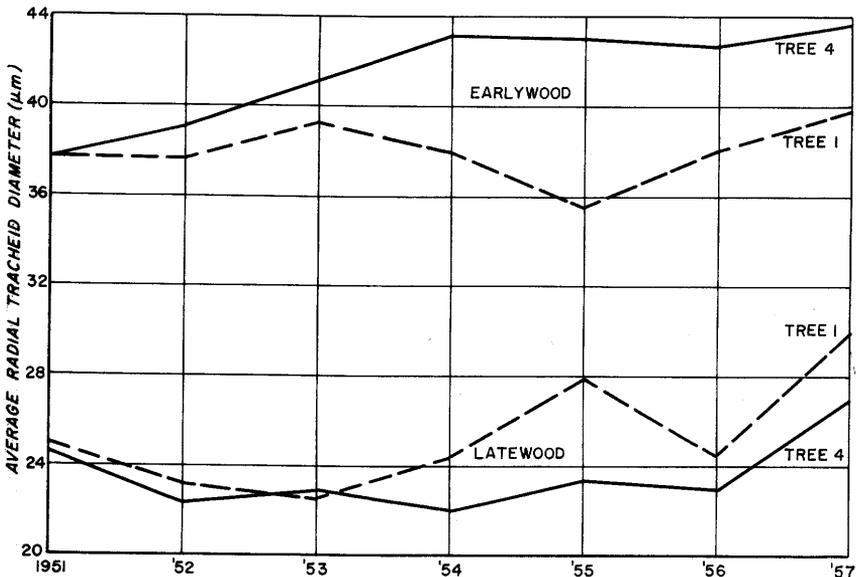


Figure 5-56.—Radial tracheid diameters at breast height in two loblolly pine trees (age 13 when sampled in April 1958). Tree 1 was from a stand heavily thinned and pruned in the winter of 1953-1954; tree 4 was from an unthinned stand of the same age. (Drawing after Smith 1968.)

related to earlywood cell wall thickness, but these factors were more closely related to cell wall thickness in latewood and to lumen and tracheid radial diameters.

Radial lumen diameters of latewood differed significantly with specific gravity and growth rate, but not with distance from the pith. Wood of low specific gravity had larger lumens (avg. 14.4 $\mu\text{m}.$) than wood of high specific gravity (avg. 13.5 $\mu\text{m}.$). Fast-grown wood had larger lumens than slow-grown. Latewood lumen diameter averaged 14.5 $\mu\text{m}.$ for fast-grown wood and 13.5 $\mu\text{m}.$ for slow-grown.

Latewood lumen diameter at two growth rates

Specific gravity	Latewood lumen diameter at two growth rates	
	Less than 6 rings/inch	More than 6 rings/inch
Less than 0.49	14.69	14.16
More than 0.49	14.26	12.78

The interaction of growth rate and specific gravity proved significant. Latewood lumen diameter decreased with increasing specific gravity at a faster rate in slow-grown than in fast-grown wood.

Stepwise regression analysis developed the following equations:

$$\text{Latewood lumen diameter, } \mu\text{m.} = 19.1758 - 10.7627 (\text{unextracted specific gravity}) \quad (5-8)$$

$$\text{Latewood lumen diameter, } \mu\text{m.} = 15.9154 - 0.2708 (\text{rings per inch}) \quad (5-9)$$

The first equation accounted for 11 percent of the variation with standard error of 1.25 $\mu\text{m}.$; the second accounted for 27 percent of the variation with standard error of 1.12 $\mu\text{m}.$ An equation incorporating both factors was not significantly better than equation 5-9.

In brief, latewood tracheids with lumens of small radial diameter were characteristic of dense, slow-grown wood. In contrast, large lumens were associated with low-density wood of fast growth.

In earlywood, radial lumen diameters increased with number of rings from the pith and decreased with increasing specific gravity (fig. 5-52). They averaged 47.9 $\mu\text{m}.$ and 44.0 $\mu\text{m}.$, respectively, for wood with specific gravity below and above 0.49. They averaged 44.0 $\mu\text{m}.$ for corewood, 46.1 $\mu\text{m}.$ for middle wood and 47.8 $\mu\text{m}.$ for outer wood. Lumen diameters were not significantly related to growth rate.

The following equation accounted for 42 percent of the variation, with a standard error of 2.69 $\mu\text{m}.$:

$$\begin{aligned} \text{Earlywood lumen diameter, } \mu\text{m.} &= 63.3636 & (5-10) \\ &+ 0.2174 (\text{number of rings from pith}) \\ &- 42.7163 (\text{unextracted specific gravity}) \end{aligned}$$

Radial **tracheid diameters** in latewood from fast-grown wood (less than 6 rings per inch) were slightly larger (average 33.8 $\mu\text{m.}$) than those from slow-grown wood (avg. 33.0 $\mu\text{m.}$); those in corewood averaged 32.8 $\mu\text{m.}$, significantly less than those in middle wood (33.6 $\mu\text{m.}$) and in outer wood (33.8 $\mu\text{m.}$). They were not significantly related to specific gravity alone.

Stepwise regression analysis provided equations indicating that tracheid diameters in latewood decreased with increasing rings per inch and increased with increasing wood specific gravity and rings from the pith. Twenty-four percent of the variation was accounted for by number of rings from the pith and rings per inch. The following equation accounted for 29 percent of the variation, with standard error of 1.15 $\mu\text{m.}$:

$$\begin{aligned} \text{Latewood tracheid diameter, } \mu\text{m.} &= 34.9734 & (5-11) \\ &- 0.3083 (\text{rings per inch}) \\ &+ 0.0128 (\text{rings from pith}) (\text{unextracted specific gravity}) \\ &(\text{rings per inch}) \end{aligned}$$

Latewood tracheids having large radial diameters were characteristic of mature wood of slow growth. In contrast, narrow tracheids were found in corewood of fast growth.

Earlywood radial tracheid diameters varied significantly with wood specific gravity, averages being 56.8 $\mu\text{m.}$ and 53.1 $\mu\text{m.}$ for wood lower and higher than 0.49 specific gravity respectively. They also varied significantly with rings from pith from 52.8 $\mu\text{m.}$ for corewood to 56.7 for outerwood. They did not vary significantly with growth rate. The equation, including specific gravity and the interaction of specific gravity and rings from the pith, accounted for 47 percent of the variation with a standard error of 2.47 $\mu\text{m.}$ Diameters decreased with increasing specific gravity and increased with increasing numbers of rings from the pith (fig. 5-54).

$$\begin{aligned} \text{Earlywood tracheid diameter, } \mu\text{m.} &= 75.1196 & (5-12) \\ &- 48.8068 (\text{unextracted specific gravity}) \\ &+ 0.4673 (\text{rings from pith}) (\text{unextracted specific gravity}) \end{aligned}$$

These results indicated that earlywood tracheids having large radial diameters were associated with mature wood of low density, while narrow tracheids were characteristic of dense corewood.

Latewood tracheid **tangential wall thickness** was positively correlated with number of rings from the pith. When averaged over all growth rates and gravities, wall thickness increased from 9.4 $\mu\text{m.}$ for corewood (0-10 rings from the pith) to 9.9 $\mu\text{m.}$ for middle wood (rings 11-20) and averaged 10.0 $\mu\text{m.}$ for outer wood (rings 21-30). Stepwise regression analysis of the continuous variables provided the following equation which accounted for 21 percent of the variation with a standard error of 0.53 $\mu\text{m.}$:

$$\begin{aligned} \text{Latewood tracheid wall thickness, } \mu\text{m.} &= 9.3607 + 0.0081 \\ &(\text{number of rings from pith}) (\text{unextracted specific} \\ &\text{gravity}) (\text{rings per inch}) & (5-13) \end{aligned}$$

Earlywood tracheid wall thickness was unrelated to number of rings from the pith, wood specific gravity, and growth rate.

Data on variation in transverse cellular dimensions with height in the tree are meager. Studies of loblolly pine by Smith and Wilsie (1961) and Wheeler et al. (1966) showed little variation of either radial or tangential tracheid diameters with height in the tree when measurements are taken at a fixed number of rings from the pith (fig. 5-57).

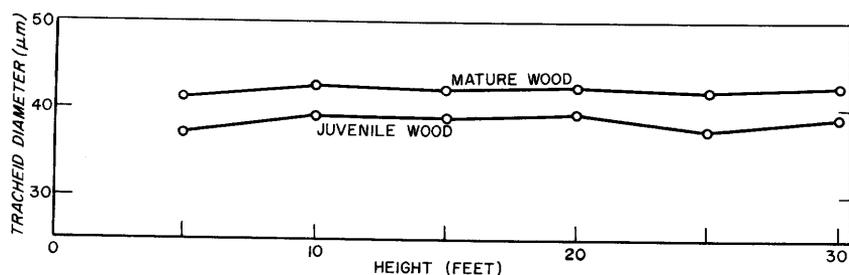


Figure 5-57.—Average tangential diameters of latewood tracheids in juvenile and mature wood of loblolly pine at different heights above ground. Each point is an average of 12 trees. Trees were from three stands averaging 20, 32, and 37 years of age. (Drawing after Wheeler et al. 1966.)

For spruce pine earlywood and latewood, Manwiller³ developed regression equations stating transverse cellular dimensions in terms of height of specimen above ground and distance of specimen from the pith. In developing his equations, which included squared terms and products of height and radial position, Manwiller was able to account for a higher percentage of the variation if distance from the pith was stated in inches rather than in number of annual rings. For numerical statement of the equations the reader is referred to Manwiller³. His data, based on a total of 1,296 sample points in 72 trees cut throughout the major range of the species, are summarized by the figures listed in the following tabulation.

Cell type and transverse dimensions	Figure number	R ²	Standard error of estimate µm.
Earlywood			
Thickness of tangential wall.....	5-58	0.17	0.51
Lumen tangential diameter.....	5-59	.39	2.54
Lumen radial diameter.....	5-59	.37	3.87
Tracheid tangential diameter.....	5-60	.51	2.38
Tracheid radial diameter.....	5-60	.40	3.97
Latewood			
Thickness of tangential wall.....	5-58	.27	.93
Lumen tangential diameter.....	5-59	.37	2.76
Lumen radial diameter.....	5-59	.09	2.40
Tracheid tangential diameter.....	5-60	.53	2.48
Tracheid radial diameter.....	5-60	.23	3.17

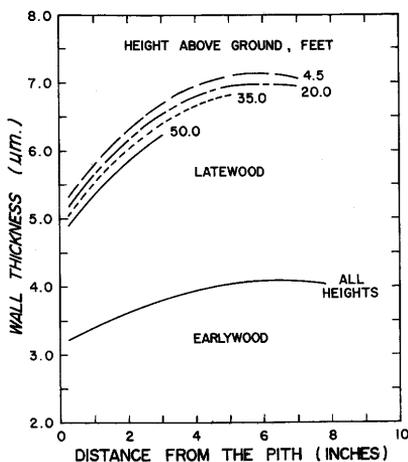


Figure 5-58.—Thickness of tangential cell wall in earlywood and latewood of spruce pine as related to distance from the pith and height above ground. (Drawing after Manwiller.³)

In assessing whole-tree averages for transverse dimensions it is useful to be able to predict tree averages from increment cores taken at breast height. For loblolly pine, Wheeler et al. (1966) concluded that if samples are taken at the 5-foot level, mature latewood tracheids provide the best indicator of tree average tangential tracheid diameter (i.e., $r = 0.973$); (fig. 5-61).

Correlation of transverse dimensions with other factors.—Some data are available that correlate tracheid tangential diameter with tracheid length.

Pine species and cell type	Reference	Correlation coefficient, r	Remarks
Loblolly (latewood)---	Wheeler et al. (1966)	0.717	Juvenile, all heights
Loblolly (latewood)---	-----do-----	.932	Mature, all heights
Loblolly (latewood)---	-----do-----	.856	
Loblolly (latewood)---	Posey (1964)	Not significant	Breast height
Spruce (earlywood)---	Manwiller ³	.567	All heights
Spruce (latewood)---	Manwiller ³	.563	All heights

Posey (1964) observed some additional correlations in loblolly latewood fibers sampled at breast height.

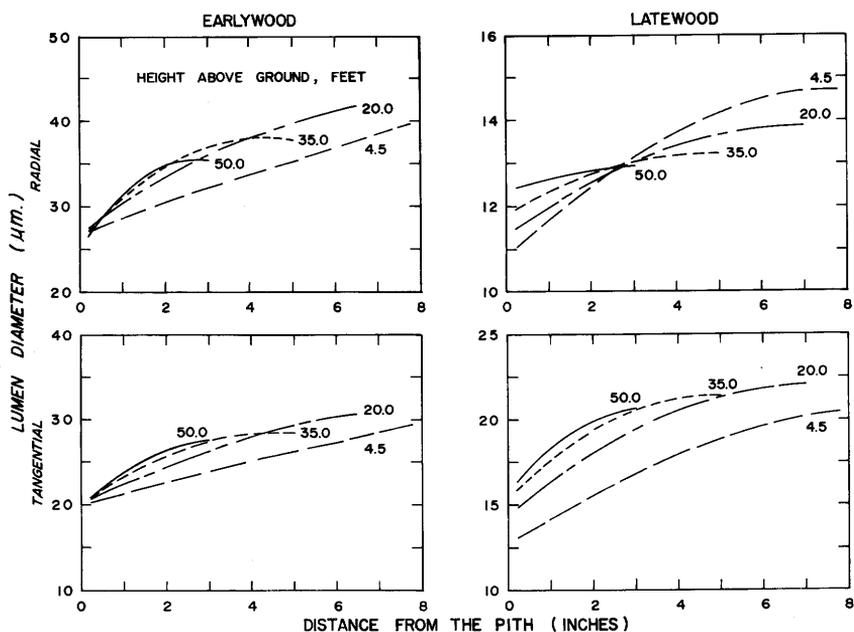


Figure 5-59.—Radial and tangential lumen diameters in earlywood and latewood of spruce pine as related to distance from the pith and height above the ground. (Drawing after Manwiller³.)

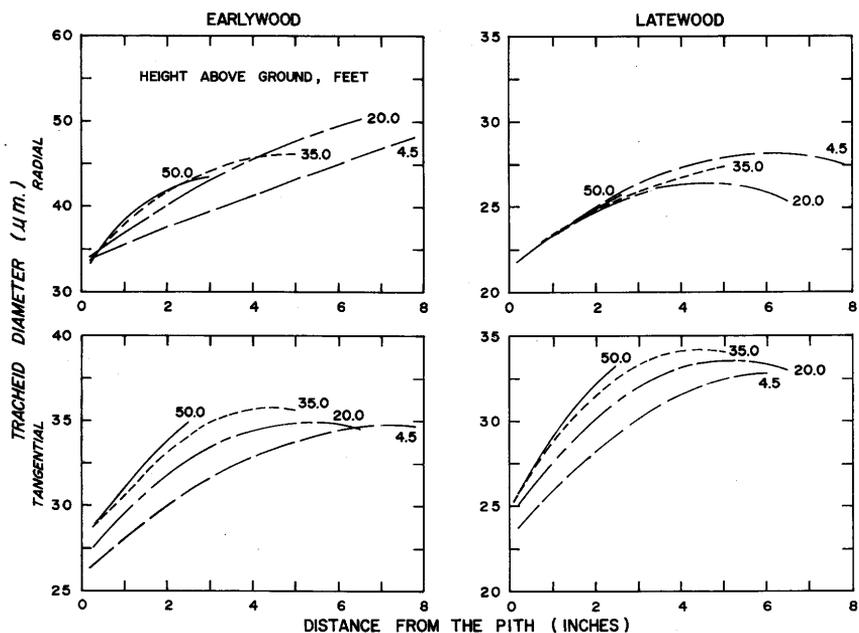


Figure 5-60.—Radial and tangential tracheid diameters in earlywood and latewood of spruce pine as related to distance from the pith and height above the ground. (Drawing after Manwiller³.)

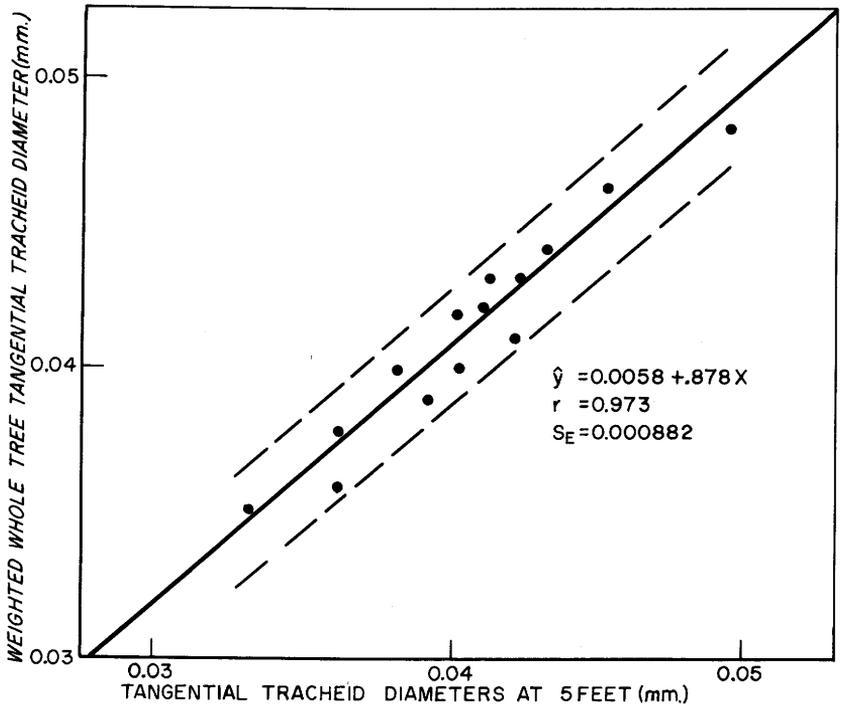


Figure 5-61.—Regression of loblolly whole-tree tracheid diameters on latewood tangential tracheid diameters in mature wood at the 5-foot level. Dashed lines show 95-percent confidence limits. (Drawing after Wheeler et al. 1966.)

Related factors	<i>r</i>
Tracheid length and radial double wall thickness.....	0.64
Tracheid length and tangential lumen diameter.....	-.54
Tangential lumen diameter and radial double wall thickness.....	-.80

Zobel et al. (1961) found correlations between specific gravity and transverse cellular dimensions of the outer wood portion of breast-height increment cores taken from 14 loblolly pines.

Related factors	<i>r</i>
Tracheid width and specific gravity.....	-0.58
Tracheid wall thickness and specific gravity.....	.56

Manwiller³ found the following correlations involving transverse cellular dimensions of spruce pine; only those values for *r* of 0.20 or higher are tabulated. Fibril angle was poorly correlated with transverse cellular dimensions.

Dimension and factor with which correlated	r	
	Earlywood	Latewood
Tracheid length		
Tracheid radial diameter -----	0.53	0.26
Tangential wall thickness -----	.22	.33
Lumen radial diameter -----	.50	.09
Lumen tangential diameter -----	.52	.38
Tracheid tangential diameter -----	.57	.56
Fibril angle -----	— .31	— .31
Number of rings to specimen -----		.46
Radial distance from pith to specimen -----		.48
Tracheid radial diameter		
Tangential wall thickness -----	.32	.73
Lumen radial diameter -----	.98	.80
Tracheid tangential diameter -----	.69	.42
Lumen tangential diameter -----	.61	
Specific gravity of earlywood -----	— .32	
Width of earlywood -----	.26	
Number of rings to specimen -----	.36	.31
Radial distance from pith to specimen -----	.51	.44
Ring width -----		.26
Percent latewood -----	— .21	
Tangential wall thickness		
Tracheid length -----	0.22	0.33
Tracheid radial diameter -----	.32	.73
Tracheid tangential diameter -----	.30	.37
Lumen tangential diameter -----		— .24
Specific gravity of earlywood (or latewood) -----	.75	.76
Number of rings to specimen -----	.27	.41
Radial distance from pith to specimen -----	.39	.44
Height above ground -----		— .29
Lumen radial diameter		
Tracheid length -----	.50	
Tracheid radial diameter -----	.98	.80
Tracheid tangential diameter -----	.65	.27
Lumen tangential diameter -----	.65	
Specific gravity of earlywood (or latewood) -----	— .51	— .41
Width of earlywood -----	.25	
Number of rings to specimen -----	.32	
Radial distance from pith to specimen -----	.45	.25
Ring width -----		.31
Percent latewood -----	— .24	
Tracheid tangential diameter		
Tracheid length -----	0.57	0.56
Fibril angle -----		— .21
Tracheid radial diameter -----	.69	.42
Tangential wall thickness -----	.29	.37
Lumen radial diameter -----	.65	.27
Lumen tangential diameter -----	.94	.81
Specific gravity of earlywood -----	— .35	
Width of earlywood -----	.27	
Number of rings to specimen -----	.41	.38

Dimension and factor with which correlated	r	
	Earlywood	Latewood
Radial distance from pith to specimen -----	.57	.57
Ring width -----	.26	.30
Lumen tangential diameter		
Tracheid length -----	.52	.38
Tracheid radial diameter -----	.61	
Tangential wall thickness -----		— .24
Lumen radial diameter -----	.65	
Tracheid tangential diameter -----	.94	.81
Specific gravity of earlywood (or latewood) ----	— .62	— .60
Width of earlywood -----	.25	
Number of rings to specimen -----	.34	
Radial distance from pith to specimen -----	.46	.32
Height above ground -----		.38
Ring width -----	.21	.27

WOOD SELECTIONS FOR TRACHEID DIMENSIONS

From table 5-4 it is observed that the six minor species have the shortest tracheids (about $3\frac{1}{2}$ mm.); loblolly, longleaf, shortleaf, and slash pines have the longest (about 4 mm.). Tree average tracheid lengths are shortest in young, slow-grown trees of high density, and longest in mature, fast-grown trees of low density. Within a tree, the shortest tracheids are in dense earlywood near the pith in lower portions of stems. The longest tracheids are from the outermost rings of mature latewood 7 to 20 feet above ground level.

With data available, it is not possible to state which species has tracheids of the largest (or smallest) diameter. Within trees, radial tracheid diameters are smallest in latewood of relatively low density near the pith of slow-grown trees. Radial diameters are largest in earlywood of low density most distant from the pith in fast-grown trees.

Tangential tracheid diameters are smallest in latewood of relatively high density near the pith in lower portions of stems from slow-grown trees. Tangential diameters are largest in low-density earlywood most distant from the pith in upper portions of stems from fast-grown trees.

With data available, it is not possible to state which of the ten species has the thickest and which the thinnest cell walls.

Within single trees, average tracheid wall thickness is less in corewood than in outer wood. In latewood—but not in earlywood—tangential walls are thinner than radial walls (table 5-5). Cell walls are thinnest in low-density earlywood near the pith of slow-grown trees. Cell walls are thickest in dense latewood most distant from the pith in lower portions of stems from fast-grown trees.

5-9 LITERATURE CITED

- Bailey, I. W., and Vestal, M. R.
1937. The orientation of cellulose in the secondary wall of tracheary cells. *J. Arnold Arboretum* 18: 185-195.
- Balatinez, J. J., and Kennedy, R. V.
1967. Maturation of ray parenchyma cells in pine. *Forest Prod. J.* 17(10): 57-64.
- Barefoot, A. C., Hitchings, R. G., and Ellwood, E. L.
1964. Wood characteristics and kraft paper properties of four selected loblolly pines. I. Effect of fiber morphology under identical cooking conditions. *TAPPI* 47: 343-356.
- Barefoot, A. C., Hitchings, R. G., Ellwood, E. L., and Wilson, E. H.
1970. The relationship between loblolly pine fiber morphology and kraft paper properties. *N.C. Agr. Exp. Sta. Tech. Bull.* 202, 88 pp.
- Bethel, J. S.
1941. The effect of position within the bole upon fiber length of loblolly pine (*Pinus taeda* L.). *J. Forest.* 39: 30-33.
- Bray, M. W., and Paul, B. H.
1934. Evaluation of southern pines for pulp production. III. Shortleaf pine (*Pinus echinata*). *Pap. Trade J.* 99(5): 38-41.
- Brown, C. L., and Klein, J.
1961. Observations on inheritance of wood specific gravity in seedling progeny of loblolly pine. *J. Forest.* 59: 898-899.
- Browning, B. L., editor.
1963. *The chemistry of wood.* 689 pp. N.Y.: Interscience Pub.
- Cole, D. E., Zobel, B. J., and Roberds, J. H.
1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. *TAPPI* 49: 161-166.
- Côté, W. A., Jr., and Day, A. C.
1969. Wood ultrastructure of the southern yellow pines. *State Univ. Coll. Forest. Syracuse Univ. Tech. Pub.* 95, 70 pp.
- Côté, W. A., Kutscha, N. P., and Timmell, T. E.
1968. Studies on compression wood. VIII. Formation of cavities in compression wood tracheids of *Abies balsamea* (L.) Mill. *Holzforchung* 22: 138-144.
- Côté, W. A., Jr., Simpson, B. W., and Timmell, T. E.
1966. Studies on compression wood. II. The chemical composition of wood and bark from normal and compression regions of fifteen species of gymnosperms. *Svensk Papperstidn.* 69(17): 547-558.
- Cronshaw, J.
1961. The nature of callitroid thickenings. *J. Inst. Wood Sci.* 8: 12-13.
- Dadswell, H. E., and Nicholls, J. W. P.
1959. Assessment of wood qualities for tree breeding. I. *CSIRO Div. Forest Prod. Tech. Pap.* 4, 16 pp.
- Demmon, E. L.
1936. Rate of formation of heartwood in southern pines. *J. Forest.* 34: 775-776.
- Dunning, C. E.
1968. Cell-wall morphology of longleaf pine latewood. *Wood Sci.* 1: 65-76.
- Dunning, C. E.
1969a. An examination of longleaf pine cell-wall morphology by electron microscopy of single fibers. (Abstr.) *TAPPI* 52: 504. Thesis available on microfilm at Univ. Microfilm, Inc., Ann Arbor, Mich.
- Dunning, C. E.
1969b. The structure of longleaf-pine latewood. I. Cell-wall morphology and the effect of alkaline extraction. *TAPPI* 52: 1326-1335.
- Echols, R. M.
1955. Linear relation of fibrillar angle to tracheid length, and genetic control of tracheid length in slash pine. *Trop. Woods* 102, pp. 11-22.
- Frey-Wyssling, A., and Bosshard, H. H.
1959. Cytology of the ray cells in sapwood and heartwood. *Holzforchung* 13: 129-136.

- Garlick, G.
1965. Structure and its relationship to utilization. *J. Inst. Wood Sci.* 3(14): 3-17.
- Gerry, E.
1915. Fiber measurement studies; length variations: where they occur and their relation to the strength and uses of wood. *Science* 41: 179.
- Gerry, E.
1916. Fiber measurement studies: a comparison of tracheid dimensions in longleaf pine and Douglas fir, with data on the strength and length, mean diameter and thickness of wall of the tracheids. *Science* 43: 360.
- Goggans, J. F.
1962. The correlation, variation, and inheritance of wood properties in loblolly pine (*Pinus taeda* L.). N.C. State Coll. Sch. Forest. Tech. Rep. 14, 155 pp.
- Goggans, J. F.
1964. Correlation and heritability of certain wood properties in loblolly pine *Pinus taeda* L.). *TAPPI* 47: 318-322.
- Goggans, J. F.
1965. Variation of tracheid width and wall thickness within and between trees of southern pine species. Proc., IUFRO Meeting, Vol. 2, Sect. 41, 10 pp. Melbourne.
- Grabow, R. H.
1923. Suitability of various American woods for pulp and paper making. *J. Forest.* 21: 462-474.
- Greene, J. T.
1966. Selection for tracheid length in loblolly pine (*Pinus taeda* L.). *Ga. Forest Res. Council. Rep.* 18, 30 pp.
- Greene, J. T., and Carmon, J. L.
1962. Variation of tracheid length in clonal lines of shortleaf pine. *Ga. Forest Res. Pap.* 13, 6 pp. *Ga. Forest Res. Council.*
- Hallock, H.
1968. Observations on form of juvenile core in loblolly pine. USDA Forest Serv. Res. Note FPL-0188, 6 pp. Forest Prod. Lab., Madison, Wis.
- Hamilton, J. R.
1963. Characteristics of tracheids produced in a gamma and gamma-neutron environment. *Forest Prod. J.* 13: 62-67.
- Harada, H., and Côté, W. A., Jr.
1967. Cell wall organization in the pit border region of softwood tracheids. *Holz-forschung* 21: 81-85.
- Harris, J. M.
1965. Enrichment of radiata pine heartwood with extractives. Proc., IUFRO Meeting, Vol. 1, Sect. 41, 13 pp. Melbourne.
- Hermans, P. H.
1949. Physics and chemistry of cellulose fibers. 534 pp. N.Y.: Elsevier Press.
- Hiller, C. H.
1954. Variation in fibril angles in slash pine. USDA Forest Serv. Forest Prod. Lab. Rep. 2003, 6 pp.
- Hiller, C. H.
1964a. Correlation of fibril angle with wall thickness of tracheids in summerwood of slash and loblolly pine. *TAPPI* 47: 125-128.
- Hiller, C. H.
1964b. Estimating size of the fibril angle in latewood tracheids of slash pine. *J. Forest.* 62: 249-251.
- Hiller, C. H., and Brown, R. S.
1967. Comparison of dimensions and fibril angles of loblolly pine tracheids formed in wet or dry growing seasons. *Amer. J. Bot.* 54: 453-460.
- Hobert, V. C.
1932. Number and distribution of resin passages in slash pine. *Forest Worker* 8(2): 8-9.
- Howard, E. T., and Manwiller, F. G.
1969. Anatomical characteristics of southern pine stemwood. *Wood Sci.* 2: 77-86.
- Isenberg, I. H.
1951. Pulpwoods of United States and Canada. Ed. 2, 187 pp. Appleton, Wis.: Institute of Paper Chemistry.
- Jackson, L. W. R.
1959. Loblolly pine tracheid length in relations to position in tree. *J. Forest.* 57: 366-367.
- Jackson, L. W. R., and Greene, J. T.
1958. Tracheid length variation and inheritance in slash and loblolly pine. *Forest Sci.* 4: 316-318.

- Jackson, L. W. R., and Morse, W. E.
1965a. Tracheid length variation in single rings of loblolly, slash, and shortleaf pines. *J. Forest.* 63: 110-112.
- Jackson, L. W. R., and Morse, W. E.
1965b. Variation in fibril angle of slash and loblolly pine. *GA. Forest Res. Council Res. Pap.* 34, 5 pp.
- Jackson, L. W. R., and Strickland, R. K.
1962. Geographic variation in tracheid length and wood density of loblolly pine. *Ga. Forest Res. Pap.* 8, 4 pp. *Ga. Forest Res. Council.*
- Jayme, G., and Azzola, F. K.
1964. Light and electron microscopy studies on beaten and unbeaten beech wood chemical and semi-chemical pulps. *Papier* 18: 549-563.
- Jurbergs, K. A.
1963. Determining fiber length, fibrillar angle, and springwood - summerwood ratio in slash pine. *Forest Sci.* 9: 181-187.
- Jurbergs, K. A.
1968. Transverse dimensions in slash pine tracheids. *TAPPI* 51: 389-394.
- Jutte, S. M., and Spit, B. J.
1963. The submicroscopic structure of bordered pits on the radial walls of tracheids in Parana pine, Kauri and European spruce. *Holzforschung* 17: 168-175.
- Kochler, A.
1932. The identification of longleaf pine timbers. *Southern Lumberman* 145(1841): 36-37.
- Kollmann, F. F. P., and Côté, W. A., Jr.
1968. Principles of wood science and technology. I. Solid wood. 592 pp. N.Y.: Springer-Verlag New York, Inc.
- Koo, K. H., and Hong, S. H.
1967. [Tracheid length and compression strength of *Pinus rigitaeda* and its backcross hybrid.] *Inst. Forest Genet. Res. Rep.* 5, pp. 85-90. Suwon, Korea.
- Kramer, P. R.
1957. Tracheid length variation in loblolly pine. *Tex. Forest Serv. Tech. Rep.* 10, 22 pp.
- MacKinney, A. L., and Chaiken, L. E.
1935. Heartwood in second-growth loblolly pine. *USDA Forest Serv. Appalachian Forest Exp. Sta. Tech. Note* 18, 3 pp.
- Manwiller, F. G.
1966. Southern pine cell walls and shrinkage. *South. Lumberman* 213(2656): 184-186.
- Martin, J. S.
1962. Kraft pulping of west Florida sand pine and longleaf pine. *USDA Forest Serv. Forest Prod. Lab. Rep.* 2248, 6 pp.
- Marts, R. O.
1955. Fluorescence microscopy for measuring fibril angles in pine tracheids. *Stain Technol.* 30: 243-248.
- McElwee, R. L., and Zobel, B. J.
1963. Some wood and growth characteristics of pond pine. *Forest Genet. Workshop Proc.* 1962: 19-25. Macon, Ga.
- McGinnes, E. A.
1963. Growth-quality evaluation of Missouri-grown shortleaf pine (*Pinus echinata* Mill.) *Mo. Agr. Exp. Sta. Res. Bull.* 841, 59 pp.
- McMillin, C. W.
1968. Morphological characteristics of loblolly pine wood as related to specific gravity, growth rate, and distance from the pith. *Wood Sci. and Technol.* 2: 166-176.
- Meier, H.
1955. [Cell-wall decomposition caused by wood-decaying fungi, and the submicroscopic structure of spruce tracheids and birch wood-fibers.] *Holz als Roh- und Werkstoff* 13: 323-338.
- Mergen, F., and Echols, R. M.
1955. Number and size of radial resin ducts in slash pine. *Science* 121: 306-307.
- Mork, E.
1928. The quality of spruce wood as it pertains to pulp wood for mechanical and chemical pulp. *Papier-fabrikant* 26(48): 741-747.
- Murmanis, L., and Sachs, I. B.
1969. Structure of pit border in *Pinus strobus* L. *Wood and Fiber* 1: 7-17.

- North Carolina State College.
1957. First annual report, N.C. State-industry cooperative, forest tree improvement program, 22 pp.
- North Carolina State University.
1969. The relationship between loblolly pine fiber morphology and kraft paper properties. 217 pp. Dep. Wood and Pap. Sci. Raleigh, N.C.: N.C. State Univ.
- Page, D. H.
1969. A method for determining the fibrillar angle in wood tracheids. *J. Microsc.* 90(2): 137-143.
- Panshin, A. J., DeZeeuw, C., and Brown, H. P.
1964. Textbook of wood technology. 643 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Paul, B. H.
1932a. The relation of certain forest conditions to the quality and value of second-growth loblolly pine lumber. *J. Forest.* 30: 4-21.
- Paul, B. H.
1932b. Variation in weight of slash pine wood and in its proportion of heartwood. *Forest Worker* 8(2): 6-7.
- Perem, E.
1958. The effect of compression wood on the mechanical properties of white spruce and red pine. *Forest Prod. J.* 8: 235-240.
- Pew, J. C., and Knechtges, R. G.
1939. Cross-section dimensions of fibers in relation to paper-making properties of loblolly pine. *South. Pulp and Pap. J.* 2(4): 7-9.
- Pillow, M. Y., and Bray, M. W.
1935. Properties and sulphate pulping characteristics of compression wood. *Pap. Trade J.* 101(26): 31-34.
- Pillow, M. Y., Chidester, G. H., and Bray, M. W.
1941. Effect of wood structure on properties of sulphate and sulphite pulps from loblolly pine. *Southern Pulp and Pap. J.* 4(7): 6-12.
- Pillow, M. Y., Terrell, B. Z., and Hiller, C. H.
1953. Patterns of variation in fibril angles in loblolly pine. USDA Forest Serv. Forest Prod. Lab. Rep. D1935, 31 pp.
- Posey, C. E.
1964. The effects of fertilization upon wood properties of loblolly pine (*Pinus taeda* L.). N.C. State Univ. Sch. Forest. Tech. Rep. 22, 62 pp.
- Preston, R. D.
1952. The molecular architecture of plant cell walls. 211 pp. London: Chapman and Hall, Ltd.
- Quirk, J. T., Kozlowski, T. T., and Blomquist, R. F.
1968. Contributions of end-wall and lumen bonding to strength of butt joints. USDA Forest Serv. Res. Note FPL-0179, 12 pp. Forest Prod. Lab., Madison, Wis.
- Roth, F.
1897. Notes on the structure of the wood of the five southern pines. In *The timber pines of the Southern United States*, pp. 133-157. USDA Div. Forest. Bull. 13.
- Sachs, I. B., Clark, I. T., and Pew, J. C.
1963. Investigation of lignin distribution in the cell wall of certain woods. *J. Polymer Sci. (Part C, Polymer Symp.)* 2: 203-212.
- Shelbourne, C. J. A., and Ritchie, K. S.
1968. Relationships between degree of compression wood development and specific gravity and tracheid characteristics in loblolly pine. *Holzforschung* 22: 185-190.
- Shepard, H. B., and Bailey, I. W.
1914. Some observations on the variation in length of coniferous fibers. *Soc. Amer. Forest. Proc.* 9: 522-527.
- Smith, D. M.
1968. Wood quality of loblolly pine after thinning. USDA Forest Serv. Res. Pap. FPL-89, 10 pp. Forest Prod. Lab., Madison, Wis.
- Smith, D. M., and Wilsie, M.
1961. Some anatomical responses of loblolly pine to soil-water deficiencies. *TAPPI* 44: 179-185.
- Snyder, E. B., and Hamaker, J. M.
1970. Specific gravity and fiber length of loblolly and spruce pines on the same site. USDA Forest Serv. Res. Note SO-103, 3 pp. South. Forest Exp. Sta., New Orleans, La.

- Strickland, R. K., and Goddard, R. E.
1966. Correlation studies of slash pine tracheid length. *Forest Sci.* 12: 54-62.
- Sullivan, J. D.
1968. Wood cellulose protofibrils. *TAPPI* 51: 501-507.
- Taras, M. A.
1965. Some wood properties of slash pine (*Pinus elliottii* Engelm.) and their relationship to age and height within the stem. Ph.D. Thesis. Univ. N.C. Raleigh. 157 pp.
- Thomas, R. J.
1967. The development and ultrastructure of the pits of two southern yellow pine species. D. F. Thesis. Duke Univ. Sch. Forest. Durham, N.C. 193 pp.
- Thomas, R. J.
1969. The ultrastructure of southern pine bordered pit membranes as revealed by specialized drying techniques. *Wood and Fiber* 1: 110-123.
- Thomas, R. J., and Nicholas, D. D.
1968. The ultrastructure of the pinoid pit in southern yellow pine. *TAPPI* 51: 84-88.
- Thomas, R. J., and Nicholas, D. D.
1969. The ultrastructure of the ray tracheid bordered pit membranes in southern pine. *TAPPI* 52: 2160-2163.
- Thor, E.
1964. Variation in Virginia pine. Part I. Natural variation in wood properties. *J. Forest.* 62: 258-262.
- Thor, E., and Bates, A. L.
1970. Relationships of some wood properties of shortleaf pine with radial growth and site factors. *TAPPI* 53: 290-294.
- USDA Forest Products Laboratory.
1953. Density, fiber length, and yields of pulp for various species of wood. USDA Forest Serv. Forest Prod. Lab. Tech. Note 191, 6 pp.
- USDA Forest Products Laboratory.
1954. Color test for differentiating heartwood and sapwood of certain oaks, pines, and Douglas-fir. USDA Forest Serv. Forest Prod. Lab. Tech. Note 253, 2 pp.
- Van Buijtenen, J. P.
1958. Experimental control of environmental factors and their effect upon some aspects of wood anatomy in loblolly pine. *TAPPI* 41: 175-178.
- Wahlenberg, W. G.
1946. Longleaf pine. 429 pp. Wash., D.C.: Charles Lathrop Pack Forest Found. in coop. with USDA Forest Serv.
- Wardrop, A. B.
1969. Fiber morphology and papermaking. *TAPPI* 52: 396-408.
- Wardrop, A. B., and Davies, G. W.
1961. Morphological factors relating to the penetration of liquids into wood. *Holzforschung* 15: 129-141.
- Wedel, K. W. von, Zobel, B. J., and Shelbourne, C. J. A.
1968. Prevalence and effect of knots in young loblolly pine. *Forest Prod. J.* 18(9): 97-103.
- Wheeler, E. Y., Zobel, B. R., and Weeks, D. L.
1966. Tracheid length and diameter variation in the bole of loblolly pine. *TAPPI* 49: 484-490.
- Whitesell, C. D., Zobel, B. J., and Roberts, J.
1966. Specific gravity and tracheid length of loblolly pine in Maryland and Delaware. N.C. State Univ. Sch. Forest. Tech. Rep. 29, 11 pp.
- Williams, R. F., and Hamilton, J. R.
1961. The effect of fertilization on four wood properties of slash pine. *J. Forest.* 59: 662-665.
- Zamski, E.
1970. The effect of microclimatic conditions on resin duct formation and resin secretion in *Pinus halepensis* Mill. *La-Yaaran* 20: 7-18.
- Zobel, B.
1961. Juvenility in wood production. In *Recent advances in botany*, pp. 1663-1665. Canada: Univ. Toronto Press.

- Zobel, B., Cole, D., and Stonecypher, R.
1963. Wood properties of clones of slash pine. Forest Genet. Workshop Proc. 1962: 32-39. South. Forest Tree Impr. Comm. and Soc. Amer. Forest. Tree Impr. Comm.
- Zobel, B. J., and Haight, A. E., Jr.
1962. Effect of bole straightness on compression wood of loblolly pine. N.C. State Coll. Sch. Forest. Tech. Rep. 15, 3 pp.
- Zobel, B., McElwee, R. L., and Browne, C.
1961. Interrelationship of wood properties of loblolly pine. Sixth South. Forest Tree Impr. Conf. Proc. 1961: 142-163.
- Zobel, B., Thorbjornsen, E., and Henson, F.
1960. Geographic, site and individual tree variation in wood properties of loblolly pine. *Silvae Genet.* 9: 149-158.
- Zobel, B. J., Webb, C., and Henson, F.
1959. Core or juvenile wood of loblolly and slash pine trees. *TAPPI* 42: 345-356.

6

Chemical constituents

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6

Chemical constituents

The principal component of the woody cell is a framework of the polymer **cellulose** in the form of microfibrils. Surrounding and permeating this framework is a matrix of non-cellulosic polymers—principally **hemicelluloses** and **lignins**. Lignin also occurs as an encrustant between cells and, to some extent, within cells. Cellulose and hemicelluloses are complex carbohydrates, called **polysaccharides**, made up of chains of sugar molecules. Together they constitute the **holocellulose**. Lignin is a phenolic polymer which also is comprised of carbon, hydrogen and oxygen.

In addition, wood has many components of low molecular weight (extractives) that are soluble in neutral organic solvents and water. It also contains small quantities of inorganic substances which remain as ash when wood is burned (table 6-1).

TABLE 6-1.—*Chemical composition of southern pine wood*

Components	Percent of oven-dry extractive-free wood				
	Loblolly	Longleaf	Slash	Shortleaf	Sand
Total carbohydrate ¹ -----	66-69	67-70	65-71	67-71	~70
Cellulose residues					
glucose-----	42-46	43-45	43-45	41-45	~43
Hemicellulose residues					
glucose-----	1-5	1-4	1-5		
mannose-----	10-11	~11	8-15		
xylose-----	~7	~7	~7		
arabinose-----	1-2	0.5-1.0	~1		
galactose-----	1.5-2.5	1-1.5	~1		
Lignin-----	27-30	27-30	26-30	27-29	~27
Uronic anhydride-----	1-3	1-3	2-4		
Acetyl-----	~1	~1	~1		
Ash-----	<0.5	<0.5	<0.5	~0.5	

¹ Based on sugar anhydride.

6-1 POLYSACCHARIDES¹

The chemical structures, amounts, and distribution of polysaccharides in woody cell walls have not yet been determined accurately. Difficulties are caused by physical and chemical heterogeneity of the cell wall and its components. Portions of a component may be less accessible to reagents because of their location within the cell wall structure. Many of the components vary in size and structure, and some are insoluble in any solvent (Timell 1957, 1965). Chemical reactions to dissolve some components often modify them and others as well. The degree of order varies from crystalline arrays inaccessible to many chemicals to partially and totally disordered materials.

A number of delignifying reactions (Browning 1967) have been used to isolate the polysaccharide or holocellulose fraction—a mixture of cellulose, glucomannans, xylans, and other polymers. This mixture is solvent-fractionated into cellulose and hemicelluloses. The cellulose, if uncontaminated, hydrolyzes to glucose. A number of solvents (Hamilton and Quimley 1957; Thompson et al. 1966b) separate the hemicelluloses into fractions which on hydrolysis yield from three to seven sugars. Each of these steps is subject to considerable error. Total holocellulose varies in amount and composition with reactants and reaction conditions; delignification is seldom complete, some cellulose is often lost in delignification, and some water-soluble hemicelluloses may be removed with the extractives. Similarly, the hemicelluloses cannot be completely separated from cellulose. Despite these problems, much has been learned about cell wall polysaccharides, and improving techniques are resolving some of the uncertainties.

The cell wall chemistry of wood has been reviewed in general by Browning (1963), Adams (1964), Zimmerman (1964), Timell (1965, 1967), Nikitin (1966), and Kollmann and Côté (1968).

STRUCTURAL ANALYSIS OF THE POLYSACCHARIDES

Selected techniques for isolating cell wall polysaccharides intact and analyzing them to determine the order and manner in which the monomer(s) are linked together have been reviewed by Whistler (1960), Ward and Morak (1962), and Timell (1967). Since the procedures are long and tedious, only limited analyses have been completed for the major southern pines. Overwhelming evidence, however, supports the conclusion that the taxonomically related southern pines all contain essentially the same polysaccharides (table 6-2) with only slight variations in amount (Aspinall 1959; Meier 1962; Timell 1965).

¹ With some editorial changes and additions, sec. 6-1 is taken from Wellons (1970) by permission of J. D. Wellons and the Forest Products Research Society.

TABLE 6-2.—*Cell wall polysaccharides in southern pine wood*

Name	Percent of extractive-free wood (approx.)	Sugar residues	Parts	Degree of polymerization (DP)	Solubility
Cellulose-----	43±2	β-D glucose	All	9000 ±1000	alkali metal complexes, e.g., cuprammonium hydroxide
Hemicelluloses					
Galactoglucomannan----	15±3	β-D mannose	3	>150	1
		β-D glucose	1		
		α-D galactose	0.1		
		O-acetyl	1.0 or 0.25		
Xylans-----	9±2	β-D xylose	10	>150	dilute alkali
		4-O-methyl D-glucuronic acid	1.5		
		L arabinose	0.75		
Arabinogalactan---	small ²	β-D galactose	11		
		L arabinose	1		water
Pectin-----	small	galacturonic acid			hot water
		galactose			
		arabinose			

¹ Galactoglucomannans with 0.1 part α-D galactose are soluble in alkali; those with 1.0 part α-D galactose are soluble in water.

² Usually removed with extractives.

Cellulose.—Cellulose is a linear homopolymer consisting of β-D glucose residues linked by 1-4 glycosidic bonds. Its chemical structure is shown in figure 6-1. Although most analyses can be made with cellulose isolated as a residue after exhaustive delignification and alkali extraction of whole wood, this residue is not usable for determining molecular weight (or degree of polymerization, DP). Consistent DP's (numbers of monomeric units in the polymer molecule) are obtained only by direct nitration of the cellulose in wood (Timell 1957; Goring and Timell 1962) to make it soluble in acetone. The highest DP's reported, 8,000-10,000, are essentially the same for all species. Isolated wood cellulose has a distribution of molecular sizes. Much of this polymolecularity must be an artifact due to the method of isolation because, as techniques have improved, larger molecular weights have been determined and their distribution has nar-

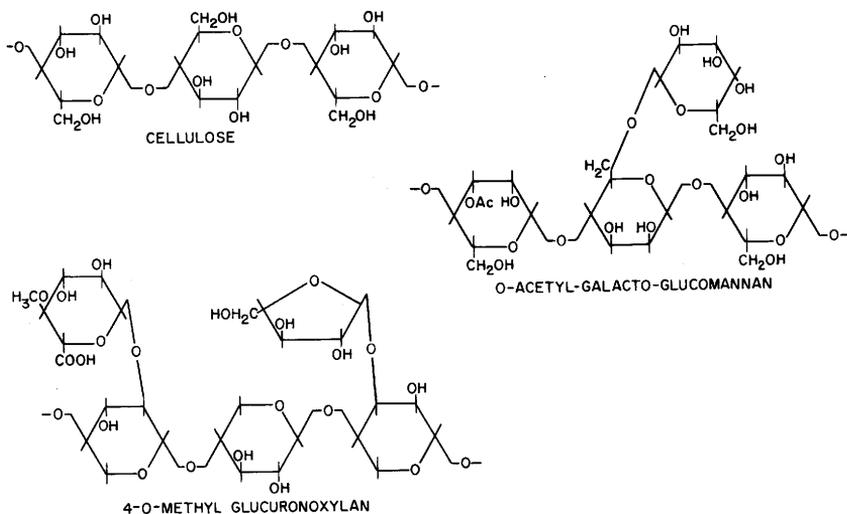


Figure 6-1.—Partial structure of major cell-wall polysaccharides in southern pine wood. (Drawing after Wellons 1970.)

rowed. To date, however, there is no conclusive evidence that cellulose in situ has a unique molecular weight, as do many biopolymers.

The exact organization of cellulose molecules into elementary fibrils and microfibrils is uncertain. Sullivan and Sachs (1966) have reviewed concepts of cellulose structure. The two models described in the following paragraphs have gained some acceptance. There are, however, other arrangements that appear to explain the observed properties of cellulose.

The Manley (1964) model for elementary fibril morphology may be summarized as follows: (1) the smallest structural unit is the cellulose molecule with a diameter of 35 A.; (2) the structure of the cellulose molecule is ribbon-like, and it is wound as a tight helix; (3) within the wound filament, the cellulose molecules have assumed a folded configuration and the elementary fibril contains no amorphous regions; (4) the elementary fibrils are arranged in a centered hexagonal array with a distance between centers of 40 A.

Mühlethaler (1965) has described a model with about 42 cellulose molecules aggregated into each elementary fibril (fig. 6-2). These elementary fibrils, approximately 35 A. units in diameter, are apparently highly crystalline along their entire length. Mühlethaler has observed that areas of low crystallinity are too small to be visible with the electron microscope and probably occur at random rather than at regular intervals.

Microfibrils are formed by the aggregation (or **fasciculation**) of two or more elementary fibrils (fig. 6-2). The width of microfibrils is therefore a multiple of about 35 A., i.e., 70 A., 105 A., 140 A., etc.; they are generally less than 300 A. in diameter.

Galactoglucomannans.—Polymers containing pyran rings of α -D galactose, β -D glucose, and β -D mannose have been isolated from southern

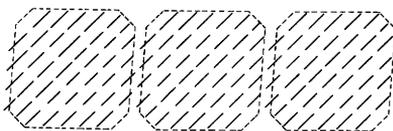


Figure 6-2.—Cross section showing fasciculation of three elementary fibrils into one microfibril. Each elementary fibril is comprised of 42 cellulose molecules. Elementary fibrils measure about 35 A. in diameter. (Drawing after Mühlethaler 1965.)

pine wood by a number of techniques. A small amount can be extracted with water from whole loblolly or slash pine wood (Timell 1965). More can be extracted from whole wood with alkali (Ball et al. 1956; Hamilton et al. 1960) and copper complex fractionation (Nelson 1960). But the last traces of galactoglucomannan may be very difficult to remove from pine cellulose preparations (Wise and Ratliff 1948). Some authors have reported significant amounts of galactose (Hamilton et al. 1960); others reported none (Vaughan et al. 1960) in the same wood. While some of the apparent discrepancies may reflect loss or modification of components during analysis, the variation in reported amounts of galactose and the results of electrophoretic analysis (Lewis and Smith 1957) support the conclusion that pine galactoglucomannans are quite heterogeneous.

The current belief is that southern pine wood contains principally two galactoglucomannans (Timell 1967). One has a ratio of galactopyranose to glucopyranose to mannopyranose of 1 to 1 to 3 and is water soluble. The other contains only 0.1 galactopyranose per 3 mannopyranose residues and is soluble only in strong alkali, particularly sodium and lithium hydroxide (Hamilton and Quimley 1957). Both contain O-acetyl groups (table 6-2). Traces of other galactoglucomannans may also be present.

The structure of southern pine galactoglucomannans is only partially known. Research by Anthis (1956) and others indicates that the backbone consists of β -D glucose and β -D mannose residues linked by 1-4 glycosidic bonds. Figure 6-1 is a statistical representation of the types of linkages occurring; it should not be interpreted as the specific structural formula of galactoglucomannan. Work by Hamilton et al. (1958a, 1960) on a slash/longleaf pine holocellulose mixture and by Jones and Painter (1957, 1959) on loblolly pine implies a random mixing of glucose and mannose in the backbone. The α -D galactose residues are end groups linked by 1-6 glycosidic bonds to the mannose residues. O-acetyl groups are attached to the second or third carbon of the mannose residues. Whether or not the polymer is branched is not definitely known, but branching is distinctly possible. Swenson et al. (1961) found that isolated slash pine galactoglucomannans had a DP of at least 150, and were polydisperse. The effect of isolation on the DP of these polymers is not known.

The galactoglucomannans are closely related in the cell wall to the cellulose microfibrils. They may be part of an oriented hemicellulosic sheath around microfibrils, or may be included with the cellulose (Preston 1960; Asunmaa 1966).

Xylans.—Polysaccharides consisting primarily of β -D xylose have been isolated with weak alkali from all southern pines studied. Jones and Painter (1950) and Ball et al. (1956) reported that loblolly pine xylans contain 4-O-methyl glucuronic acid but no L-arabinose. Hamilton et al. (1958b) reported both 4-O-methyl glucuronic acid and L-arabinose in a slash pine, longleaf pine mixture. Since the L-arabinose group would be lost readily during analysis, and since such species differences are otherwise unknown, southern pine xylans probably contain L-arabinose (Timell 1965). The ratio of sugars reported by Hamilton et al. (1958b) is 10 to 1.5 to 0.75 β -D xylose to 4-O-methyl α -D glucuronic acid to L-arabinose.

Figure 6-1 (bottom) describes the most likely arrangement of monomers in pine xylans (Hamilton et al. 1958b; Timell 1967). The backbone consists of β -D xylose linked by 1-4 glycosidic bonds. Some evidence supports xylan branches (Aspinall 1959). Furan rings of L-arabinose are linked as end groups to the xylose by 1-3 glycosidic bonds. Other xylose units have 4-O methyl α -D glucuronic acid residues attached to them by 1-2 glycosidic bonds. DP values of approximately 100 have been measured on southern pines. The evidence accumulated for other pines indicates that the DP may be greater than 150. Xylans appear to be associated with cellulose microfibrils but to a lesser degree than galactoglucomannans.

Arabinogalactan.—Small amounts of an arabinogalactan have been extracted with water from loblolly pine (Brasch et al. 1959) and longleaf pine (Foreman and Englis 1933) as well as from other southern pines. This material has not been completely analyzed, but appears to be composed of one L-arabinose to 11 β -D galactose; some glucuronic acid may also be present. It is a highly branched 1-3 glycosidically linked galactan with the L-arabinose predominantly occurring as end groups.

Trace polysaccharides.—Other polysaccharides are also present in pine wood in trace amounts (Zimmerman 1964). Starch, a polymer of α -D glucose, is often present in sapwood epithelial cells. Pectin, a complex polymer of galacturonic acid with some D-galactose and L-arabinose, is a principal component in the primary wall of developing tracheids. A galactan has been reported in compression wood of many conifers (Timell 1967), but has not yet been isolated in southern pine wood.

QUANTITATIVE ANALYSIS OF POLYSACCHARIDES

Since the above polymeric types cannot all be quantitatively isolated from wood, empirical methods must be used to approximate the amount of each. The cellulose fraction can be estimated by exhaustive extraction of the holocellulose with alkali (Browning 1967). Much mannan may be left adsorbed on southern pine cellulose (Wise and Ratliff 1948; Most

1957), but if the mannose residue is determined by sugar analysis, the true cellulose content can be determined by subtracting the glucomannan impurity.

Sugar determinations are required to obtain quantitative estimates of the noncellulosic polysaccharides. Detailed techniques are discussed by Whistler et al. (1962) and Browning (1967). Basically the total polysaccharide fraction is hydrolyzed to monomeric sugars which are separated and quantified. The amount of each polysaccharide is then estimated from its known sugar composition. While gross errors in such techniques can be revealed by comparing the sum of individual determinations with the whole, compensating errors may remain undetected.

Because of the extreme variability in extractives content, most results are reported on an extractive free basis.

Loblolly pine has been studied more thoroughly than any other southern pine. Sugar determinations have been reported by Wise and Ratliff (1947), Mitchell et al. (1956), Leopold (1961), Browning (1963), and Daleski (1965). Reasonable agreement between these authors and supporting information from Bray et al. (1939), Anderson (1946), Simmonds and Chidester (1960), Stamm and Sanders (1966), allow good estimates of the polysaccharides (summarized in table 6-1) after estimating and correcting for the bias in each analysis.

Longleaf pine has been studied less than loblolly. Thompson et al. (1966a b) and Spiegelberg (1966) reported complete sugar determinations, while Foreman and Englis (1933), Campbell and Bamford (1939), and Martin (1962) reported partial sugar determinations. Slash pine received similar attention from Wise and Ratliff (1947), Wise and Jahn (1952), Anthis (1956), Vaughan et al. (1960), Nelson (1961), and Fahey and Laundrie (1968). The results are essentially the same as for loblolly and longleaf pine (see table 6-1). A complete sugar analysis by Hamilton and Thompson (1959) for a mixture of loblolly and slash pine agreed with this. None of the remaining southern pines has been studied in sufficient detail to allow complete analysis (Bray and Paul 1934; Bray et al. 1939; Bray and Martin 1942; Keller et al. 1959; Martin 1962).

In an extensive study of southern pine Zobel et al. (1966) reported chlorite holocellulose (a modified procedure for large numbers of small samples) and alpha-cellulose (residue of holocellulose after 17.5-percent NaOH extraction) values for 5,627 trees of seven southern pines. They reported no significant species difference in either holocellulose or alpha-cellulose. Cole et al. (1966) reported the same for holocellulose and alpha-cellulose analyses of 50 trees each of loblolly, slash, and longleaf pine, all from the same mixed stand. Additionally, chemical and pulp yield studies (Chidester et al. 1938; USDA Forest Products Laboratory 1964) including all southern pines except spruce pine and Table-Mountain pine also indicate no specific difference in chemical composition. The values in table

6-1 are quite consistent with those reported for other pines (Nikitin 1966; Timell 1967).

POLYSACCHARIDE VARIATION WITHIN SPECIES

While average polysaccharide percentages determined from large numbers of southern pine trees do not vary significantly by species, individual samples may vary more than 7 percentage points from tree to tree (Zobel and McElwee 1958; Zobel et al. 1966). No geographic or site pattern accounts for this variation (Zobel et al. 1960). Manwiller² analyzed 72 spruce pine trees drawn from the major range of the species and observed no significant differences in polysaccharide percentages among trees grouped by age and growth rate.

Compression wood differs from normal wood in quantity of cell wall polysaccharides. Zobel et al. (1960) reported a strong negative correlation between alpha-cellulose yield and percentage of compression wood for loblolly pine. Pillow and Bray (1935) reported on the basis of one tree that loblolly pine alpha-cellulose from Cross and Bevan analysis varied from 46 percent in normal wood to 35 percent in compression wood. Lignin content was 28 and 35 percent respectively; no difference in total pentosans was observed. Alpha-cellulose in compression wood had substantially reduced DP, but this may have resulted from the more difficult and, hence, severe delignification. Curran (1936) reported similar findings. Seemingly the increase in lignin occurs at the expense of cellulose or galactoglucomannan or both. Low (1964) reported the same for other conifers.

Polysaccharide concentration is also related to position in the tree. Increases of 1 to 3 percentage points in polysaccharide content with increasing height in the tree have been reported, but these small differences cannot be attributed to a specific component (Zobel et al. 1959; Byrd 1964).

Changes across tree diameter are significant because of juvenile wood. Zobel and McElwee (1958) and Byrd et al. (1965) reported that loblolly pine outer wood contained 1 to 3 percent more holocellulose, and 4 to 7 percent more alpha-cellulose than corewood. Stamm and Sanders (1966) and Ritter and Fleck (1926) reported outer wood alpha-cellulose content to be 7 to 9 percentage points higher than that of corewood. All these determinations were on an extractive-free basis. In a recent study, McMillin (1968) reported much smaller differences, but the same trend in alpha-cellulose content was observed. The greater difference for alpha-cellulose than for holocellulose indicates that the cellulose or galactoglucomannan content of outer wood is greater than that of corewood.

² Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1, dated May 1, 1972.

Polysaccharides also vary within the growth increment. Latewood of loblolly pine has about 3 percent higher alpha-cellulose content than earlywood, and 2 percent lower lignin content (Ritter and Fleck 1926; Curran 1936; Watson and Hodder 1954; Stamm and Sanders 1966). As an isolated factor, growth rate or width of annual increment does not seem to influence polysaccharide content (McMillin 1968; Manwiller²).

McMillin (1968) determined polysaccharide content in loblolly pine wood segregated factorially by specific gravity, growth rate, and radial position in the tree. While he observed no major variation in holocellulose content, he concluded that higher alpha-cellulose contents were characteristic of slow-grown, dense, mature wood; lower contents were associated with low-density corewood. Conversely, higher hemicellulose contents were characteristic of low-density corewood, while lower contents were associated with mature wood of high density.

How the various polysaccharides are distributed within the cell wall is not well understood. Cellulose is known to aggregate in microfibrils. Similar arrangement of the other polysaccharides seems unlikely since they are not inclined to crystallize (Timell 1967). Wise and Ratliff (1948) concluded that mannans were more intimately associated with the cellulose than xylans because they could not be completely extracted from cellulose as could the xylans. Differences in solubility do not necessarily reflect the degree of association, however. Nelson (1961) found that extraction of the arabinoglucuronoxylan from slash pine holocellulose had little effect on residue crystallinity, whereas removal of the galactoglucomannan increased crystallinity. He suggested that the mannan was more or less included within the cellulose microfibrils and that the xylan was between them. His results could also mean that neither is within the microfibrils but that more mannan than xylan occurs in cell wall layers where cellulose predominates.

The concentration of polysaccharides in the different cell wall layers of southern pine wood has not been determined. The results of Meier (1961, 1962) for Scotch pine (*Pinus sylvestris* L.) may be applicable since it is not otherwise chemically different from the southern pines. Meier found that cellulose concentration was low in the primary wall, increased rapidly to a maximum in the S_2 layer of the secondary wall, then decreased to a minimum in the S_3 layer. Galactoglucomannan increased slightly from the S_1 to the S_3 layer. Thus, glucomannan and cellulose would be more abundant in cells with a thicker S_2 layer. The xylan was most heavily concentrated in the S_3 layer. Because of location, xylan should be the most readily extracted component if cellulose, mannan, and xylan were equally soluble.

Meier's analysis relates much of the variation in polysaccharide content to specific gravity. Stamm and Sanders (1966) were able to account for the variation in polysaccharides between earlywood and latewood of loblolly pine by estimating the additional amount of the S_2 layer on the

basis of specific gravity. The differences reported by Zobel and McElwee (1958) in the alpha-cellulose content of loblolly pine core and outerwood are consonant with their relative specific gravities. In his study of Louisiana loblolly pine, McMillin (1968) found that slow-grown outer wood of high density had a larger alpha-cellulose content than slow-grown outer wood of low density.

6-2 LIGNIN³

Intimately associated with the framework of cellulose fibrils within the woody cell wall is the lignin, which constitutes nearly a third of the wood substance. Lignin is a complex, water-resistant polyphenolic material with a high wet strength. Since cellulose and the other polysaccharide components of cell walls are flexible when wet, it is the lignin, binding together the 5 to 15 billion tracheids in each cubic foot, that accounts for most of the rigidity in the wood of living trees.

CHEMICAL NATURE OF CONIFEROUS LIGNINS

The nature of lignin as it exists in wood has been the subject of numerous studies conducted throughout the world. The voluminous literature has been extensively reviewed (Brauns 1952; Brauns and Brauns 1960; Sarkanen 1963; Schubert 1965; Marton 1966; Pearl 1967). While the studies have largely involved extracted spruce lignins, present indications are that the structure of pine lignins are quite similar (Sarkanen et al. 1967).

Lignin in wood has no precise repeating chemical structure, but has a series of relatively well defined chemical groupings. Coniferous lignins appear to be principally produced by a type of free radical polymerization of dehydrogenated coniferyl alcohol derivatives. Figure 6-3 shows a chemical structure which incorporates the various chemical groupings found in spruce native lignin. Lignin provides the wood fibers an effective three-dimensional binder and coating; its complexity of bonding makes it resistant to attack by decay organisms and enzymes.

Lignin makes up 25 to 30 percent of coniferous wood but only 15 to 25 percent of most hardwoods. Conifer lignin analyzes about 14 percent methoxyl, contrasting with hardwood lignin which analyzes about 21 percent. The conifer lignins appear to be a relatively homogeneous class of polymers, based essentially on a guaiacylpropane structure. Sarkanen et al. (1967) indicated that, although ultraviolet and infrared spectra show identical basic structure in conifer lignins, small species differences in ester groups may exist. Their data indicated that pine lignins contain acetyl ester groups in addition to the phenolic ester groups formed in other conifers.

³ With some editorial changes, sec. 6-2 is taken from Ball, F. J. Lignin in the cellular structure of southern pine wood and lignin products from southern pine. Presentation at a symposium, "Utilization of the southern pines", Alexandria, La., November 6-8, 1968.

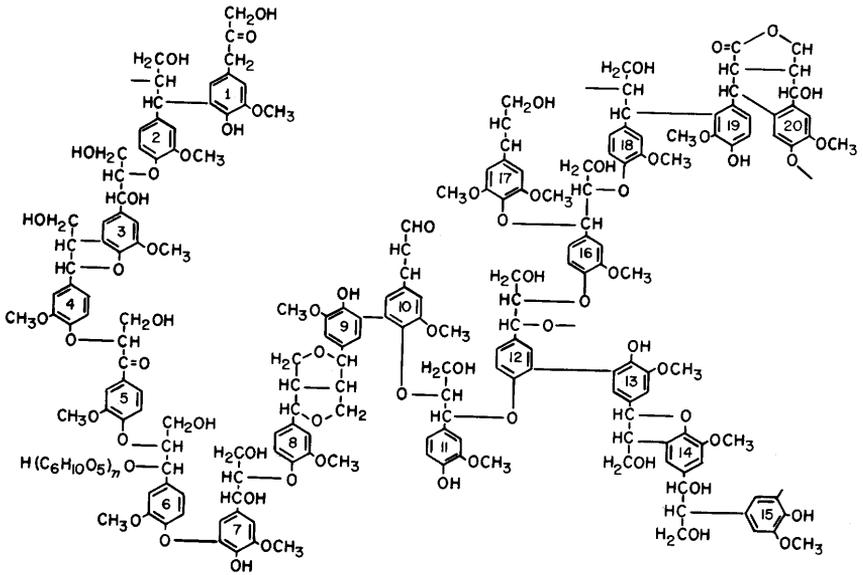


Figure 6-3.—Constitutional scheme of softwood lignin. (Drawing after Ball³.)

Aqueous alkaline cooking liquors used in pulping most southern pine wood promote lignin dissolution by splitting open the polyphenolic ether bonds in the lignin polymer. This reduces molecular size and permits solubilizing salt formation with the additional phenolic groups formed. Thus dissolved lignin produced in pulp manufacture is drastically modified from the native lignin in wood.

The chemical structure of the reproducible product obtained by acidifi-

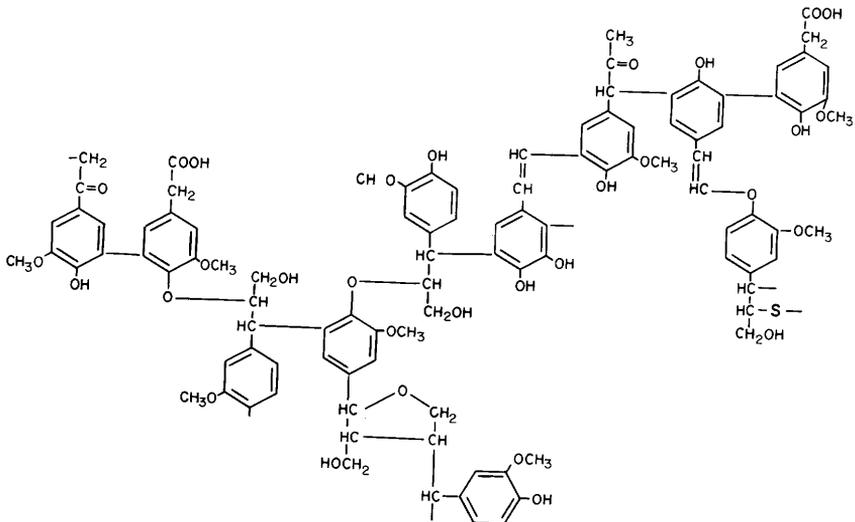


Figure 6-4.—Constitutional scheme of kraft pine lignin. (Drawing after Ball³.)

cation, coagulation and purification of spent pine cooking liquor is best represented by figure 6-4. Information pertinent to the chemical structure, reactivity and physical properties of this southern pine product, called "alkali lignin", "kraft lignin", or "sulfate lignin", has been presented by Marton and Adler (1963), Marton (1964, 1966), Marton et al. (1966), and Falkehag et al. (1966).

DISTRIBUTION OF LIGNIN IN CELL WALLS

Until recently it was generally believed that most of the lignin in woody plants was located in the middle lamella and primary wall, collectively known as the compound middle lamella. Ritter (1925) dissolved away the carbohydrate material of western white pine (*Pinus monticola* Dougl.) by acid hydrolysis, yet retained the cellular outline with very narrow walls. Over three-fourths of the lignin was retained and termed "middle lamella lignin", while the dispersed lignin removed was called "cell wall lignin". Bailey (1936a, b) isolated the middle lamella from Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) by microdissection, and it analyzed 71 percent lignin, 14 percent pentosans, and 4 percent cellulose. Lange's (1958) studies using microscopic ultraviolet absorption techniques clearly demonstrated that about 75 percent of the compound middle lamella in spruce was lignin, while across the broad secondary wall the content remained constant at about 15 percent lignin.

Improved microscopic techniques and interpretations now define the middle lamella with considerable precision and show it to be narrower than formerly thought. Berlyn and Mark (1965) calculated that less than half of the lignin content in coniferous wood is in the compound middle lamella. It now appears likely that in coniferous wood much more lignin is dispersed among the cell-wall microfibrils than is concentrated between cells to bind tracheids to each other.

Some evidence has been presented that in poplar (*Populus sp.*) trees microfibrils are formed during the day and that lignin is deposited on the new layer of microfibrils during the night (Necessary et al. 1965). Substantiation of these findings and extension to coniferous species would be of interest.

Lignin distribution in loblolly and slash pine has been graphically shown by electron microscopy of wood cross sections from which carbohydrates had been removed by hydrofluoric acid treatment (e.g., figs. 5-10D and 6-5). An even low lignin distribution has been pictured across the wide secondary wall with some increase possible at the lumen wall and dense concentrated lignin evident in the compound middle lamella region (Sachs et al. 1963). This same technique was used to demonstrate that tori in bordered pits of loblolly pine are primarily lignin (Sachs 1963).

GROSS DISTRIBUTION OF LIGNIN

Lignin content and distribution varies between: (1) tree species, (2)



Figure 6-5.—Lignin is seen to be uniformly distributed throughout the S_2 layer of the secondary wall in the tangential section of a ray tracheid treated with hydrofluoric acid. The highly lignified compound middle lamella is evident (slash pine, earlywood from heartwood). Scale mark shows 1 μm . (Photo from Côté and Day 1969.)

corewood and outer wood, (3) earlywood and latewood, and (4) normal and compression wood.

Little evidence is available to firmly establish any differences in the lignin content of the various southern pine species. Pines, like most other coniferous species, usually analyze 25 to 30 percent lignin. Lignin analyses of 26.4, 27.3, 27.9, and 28.1 percent were reported for samples of shortleaf, slash, longleaf, and loblolly pines respectively (Chidester et al. 1938), but in a breast-height sampling of 24 even-aged loblolly pines from one location lignin content ranged from 26.1 to 30.0 percent (Van Buijtenen et al. 1961). Since lignin content of a coniferous tree can be significantly affected by its compression wood content and age, well-controlled testing is required to determine if the average lignin content varies between species.

Manwiller², in a study of 72 spruce pine trees drawn from the major range of the species and stratified by both age (15, 30, and 45 years) and growth rate (more than 6 and less than 6 rings per inch at 1-foot level), generally found no significant differences in tree-average values of lignin content. The only exception was in the 45-year-old age class; slow-growing trees had a percentage point more lignin (28.4 percent) than fast-growing trees (27.5 percent).

McMillin's (1968) factorially designed study of wood from 50 loblolly pines cut in central Louisiana permitted him to study the independent relationships of density, growth rate, and radial position to lignin content. Lignin content did not vary with the primary factors of specific gravity, position, and growth rate; but an interaction of growth rate and rings from the pith proved significant. Corewood of slow growth had a higher lignin content (average 30.15 percent) than corewood of fast growth (29.22 percent). In contrast, outer wood of slow growth had less lignin (29.01 percent) than outer wood of fast growth (30.30 percent).

In a study of 130 uneven-aged loblolly pines in the Carolinas with average age of 31 years, Einspahr et al. (1964) observed that for breast-height increment cores, percentage of lignin was negatively correlated with tree age and was equal to $29.66 - 0.04$ (tree age in years).

Ritter and Fleck (1926), in a limited sample of loblolly pine found that earlywood contained more lignin than latewood and that sapwood had more lignin than heartwood, as follows:

Type of wood	Trees sampled	Lignin content	
		Earlywood	Latewood
	Number	--Percent--	
Sapwood.....	1	28.1	26.8
Heartwood.....	1	26.8	24.2
Wood 6 to 11 years old.....	34	29.8	28.8

Compression wood is characterized by an abnormally high lignin content. Bland (1958) found a reduced methoxyl content in lignin of compression wood of Monterey pine (*Pinus radiata* D. Don); southern pine lignin probably varies similarly.

Pine species	Lignin		Reference
	Normal wood	Compression wood	
	--Percent--		
Loblolly.....	28.3	35.2	Pillow and Bray (1935)
Pitch.....	28.1	37.6	Côté et al. (1966)
Radiata.....	24.2	34.4	Bland (1958)

Distribution of this high lignin content in compression wood differs from that in normal wood. In tamarack (*Larix laricina* (Du Roi) K. Koch),

Côté et al. (1968) found that only a small proportion of the total lignin in compression wood tracheids was present in the compound middle lamella. The thick S_1 layer was only slightly lignified. The outer portion of the S_2 layer consisted largely of lignin; the inner portion of the S_2 containing the helical cavities consisted of lamellae of cellulose microfibrils uniformly encrusted with lignin. It is likely that the southern pines have a similar lignin distribution in compression wood tracheids.

6-3 EXTRACTIVES ⁴

While cellulose, hemicellulose, and lignin usually comprise more than 90 percent of wood, a class of more soluble compounds, making up 3 to 9 percent, is important in wood utilization. Strictly speaking, these **extractives** in wood are soluble in neutral solvents and cold water.

Wood extractives comprise a heterogeneous group of compounds, present in low concentration. They include sugars, starches, fats, oils, resins, waxes, gums, pectins, tannins, dye stuffs, amino acids, proteins and organic acids. These materials occur in the cytoplasm within cell lumens, intercellularly (as in resin canals) and to some extent within the cell wall (Wangaard and Granados 1967, p. 272).

Of primary interest among extractives of southern pines are the resins and related materials comprising pine oleoresin. Natural oleoresin exudate from pine resin ducts contains about 66 percent resin acids, 25 percent turpentine, 7 percent nonvolatiles, and 2 percent water (Wise and Jahn 1952, p. 591). Most resin products and turpentines marketed in the United States are from the southern pines, produced from living longleaf or slash pine trees as gum naval stores, extracted from resinous stumpwood, or recovered from pulping processes (Anderson 1967). For process details, see chapter 28.

Extractives were, for many years, a major deterrent to use of the southern pines for mechanical pulp, but methods have been found to cope with the problem (see sec. 27-1). In the kraft process, extractives cause foaming and complicate recovery of the cooking chemicals.

The substantial amounts of extractives present in southern pine impart color as well as odor to the wood. A high extractive content markedly increases the unextracted specific gravity of southern pine wood (see sec. 7-3), but decreases the rate at which water can be driven off during kiln-drying. Finishing of southern pine lumber is sometimes made difficult by exudation of extractives.

Russia, in 1968, erected the first industrial plant producing steroids as a pulp byproduct (Nekrasova et al. 1968) thus putting into practice the findings of Hall and Gisvold (1936). Proteins isolated from the living

⁴ With some editorial changes and additions, sec. 6-3 is taken from Stanley (1969) by permission of R. G. Stanley and the Forest Products Research Society.

wood of slash pine have been applied to synthesize microlevels of cellulose and polyglucan-like polymers in a test tube (Stanley 1966; Stanley and Thomas 1968). It is probable that additional uses for extractives from southern pine wood will continue to be developed.

PHYSIOLOGICAL ROLE OF EXTRACTIVES

Biochemically, the extractives are often intermediate metabolites, chemical "building-blocks" of the tree. The photosynthesizing organs, the pine needles, are the primary site of synthesis and storage of the sugars and acids from which the extractives are derived.

Physiologically, extractives function in several roles. Sugars, starches, fats, and fatty acids may be food reserves; terpenes, resin acids, and phenols may function as protectants or detoxifying pools; sterols and other acid derivatives may function as hormones; extractive proteins are often enzymes, the cell substances which synthesize the complex cell wall polymers and cellulose (Buchanan 1963).

Extractive content varies with location in the tree. Accumulation of extractives in heartwood and resin ducts causes a maximum concentration in the base of older trees; resin in the sapwood, however, is least in the base of the tree and increases with height (Bishop and Marckworth 1933). Extractive content of needles is directly correlated with photosynthetic activity (Hillis 1962, p. 101).

Environment can modify sapwood extractive content. Bishop and Marckworth (1933) observed that high moisture content in wood and low temperature were correlated with low resin content in loblolly and slash pine. They noted that monthly patterns of percent resin extractives in sapwood were related primarily to environmental factors and tree metabolic activity. Factors that modify wood growth to increase the ratio of earlywood to latewood should increase tree average extractive content (Kurth 1933; Posey and Robinson 1969).

METHODS FOR EXTRACTIVE ANALYSIS

Methods of preparing wood extractives are reviewed by Browning (1967). Three widely used extraction treatments are:

- Ether or hot ethyl ether extracting of ground work for eight hours. This removes resins, fats, fatty acids, oils, and sterols.
- Alcohol-benzene extractives are obtained by extracting the ether extracted residue in a mixture of ethanol and benzene (ratio of 33:67 on volume basis) for 6 to 8 hours. This extraction removes essential oils, tannins, phlobaphenes (polymerized tannins), and some waxes, fats, and resins not soluble in ether.
- Water extraction, 48 hours at 23° C., removes cell lumen carbohydrates, salts, pectins, some flavones, pigments, and acids. Many wood components soluble in organic solvents are soluble in water.

For green loblolly pine wood, Max (1945b) has shown that the solvent strongly affects the amount of extractives removed; alcohol-benzene removes the greatest amount.

Since many extractives are soluble in more than one of these solvents, the amount removed varies with the order in which solvents are applied, as well as with temperature. Max (1945b) reported the following results for the extraction of green loblolly pine wood.

<u>Solvent</u>	<u>Extractives removed</u> <i>Percent of unextracted ovendry weight</i>
Alcohol-benzene -----	2.76
Ether -----	1.83
Hot water (on wood previously extracted with alcohol-benzene) -----	1.24
Ether (on wood previously steam-distilled) -----	1.35
Alcohol (on wood previously steam-distilled and extracted with ether) -----	.21

In reporting extractive analyses, prior treatment and source of the wood sample should be noted. If wood is seasoned prior to extraction, the extractives removed by alcohol-benzene or ether are reduced compared to the amount removable from green wood (Max 1945a).

<u>Solvent</u>	<u>Extractives removed (slash pine)</u>	
	<u>Green wood</u>	<u>Seasoned wood</u>
	<i>Percent of unextracted ovendry weight</i>	
Alcohol-benzene -----	3.0	2.1
Ether -----	2.3	1.4
Hot water (on wood previously extracted with alcohol-benzene) -----	.6	1.0
Ether (on wood previously steam-distilled) ---	1.1	.8
Alcohol (on wood previously steam-distilled and extracted with ether) -----	.2	.3

Seasoning also modifies composition of tall oils recovered. Oleoresins in seasoned woods are viscous; therefore seasoned wood is less sticky than green wood. Hillis (1962, p. 351) reported that unsaturated fatty acids in extractives decreased after wood was seasoned; total free fatty acids, however, increased during seasoning. The physical form in which wood is seasoned affects the change in percent extractives; aging chips 2 weeks is equivalent to aging log bolts 6 months (Hillis 1962, p. 433).

The TAPPI standard methods of analysis (T6m) recognize that neutral solvents do not always remove all extractives (TAPPI Forest Biology Subcommittee No. 2 1963). In fact, no single solvent removes all substances classified as extractives (Browning 1967, p. 76). Saponifiable extractives, i.e., those removed by 1 percent or 4 percent NaOH, are sometimes reported. Saponified extractives may be correlated with neutral

and water extractives or may be used to indicate percent of wood decay (TAPPI standard T4m). However, alkali treatment as well as hot water extraction degrades and removes certain hemicellulose and other wall components (Wise 1962).

VARIABILITY OF EXTRACTIVE QUANTITY AND COMPOSITION

Reviews of literature on wood extractives show that few southern pines have been characterized in any detail (Kitao and Sato 1965; Kollmann and Côté 1968, pp. 70-78). Wehmer (1929) listed extractive chemicals by species; he cited 20 references for longleaf pine and only one each for sand, pond, shortleaf, and spruce pine compared to 91 citations for scotch pine and 23 for stone pine (*Pinus pinaster*). Karrer (1958) reviewed the main additions made to southern pine extractive chemistry since Wehmer's compilation. Additions cited are largely the work of Mirov (1961) on pine turpentine, Erdtman (1959) on heartwood, and Hall and Gisvold (1935, 1936) on stem steroids.

Between-species variation.—Genetic variation exists between genera and between species. Extractive constituents have been used as key compounds in the chemical identification of some species (Alston and Turner 1963). However, within-tree variability is considerable; to date, no procedure has been devised whereby small dry sapwood specimens from the ten species of southern pine can be conclusively distinguished.

Taras and Saucier (1967) took breast-height samples from many trees throughout the range of the four major species and extracted them in alcohol and benzene for 16 hours, then in ethanol for 6 hours, and finally in hot water for 2 hours. Loblolly pine was the most variable, with an average breast-height extractive content of 6.50 percent and range from 1.13 to 11.87 percent. Species differences in extractive content were not significant.

Pines species	Average tree age	Trees sampled	Extractive content
	Years	Number	Percent of extracted oven-dry weight
Loblolly.....	48 ±	94	6.50
Longleaf.....	48 ±	143	7.36
Shortleaf.....	48 ±	140	6.72
Slash.....	30	123	5.85

Cole et al. (1966), however, found that longleaf pine had higher alcohol-benzene extractives content in breast height increment cores than

Pine species	Extractive content		
	Corewood	Mature wood	Weighted average
	-----Percent of extracted oven-dry weight-----		
Loblolly.....	3.1	2.7	2.7
Longleaf.....	13.6	2.4	3.5
Slash.....	5.0	1.8	2.1

loblolly and slash pines growing in the same mixed stand in Georgia. Trees were 10 to 11 inches in diameter and showed 16 to 21 rings at breast height. Fifty trees of each species were sampled.

With alcohol-benzene as the solvent, Kurth (1933) found the average extractive content of longleaf and shortleaf pine was 3.5 to 5.5 percent of the dry weight of wood. Rapidly growing trees had a higher extractive content than slowly growing trees.

Among the southern pines, spruce pine may have the least extractives. With alcohol-benzene as the solvent (TAPPI Standard Method T6 os-59), 72 trees drawn from throughout the species major range had extractives averaging only 2.7 percent of oven-dry weight (Manwiller²); trees were sampled from the 1-foot level to a 4-inch top in three age classes (15, 30, and 45 years).

Tables 6-3 through 6-6 show various breakdowns of extractive constituents by species; the reader is cautioned that the variation within species may be greater than the variation indicated between species.

The turpentines of all known pines have been systematically studied over the past 40 years by Mirov (1961, 1967). With the exception of pond pine, the turpentine of all southern pines contains a predominance of α - or β -pinene (table 6-4). This is true of turpentine made from steam-distilled wood as well as that from exuded oleoresin taken from living trees. The content of d- or l- α -pinene isomers are clues to differentiate the two morphologically similar species, longleaf and slash pine; the former occurs in the gum turpentine of longleaf pine, while the latter is present in gum turpentine from slash pine (Buchanan 1963, p. 318).

Heartwood and sapwood extractives also contain fats, fatty acids, organic acids and sugars. These compounds, now usually recovered from tall oils, have seldom been characterized in pine wood. Buchanan et al. (1959) analyzed and reviewed the fatty acids and benzene extractives in a few southern pines. Unsaturated free fatty acids in pine wood are oleic and linoleic; the most common saturated fatty acids are stearic and palmitic (Van Buijtenen et al. 1961).

TABLE 6-3.—*Ether soluble extractives in whole wood* (Rydholm 1965, p. 224)

Pine species	Extractive fraction recovered ¹	Composition of ether extractives			
		Resin acids	Free fatty acids	Fats	Unsaponifiables
		Percent			
Loblolly.....	2.5	44	11	38	6
Longleaf.....	2.0	36	6	49	9
Pond.....	2.8	40	18	28	14
Shortleaf.....	3.1	40	16	36	9
Slash.....	2.4	26	14	46	13
Virginia.....	2.5	44	9	40	7

¹ Percent of unextracted oven-dry weight.

TABLE 6-4.—*Composition of southern pine gum turpentine (Mirov 1961)*

Pine species	pinene ¹				l-limonene	other
	d- α	l- α	α	l- β		
	----- Percent -----					
Loblolly.....	71			22	1	sesquiterp. 1 m-chavicol 1 tails 5
Longleaf.....			d, dl = 64	31		
Pitch.....		65		20	10	
Pond.....	5				90	sesquiterp. 3 m-chavicol 1 l-camphene 10
Sand.....		10		75		
Shortleaf.....	85			11		
Slash (var. <i>densa</i> Little & Dorman).....			l, dl = 71	3-4		phellandrene 21 m-chavicol 3
Slash (var. <i>elliottii</i> Little & Dorman).....		61		34		tails 5
Spruce.....			d = 45	45	8	sesquiterp. 1
Table-Mountain.....			d = 70	20	9	
Virginia.....	98					

¹ d- α is α -pinene in the d form; d,dl is a mixture of α -pinenes containing both d and l forms with the predominant form being d (i.e., dextrorotary when measured optically).

TABLE 6-5.—*Fatty acids and related compounds in wood extractives of southern pine (Buchanan et al. 1959)*

Pine species	Free fatty acids	Combined fatty acids	Glycerol	Free sterols	Total sterols	Unsaponifiables
	----- Percent of unextracted oven-dry weight -----					
Shortleaf.....	0.54	0.92	0.086	0.013		0.28
Slash.....	.46	1.04	.099			.24
Longleaf.....	.11	1.00	.089	.006	0.061	.19
Pond.....	.50	.73	.039			.40
Loblolly.....	.30	.85	.057	.008	.062	.15
Virginia.....	.22	1.01	1	1	1	.17

¹ Data not given.

The levels of free fatty acids, glycerol (with which the acids combine to form fats), and sterols found in southern pines are listed in table 6-5. Tree to tree variation, because of genetic, seasonal, or other factors, may account for most of the observed differences.

TABLE 6-6.—*Heartwood extractives of southern pine soluble in ether or acetone* (Lindstedt and Misiorny 1951)¹

Pine species	Pino- sylvin	PSM ²	Pino- cembrin	Pino- banksin	Unknown compounds			
					D	E	F	G
Loblolly.....	+	+	+	+	+	-	-	-
Longleaf.....	³	+	+	+	+	+	+	+
Pond.....	+	+	+	+	⁴	⁴	⁴	⁴
Sand.....	+	+	+	+	-	-	-	-
Shortleaf.....	+	+	+	+	+	+	³	+
Slash.....	-	+	+	+	+	+	+	+
Spruce.....	+	+	+	+	+	+	+	+
Table-Mountain.....	+	+	+	+	+	+	+	+
Virginia.....	³	+	+	+	³	+	+	-

¹ (+) indicates presence and (-) absence of a constituent.

² Pinosylvin monomethyl ether.

³ Possible constituent.

⁴ Not investigated.

Many phenolic compounds—e.g., the flavones pinocembrin and pinobanksin, the stilbene pinosylvin monomethyl ether, and usually pinosylvin (table 6-6)—characterize the heartwood of southern pine. From table 6-6, the absence of pinosylvin in heartwood of slash pine is a clue to its identification; similarly the absence of unidentified phenolic compounds from loblolly and sand pine heartwood may be helpful in proving their identity (Erdtman 1959).

Between-tree variation.—Variations in extractive content are greater in mature southern pines than in young trees. In a mature, even-age stand of loblolly pine, alcohol-benzene extractive content in breast-height cores averaged 8.33 percent and varied from 5.2 to 14.3 percent with standard deviation of 2.37 (Van Buijtenen et al. 1961).

Alcohol-benzene extractive content of green increment cores taken at breast height from 20-year-old slash pines ranged from 1.8 to 10.0 percent compared to a range of 3.3 to 4.6 percent in 6-year-old slash pines from ten different locations in north Florida and south Georgia. No significant variation was attributed to geographic source (Goddard and Cole 1966).

Posey and Robinson (1969), in a 480-tree sample of Oklahoma shortleaf pine, found that variations in alcohol-benzene extractive content between trees within the 48 stands sampled, and between stands, was very large. They analyzed a pair of opposed breast-height cores from each tree (trees ranged from 20 to 165 years in age) and expressed results as a percent of extracted dry weight. In juvenile wood (rings 1 to 10) extractives ranged from 8 percent in 21-year-old trees to 33 percent in 76-year-old trees.

Posey and Robinson observed that in juvenile wood of shortleaf pine, concentration of extractives begins when trees are about 15 years old, and continues over the next 40 years to a maximum of approximately 30 percent of dry weight. High concentration of extractives is not initiated in annual rings 11 to 20 until about age 45 and in annual rings 21 to 30 until age 55.

They concluded that a pulpwood rotation of 30 years should minimize extractives in the stem at breast height at approximately 6.3 percent of dry weight, while a rotation of 65 years would maximize extractive content for the first 30 rings from the pith at about 19 percent of dry weight. Tree age was the most important factor affecting extractive content; age alone accounted for 45 percent of the variation between trees (fig. 6-6). Ten percent of the variation in extractives was related to differences in percentages of latewood; trees with a low percentage of latewood have relatively high extractive content. No relationship was found between number of resin canals and extractive content.

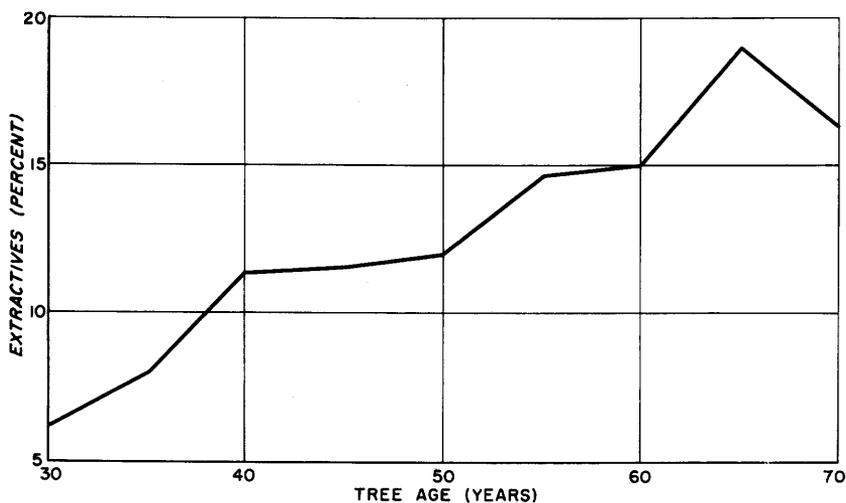


Figure 6-6.—Influence of age of tree on extractive content (percent of extracted dry weight) of annual rings 1 through 30 at breast height in shortleaf pine. (Drawing after Posey and Robinson 1969.)

In a study of 195 Virginia pine trees located in 13 stands in Kentucky and Tennessee, Thor (1964) found the average extractive content of breast height increment cores (10th to 25th growth rings) to be 4.8 percent of the unextracted oven-dry weight. Wood was first extracted with alcohol and benzene for 16 hours and then with alcohol for 6 hours. Extractive content varied significantly between stands and between trees. Rapid growth rate was associated with relatively high extractive content. Some breast height samples had extremely large amounts of extractives; usually these were from trees of high unextracted specific gravity, but this was not always the case. Of 13 trees with unextracted specific gravity of 0.58 or more, four had extractive contents of less than 4 percent; the rest

ranged from 7.6 percent to 20.6 percent. High extractive contents appeared to be associated with poor stands and low site index.

Manwiller² analyzed 72 spruce pine trees drawn from the major range of the species and observed no differences in tree-average values. Alcohol-benzene extractives content was assessed in accordance with TAPPI Standard Method T6 os-59 and expressed as a percentage of the oven-dry unextracted wood. The wood had been kiln-dried to 10- to 15-percent moisture content.

<u>Tree age class and growth rate</u> (rings per inch 1 foot above ground)	<u>Extractive content</u>
	<i>Percent</i>
15 years	
More than 6 -----	2.7
Less than 6 -----	2.7
30 years	
More than 6 -----	2.8
Less than 6 -----	2.5
45 years	
More than 6 -----	2.6
Less than 6 -----	2.8
Grand mean -----	2.7

Within-tree variation.—There are more extractives in earlywood than in latewood (Kurth 1933; Posey and Robinson 1969). Normal wood has higher extractive content than compression wood, and heartwood higher than sapwood (table 6-7).

Heartwood of older pine trees contains large concentrations of many other chemicals besides oleoresins (table 6-6), and varies less in extractive content than sapwood. The specific heartwood polyphenolics (table 6-6) are seldom found in pine sapwood (Lindstedt 1949). Catechin and leucocyanidins are present in sapwood but not in heartwood of slash pine; heartwood contains, in addition to the phenolics listed in table 6-6, a tannin polymer of leucocyanidin not found in the sapwood. Movement of constituents from sapwood to heartwood often appears to be accompanied by polymerization of the molecules.

Terpene components vary with height in the tree. The proportion of β -phellandrene and β -pinene in slash pine xylem extract increases, and of α -pinene decreases, with distance from the base of the stem (Fisher 1966). Myrcene occurs in cortex tissue of slash pine terminal buds, but is seldom found in stem gum. Highly significant differences in the proportion of α -pinene (29 versus 57 percent) are found between gum from branch cortex tissue and gums from stemwood (Fisher 1966). A shift of terpene components occurs in slash pine oleoresins at the wounded chip face, compared to the nonchipped side (Roberts 1968).

Ether extracts of phloem tissues from slash pine saplings and shoot tips show a greater variety of fatty acids and related alcohols and steroids than

TABLE 6-7.—*Distribution of extractives in loblolly pine wood* (Ritter and Fleck 1926; Wahlenberg 1960, p. 445)

Solvent ¹	Sapwood			Heartwood			
	Early-wood	Late-wood	Compression wood	Early-wood	Late-wood		
	----- Percent of unextracted oven-dry weight -----						
Alcohol-benzene....	4.2	2.5	2.7				
Ether.....	3.6	1.5	1.3				
Cold water.....				3.3	2.2	7.5	7.6
Hot water.....		2.0		3.5	3.0	7.2	6.4
Hot-1% NaOH....	14.0	12.9	12.6	11.1	11.0	18.1	21.2

¹ Solvents used alone, i.e., not in sequence or combination.

from wood (Hall and Gisvold 1935, 1936). Phloem extract contains a complex $C_{30}H_{56}O_3$ waxy alcohol, plus n-caproic, dodecosanic, palmitic, oleic, and linoleic acids, sitosterol and sterolin along with substantial levels of fats and sugars. Extractives from the growing tip contain, in addition to most of these phloem components, paraffins in the C_6 - C_9 range, melissic acid, melissyl alcohol, behenic acid and abietic acid. The unique components may serve as substrates for insects which prefer growing tips of particular pine species.

McMillin (1968) measured the extractive content of samples in his factorial study of wood from 50 Louisiana loblolly pines. The design enabled him to relate results to specific gravity, rate of growth, and radial position in the tree. Alcohol-benzene extractive content was assessed in accordance with TAPPI Standard Method T6 os-59 and expressed as a percentage of the oven-dry weight of unextracted wood. The wood had not been previously dried. His conclusions follow.

By variance analysis, extractive content differed with the level of each primary variable except growth rate. For all growth rates and distances from the pith, wood of low specific gravity (< 0.49) contained less extractive (avg. 5.27 percent) than wood of high specific gravity (avg. 6.88 percent).

Extractive content decreased with increasing distance from the pith. Corewood (rings 0 to 10) averaged 9.64 percent, middle wood (rings 11 to 20) 4.83 percent, and outer wood (rings 21 to 30) 3.77 percent.

For all study variables combined, the mean extractive content was 6.08 percent.

The interaction of specific gravity and position (UG x NR) was significant. In corewood, wood of high specific gravity had a greater extractive content (avg. 11.85 percent) than did wood of low gravity (avg. 7.42 percent). In middle and outer wood, no differences could be discerned.

The interaction of growth rate and position (RI x NR) proved significant. Corewood of slow growth had a higher extractive content (avg. 10.24 percent) than did corewood of fast growth (avg. 8.96 percent). No differences were found between slow- and fast-grown wood in middle or outer positions.

A three-factor interaction (UG x NR x RI) also proved significant. When specific gravity was low, extractive content did not differ between growth rates at any given position. In core or middle wood of high specific gravity, the extractive content was greater in slow- than in fast-grown wood. The extractive content of outer wood did not differ with either growth rate or density.

In corewood, the extractive content of dense wood was higher than that of low-density wood. In middle wood of fast growth, dense wood had less extractive content than wood of low specific gravity; but in middle wood of slow growth there was no significant difference in extractives between wood of low and high density. The interactions are shown in the following tabulation of extractive contents.

Specific gravity	Corewood		Middle wood		Outer wood	
	Fast	Slow	Fast	Slow	Fast	Slow
	----- <i>Percent of weight of unextracted oven-dry wood</i> -----					
Less than 0.49	7.00	7.84	5.71	4.20	3.21	3.69
More than 0.49	10.91	12.80	3.90	5.52	4.17	3.99
3.21 3.69 3.90 3.99 4.17 4.20 5.52 5.71 7.00 7.84 10.91 12.80						

Comparisons within interactions were by Duncan's multiple range test. If the figures are underscored by the same line, they are not significantly (0.05 level) different; otherwise, they are significantly different.

The following equation accounted for 82 percent of the variation in extractive content (standard error of 1.33 percent):

$$EC = \text{extractive content—percent of weight of unextracted oven-dry wood} + 53.1068(UG)$$

where:

EC = extractive content—percent of weight of unextracted oven-dry wood.

UG = unextracted chip specific gravity—green volume and oven-dry weight.

NR = number of rings from the pith.

As illustrated in figure 6-7, extractive content decreased with increasing number of rings from the pith for wood of both high and low density.

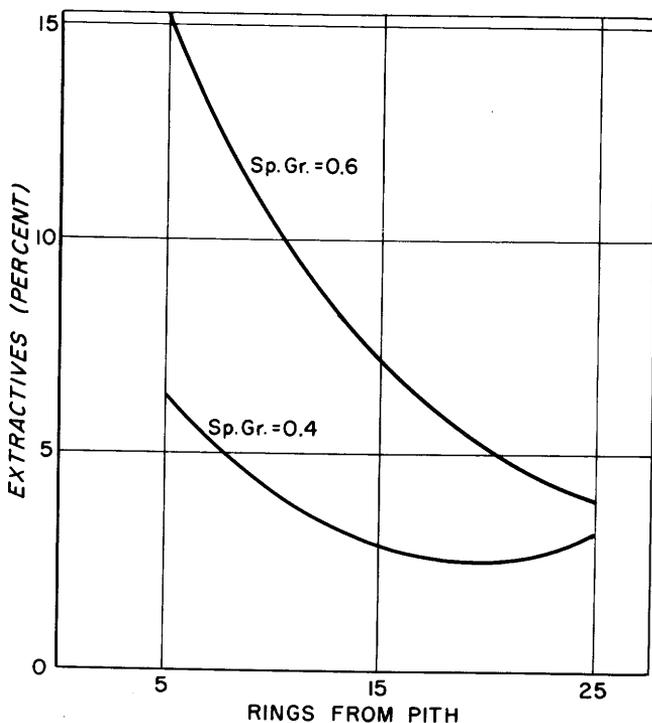


Figure 6-7.—Extractive content in loblolly pine as related to rings from pith and unextracted specific gravity. The graphed lines were obtained by substituting a range of values for the variable on the X-axis and fixing the remaining variables in the regression equation at their mean values. (Drawing after McMillin 1968.)

With wood of low density, the rate of decrease became minor after 15 rings from the pith. For a given number of rings from the pith, extractive content increased with increasing unextracted specific gravity; the rate of increase was reduced as rings from the pith increased.

Quijada (1967) determined alcohol-benzene extractives (as a percentage of extracted oven-dry weight) from 300 longleaf pine trees, 8 to 12 inches in diameter, from dry and moist sites in North Carolina. Samples were soaked in cold water, oven-dried and re-soaked before extraction. Corewood (rings 0 to 11) at all levels in the tree contained a much higher percentage of extractives (16.7 percent at breast height, 5.5 percent tree average) than did outer wood (3.5 and 2.8 percent, respectively). Extractives content of wood from moist sites was not significantly different from that from dry sites. Tree to tree variation was very high.

There was a very weak relationship between extractives percentages and specific gravity. The relationship between extractives values from increment cores and total tree values was significant, but too weak ($r = 0.352$) for estimating total tree extractives content.

Extractives content of corewood declined with height in the lower 15 or 20 feet of the tree, but tended to be constant in the upper bole. In

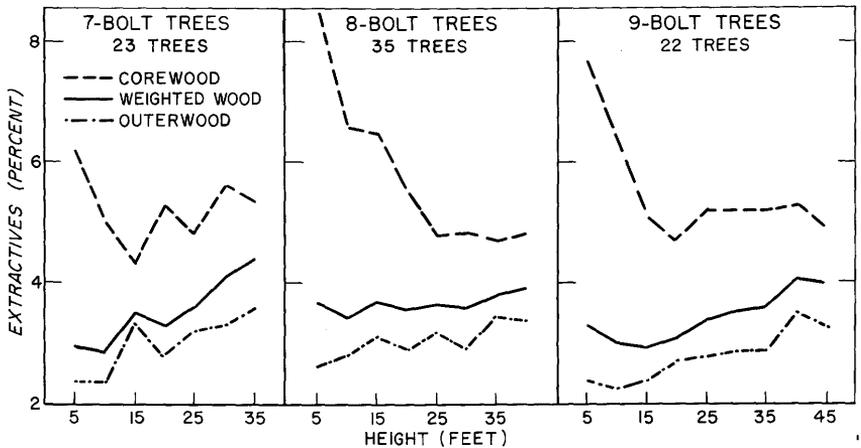


Figure 6-8.—Extractives content (percent of extracted oven-dry weight) in longleaf pine trees grouped by merchantable height. Bolts are 5 feet long; corewood includes rings 0 to 11. (Drawing after Quijada 1967.)

outer wood, extractives content tended to increase slightly with height in the tree (fig. 6-8). Quijada conjectured this may be related to frequency of knots.

6-4 INORGANIC COMPONENTS⁵

Inorganic components in wood comprise those non-constituent elements, largely metallic or alkaline earth, that are present as a natural result of growth. These elements are normally brought into the tree from the soil through the root system and sap stream; perhaps some also come from precipitation and particles. As elements of the biogenesis of wood formation, mineral components apparently play an important role in determining cell wall thickness, cell length, cell type distribution, sap transport, enzyme activity, and in the deposition of crystals and perhaps extractives. Precise pathways and modes of uptake, distribution, and deposition are largely unknown. Quantities rarely exceed 1/2-percent of dry weight of the wood.

Since specific elements are essential for plant growth, greatest scientific attention has been devoted to the occurrence of these inorganic nutrients in the soil, and to their cycling from soil to plant and return to soil through decay (Tamm 1964). Much research has been concerned with soil deficiencies and their correction through fertilization and special treatments (Goodall and Gregory 1947; Stoate 1950; Kramer and Kozlowski 1960; Behan 1968; Hacskaylo et al. 1969). Analysis of leaves, entire seed-

⁵ Information in sec. 6-4 is primarily from McMillin (1969, 1970), Manwiller², and from: Ellis, E. L. Mineral composition of southern pine wood: A review. presentation at a symposium, "Utilization of the southern pines", Alexandria, La., November 6-8, 1968.

lings, or small trees to indicate nutritional status is common practice. Use of wood to reflect available nutrient levels is unreported in the literature. Hamilton (1963) investigated tracheid length and wall thickness in slash and loblolly pines grown with supplemental nutrients. A functional classification of elements generally applicable to trees such as the southern pines has been proposed by Altman and Dittmer (1964).

Constituent: C, O, H, N, P, S, Cl

Essential:

Major—Ca, K, Mg, Na, Si

Minor—B, Mn, Fe, Mo, Cu, Zn

Commonly found: Ag, Al, Ba, Co, Cr, Ni, Pb, Rb, Sr, Ti

A wide variety of other elements has been reported; presumably their presence depends on site and geographic location as well as other factors (Wilcox 1940; Ellis 1959).

Work specific to the southern pines has been primarily concerned with minerals as they relate to tree growth. A partial list follows:

Fowells and Krauss (1959)

McDermott and Fletcher (1960)

Duncan and Epps (1958)

May et al. (1962)

Hamilton (1963)

Box and Linnartz (1967)

Brendenmuehl (1967)

Danielson and Davey (1967)

Grigsby (1967)

Maki and Terzi (1967)

Inorganic elements in wood—i.e., the mineral or ash contents—have not been the subject of extensive investigation. Even general information is sparse for most species (Ellis 1962, 1965; Young and Guinn 1966; Young and Carpenter 1967). However, some data specific to southern pine wood has been provided by McMillin (1969, 1970) and by Manwiller².

METHODS OF ANALYSIS FOR INORGANIC CONTENT

Limited knowledge of the factors affecting the variation in inorganic content of wood makes difficult the adequate sampling of tree populations for determinations of these elements. If, as seems probable, inorganic content varies seasonally, or if it increases with time after wood is formed, misleading information might result from the time or manner of sampling. Because these elements are present in wood only at very low levels—usually measured in parts per million (p.p.m.) of dry matter—great care in sampling is necessary to avoid contamination, and highly precise laboratory methods are essential.

Nondestructive analysis.—Bowen and Gibbens (1963) described a technique (activation analysis) that does not require prior ashing to make

determinations for manganese, copper, potassium, sodium, calcium, magnesium, vanadium, cobalt, zinc, and molybdenum content. Procedures and detection limits were given by Young and Guinn (1966).

Destructive analysis.—Relatively large samples and highly precise methods are necessary to achieve repeatability of destructive analyses. It is usual to first “dry” ash the sample in an electric muffle furnace or “wet” ash it with oxidizing acids. These procedures eliminate the majority of organic components and concentrate the inorganic components in the form of ash. Control of temperature is necessary to limit loss of the more volatile elements. Ellis (1959) has reviewed the methodology.

McMillin (1969), in his experiments with loblolly pine, obtained accurate and consistent results with minimum loss of volatile metallic compounds; his ashing procedure began with air-dried chips ground on a Wiley mill to pass a 40-mesh screen.

Approximately 1 g. of the resulting meal (ovendry basis) was transferred to a clean, tared crucible. The crucible and meal were dried for 12 hours at 105° C., and the ovendry weight of meal was then determined to the nearest 0.01 mg. Five ml. of concentrated nitric acid were pipetted into the crucible in 1-ml. steps and the sample allowed to nitrate to dryness on a hotplate held at a temperature sufficiently low to prevent splatter.

The resulting partially decomposed ash was placed in a muffle furnace at room temperature. The temperature was slowly increased over a ½-hour period to 475° C. and maintained for 6 hours. After the crucible and ash had cooled for 1 hour in a desiccator containing phosphorus pentoxide, the ovendry weight of ash was determined to the nearest 0.01 mg. Ash content was expressed as a percentage of the ovendry weight of wood.

To determine mineral content, the ash was dissolved in 100 ml. of 0.3 normal nitric acid containing 1,500 p.p.m. strontium ion. The quantity of each metallic element in ovendry wood (p.p.m.) was determined from the solution by use of an atomic absorption spectrophotometer. The elements considered were manganese (Mn), calcium (Ca), sodium (Na), magnesium (Mg), iron (Fe), and potassium (K). Phosphorus (P) content was determined by colorimetry.

To avoid loss of the more volatile elements, a low-temperature plasma technique has been used to determine the ash content of a limited sample of loblolly pine from Virginia (Zicherman 1970). In this technique, wood—chipped so that it will pass a 40-mesh screen—is placed in a glass reaction tube into which diatomic oxygen is introduced at low pressure. The tube is then heated by a surrounding induction coil so that a portion of the diatomic oxygen becomes ionized; the ionized oxygen reacts with carbon present in wood to convert it to CO or CO₂ and with metals present to form oxides. By this method Zicherman ashed 2.5-gram specimens of wood in about 25 hours and found the ash content to be 0.335 percent; matched specimens ashed in a muffle furnace yielded a significantly lower percentage (0.250 percent). Zicherman found that wood ashed by the

low-temperature plasma technique yielded significantly higher percentages of calcium, potassium, zinc, and copper than wood ashed in a muffle furnace; contents of magnesium and manganese, however, were not different for wood ashed by the two methods.

VARIABILITY IN ASH AND MINERAL CONTENT

No data are at hand to document differences among the 10 species of southern pine.

Within-species variability.—Manwiller², in a study of 72 spruce pines taken from throughout the major range, observed substantial variation in tree-average values. He used McMillin's (1969) ashing procedure. Each value tabulated below is a 12-tree average.

<u>Tree age class and growth rate</u> (rings per inch 1 foot above ground)	<u>Tree average</u> <u>ash content</u>
	<i>Percent of oven-dry weight</i>
15 years	
More than 6 -----	0.46
Less than 6 -----	.52
30 years	
More than 6 -----	.51
Less than 6 -----	.39
45 years	
More than 6 -----	.43
Less than 6 -----	.43

Since variability among trees was great, the foregoing averages proved not significantly different; nor did ash content vary significantly with latitude and longitude.

Within-tree variability.—Young and Guinn (1966) examined total tree nutrient content for seven species in Maine subdivided with respect to roots, merchantable and unmerchantable bole, branches, leaves, and bark. Mineral components were highest in leaves (3 to 8 percent ash), intermediate in bark (2 to 6 percent ash; high in calcium, magnesium, silicon), and lowest in wood (less than 1 percent ash).

Orman and Will (1960) found that heartwood of Monterey pine had a higher level of calcium than sapwood. In contrast, nitrogen, phosphorus, and potassium levels were highest in outer sapwood and in the heartwood transition zone near the top of the tree. The transition zone between sapwood and heartwood regularly showed high levels of these three elements. They concluded that N, P, and K were required for metabolic activity to convert sapwood to heartwood.

Metz and Wells (1965) measured the nutrient elements in above-ground parts of 10 loblolly pines. The trees, cut in South Carolina, ranged from 7 to 21 years of age, 3 to 7 inches in base diameter, and 8 to 46 feet high. Of the five elements studied, nitrogen was present in the greatest percentage in all parts of the tree, followed in order by potassium, calcium,

magnesium, and phosphorus. An exception occurred in the branches, where the percentage of calcium exceeded that of potassium.

Element	Average content			
	Needles	Stembark	Branches	Stemwood
	----- <i>Percent of dry weight</i> -----			
Nitrogen.....	1.016	0.421	0.324	0.138
Potassium.....	.431	.315	.186	.102
Calcium.....	.287	.214	.239	.064
Magnesium.....	.123	.089	.062	.026
Phosphorus.....	.099	.063	.043	.020

The needles had the greatest percentage of all five elements, followed by stembark, branches, and stemwood. Again, the only exception was the calcium content of the branches—it was higher than that of the bark. Needles had an ash content of over 2 percent, stemwood about one-half percent.

McMillian (1969) measured the ash and mineral content of wood removed from the stems of 50 loblolly pine trees cut during August in central Louisiana. Logs analyzed showed at least 40 rings. In his study, wood was stratified into classes of high and low density (more or less than 0.49), slow and fast growth (more or less than 6 rings per inch), and by radial position (corewood rings 0 to 10; middle wood, rings 11 to 20; and outer wood, rings 21 to 30), as well as by cell type (earlywood and latewood). This factorial design permitted isolation of the independent relationship of each factor—a characterization quite distinct from studying the varia-

TABLE 6-8.—*Relation of variables to loblolly pine ash content*¹
(McMillin 1969)

Factor	Ash content
	<i>Percent</i>
Unextracted wood specific gravity	
Less than 0.49 (average 0.45)	0.407
More than 0.49 (average 0.53) .....	.412
Radial position in tree	*
0 to 10 rings from pith (core) .....	.423
11 to 20 rings from pith (middle) .....	.425
21 to 30 rings from pith (outer) .....	.381
Rings per inch	
Less than 6 (average 5.1) .....	.399
More than 6 (average 9.3) .....	.420
Cell type	*
Early wood .....	.430
Latewood .....	.389
Grand mean	0.410

¹ All factors were tested at the 0.05 level; values in each group immediately below an asterisk differ significantly.

tion in stems. Ashing procedure was described above in the paragraphs on methods.

Ash content ranged from 0.342 to 0.548 percent in earlywood and from 0.282 to 0.478 percent in latewood. Table 6-8 lists mean ash contents according to unextracted wood specific gravity, number of rings from the pith, rings per inch of growth rate, and cell type. By variance analysis, ash contents differed significantly with radial position and with cell type but not with growth rate or specific gravity.

For all specific gravities, numbers of rings from the pith, and growth rates, the ash content of earlywood was significantly higher (0.430 percent) than the ash content of latewood (0.389 percent).

For all specific gravities, growth rates, and cell types, ash averaged 0.424 for core and middle wood, significantly higher than the average of 0.381 for outer wood.

While ash content of latewood did not vary with radial position (or growth rate), that of earlywood was lowest in outerwood (0.37 percent compared to about 0.46 in core and middle wood). Figure 6-9 relates earlywood ash content to radial position and growth rate as expressed by the regression equation:

$$A_{ew} = 0.45013 - 0.00028(NR)^2 + 0.00059(NR)(RI) \quad (6-2)$$

where:

A_{ew} = earlywood ash content in percent

NR = number of rings from the pith

RI = rings per inch of growth rate

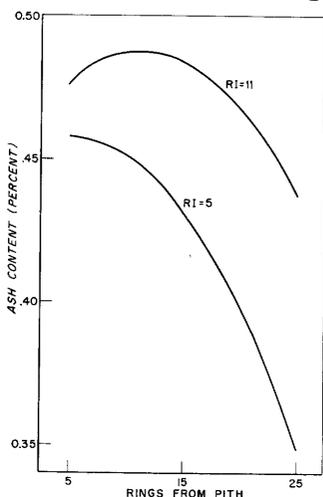


Figure 6-9.—Earlywood ash content as related to number of rings from the pith and rings per inch (RI) of growth rate. (Drawing after McMillin 1969.)

The equation accounted for 56 percent of the total variation in ash; the standard error of the estimate was 0.040 percent.

McMillin (1970) determined the content of certain elements (Mn, Ca, Na, Mg, Fe, K, and P) in the loblolly pine ash from his study reported in 1969. The procedure for metals determination was described in the paragraphs on methods. Table 6-9 summarizes his results.

TABLE 6-9.—Relation of some variables to loblolly pine mineral constituents (McMillin 1970)¹

Factor	Earlywood							Latewood						
	Mn	Ca	Na	Mg	Fe	K	P	Mn	Ca	Na	Mg	Fe	K	P
	-----P.p.m.-----													
Unextracted chip specific gravity			*							*				
Less than 0.49 (average 0.449).....	112	1,155	256	311	68	125	44	95	889	197	250	56	104	31
More than 0.49 (average 0.529).....	129	1,127	204	341	75	108	37	109	881	162	230	56	92	25
Radial position	*	*		*	*			*	*	*	*	*	*	*
0 to 10 rings from pith (core).....	134	1,267	245	398	65	148	32	117	980	211	317	46	133	22
11 to 20 rings from pith (middle)....	125	1,160	232	299	65	108	44	106	898	168	200	49	81	32
21 to 30 rings from pith (outer)....	103	997	214	280	85	93	45	84	778	162	205	73	80	31
Growth rate in rings per inch		*							*					
Less than 6 (average 5.10).....	114	1,088	225	286	67	132	41	96	841	170	251	56	105	29
More than 6 (average 9.26).....	127	1,194	236	365	75	101	39	108	929	190	229	56	91	28
Grand mean.....	121	1,141	230	326	72	116	40	102	885	180	240	56	98	28

¹ All factors were tested at the 0.05 level; values in each group immediately below an asterisk differ significantly.

Content of each of the elements studied was higher in earlywood than in latewood. This was true for each of the density, position and rate of growth groupings, as well as for the average of all determinations.

Phosphorus was the only element studied whose concentration did not vary with any of the study variables except cell type. Only sodium varied significantly with wood specific gravity, its concentration being greater in wood averaging less than 0.49 than in denser wood, both in earlywood and latewood. Only calcium varied significantly with growth rate, being more abundant in slow-grown wood (more than 6 rings per inch); differences were in the same direction, and significant, in both earlywood and latewood.

In latewood significant differences in the abundance of all study elements except phosphorus were related to radial position. In earlywood, differences were significant only for manganese, calcium, magnesium, and iron. Except for iron, concentration of minerals with significant differences was highest in corewood; highest concentration of iron was in outer wood.

Regression analyses developed equations expressing relations between significant wood variables and abundance of each of the elements studied.

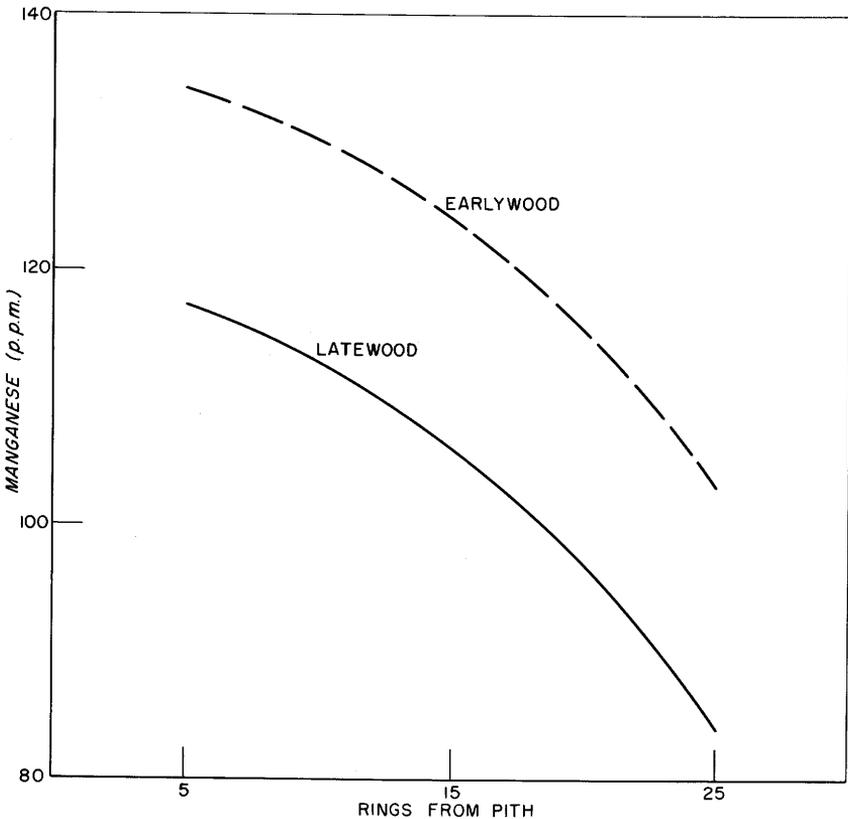


Figure 6-10.—Manganese content of loblolly pine earlywood (dashed line) and latewood (solid line), as related to number of rings from the pith. (Drawing after McMillin 1970.)

TABLE 6-10.—Equations expressing relation of significant factors to content of specific minerals in loblolly pine wood (after McMillin 1970)

Equation number	Dependent variable	Constant	Variable A		Variable B		Variation accounted for	Standard error
			Coefficient	Symbol ¹	Coefficient	Symbol ¹		
6-3	Earlywood manganese content, p.p.m.	135.750	-0.052	(NR) ²	-----	-----	Percent 29	P.p.m. 21
6-4	Latewood manganese content, p.p.m.	118.133	-0.055	(NR) ²	-----	-----	34	20
6-5	Earlywood calcium content, p.p.m.	1,143.745	-0.434	(NR) ²	+17.242	RI	75	73
6-6	Latewood calcium content, p.p.m.	847.781	-0.320	(NR) ²	+18.203	RI	79	52
6-7	Earlywood sodium content, p.p.m.	516.253	-623.237	EG	-----	-----	25	55
6-8	Latewood sodium content, p.p.m.	422.181	-527.345	EG	-----	-----	25	47
6-9	Earlywood magnesium content, p.p.m.	411.218	-15.632	NR	+1.403	(NR)(RI)	48	74
6-10	Latewood magnesium content, p.p.m.	359.178	-30.177	(EG)(NR)	+0.1324	(NR) ²	51	49
6-11	Earlywood iron content, p.p.m.	53.989	+0.165	(NR)(RI)	-----	-----	30	17
6-12	Latewood iron content, p.p.m.	42.422	+0.046	(NR) ²	-----	-----	23	22
6-13	Earlywood potassium content, p.p.m.	185.995	-21.080	(EG)(RI)	-----	-----	17	59
6-14	Latewood potassium content, p.p.m.	138.953	-5.486	(NR)(UG)	-----	-----	28	39

¹ Symbols: EG—specific gravity of extracted wood (green volume and oven-dry weight).

NR—Number of rings from pith.

(NR)²—Square of the number of rings from pith.

RI—Growth rate in rings per inch.

UG—Specific gravity of unextracted wood (green volume and oven-dry weight).

Table 6-10 presents the best fit equations for each element, together with the estimated percent of the variation accounted for by each equation, and its standard error of estimate. The left hand column lists equation numbers.

Manganese content in both earlywood and latewood (equations 6-3, 6-4; fig. 6-10) was negatively correlated with number of rings from the pith; the rate of decrease increased as number of rings from the pith increased. The equations accounted for 29 and 34 percent of the variation in earlywood and latewood, respectively.

Calcium content in both earlywood and latewood (equations 6-5, 6-6; fig. 6-11) was higher for slow-grown wood than for fast-grown, and declined with number of rings from the pith; the rate of decrease accelerated as number of rings from the pith increased, especially in earlywood. The equations accounted for 75 percent or more of the observed variation.

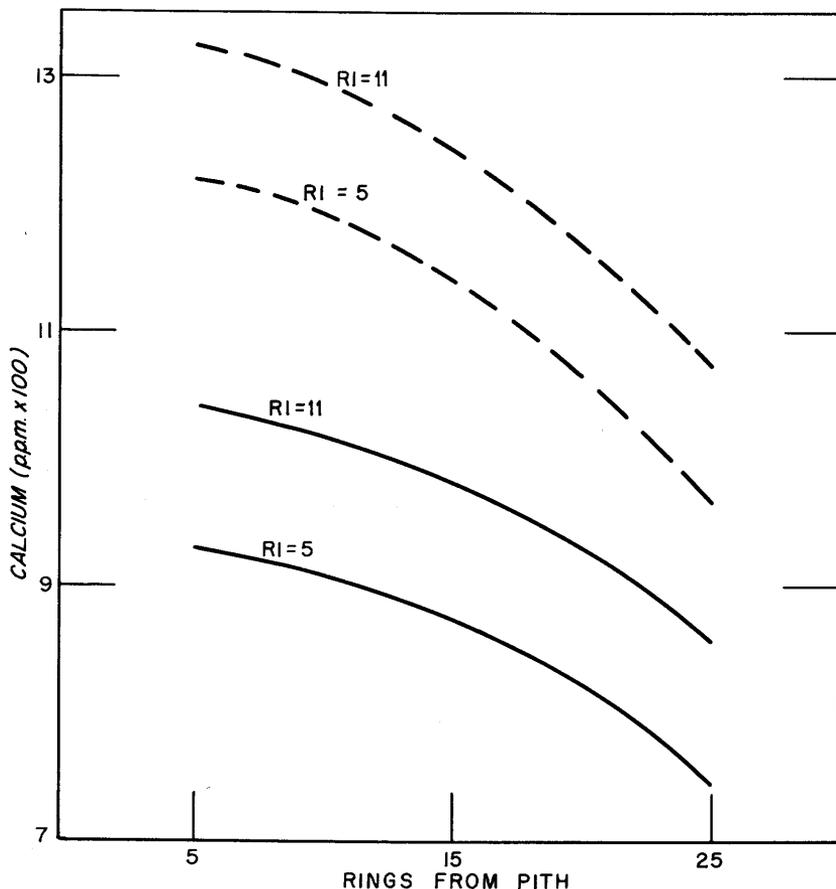


Figure 6-11.—Calcium content of loblolly pine earlywood (dashed line) and latewood (solid line), as related to number of rings from the pith and rings per inch. (Drawing after McMillin 1970.)

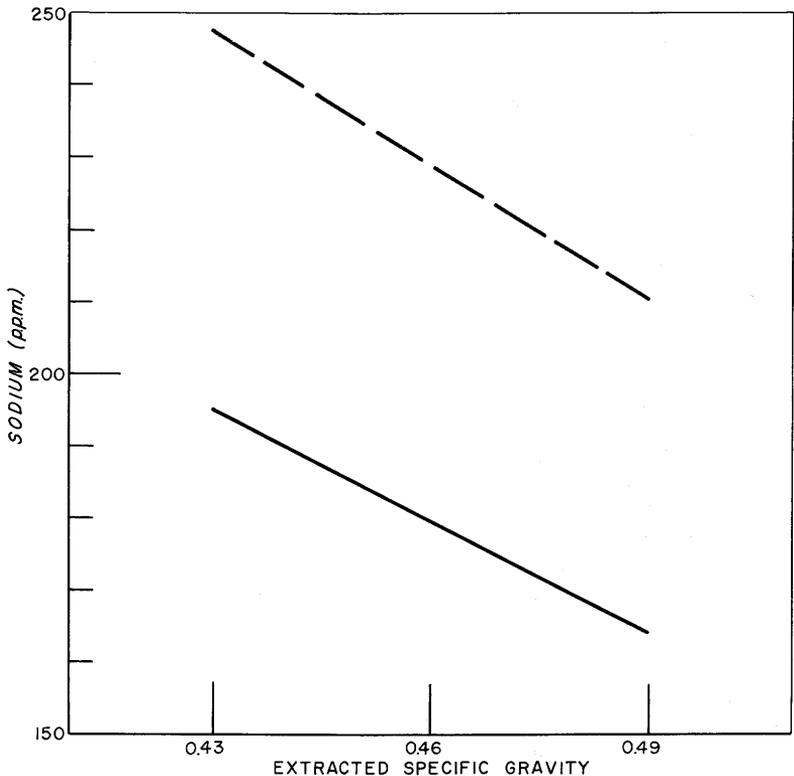


Figure 6-12.—Sodium content of loblolly pine earlywood (dashed line) and latewood (solid line) as related to specific gravity of extracted chips. (Drawing after McMillin 1970.)

Sodium content in both earlywood and latewood (equations 6-7, 6-8; fig. 6-12) decreased linearly with specific gravity of extracted wood. For each class of wood, the equation accounted for only 25 percent of the observed variation.

Magnesium content (equations 6-9, 6-10; fig. 6-13) of earlywood was higher in slow-grown than in fast-grown wood; it declined with number of rings from the pith, very slightly in slow-grown wood, but much more sharply in fast-grown. In latewood, magnesium content was not related to rate of growth, but varied in a curvilinear relationship with radial position and extracted specific gravity, being highest in less dense wood. It declined with number of rings from the pith in wood of both high and low density, but the decline was less steep as the number of rings from the pith increased. The equations accounted for about half of the observed variation.

Iron content (equations 6-11, 6-12; fig. 6-14) of earlywood was higher for slow-grown than for fast-grown wood, the difference being most pronounced in mature wood; in both slow-grown and fast-grown wood, iron content increased linearly with number of rings from the pith. Iron con-

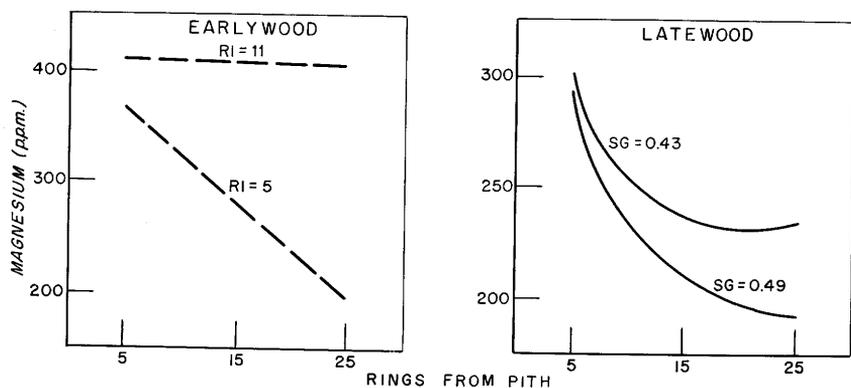


Figure 6-13.—Magnesium content of loblolly pine earlywood and latewood, as related to radial position, rings per inch, and extracted specific gravity. (Drawings after McMillin 1970.)

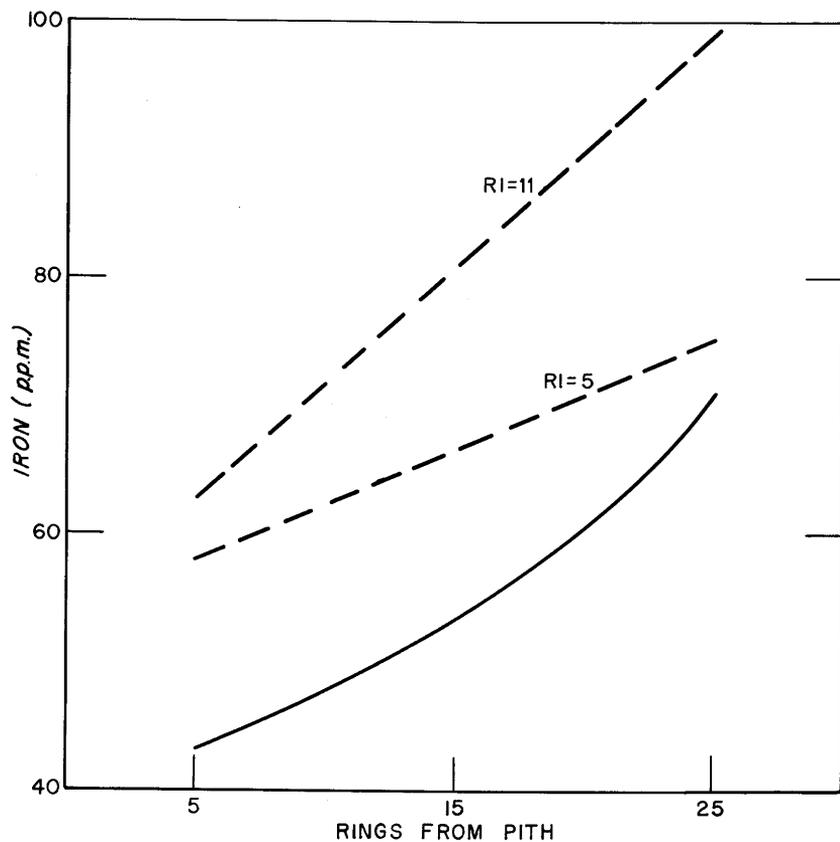


Figure 6-14.—Iron content of loblolly pine earlywood (dashed lines) and latewood (solid line), as related to radial position and rings per inch. (Drawing after McMillin 1970.)

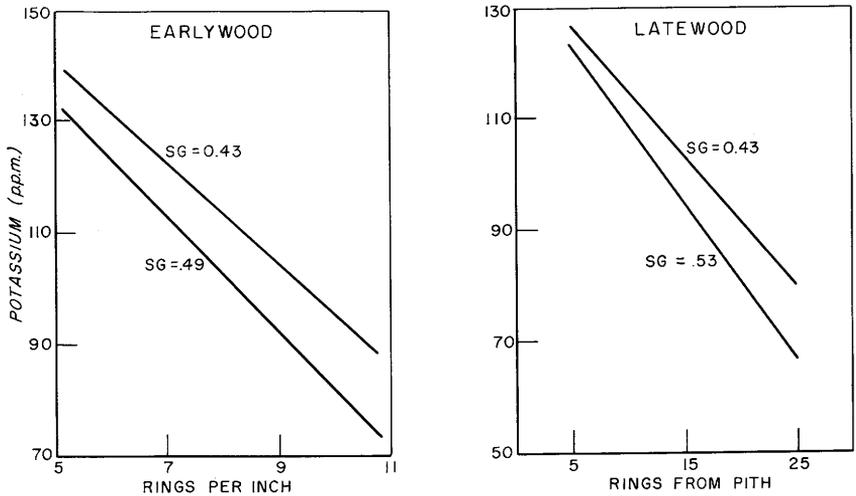


Figure 6-15.—Potassium content of loblolly pine earlywood and latewood, as related to rings per inch, radial position, and unextracted specific gravity. (Drawing after McMillin 1970.)

content of latewood was not related to growth rate, but increased with number of rings from the pith; the rate of increase accelerated as number of rings from the pith increased. The equations accounted for 30 percent of the variation in iron content in earlywood and 23 percent in latewood.

Potassium content (equations 6-13, 6-14; fig. 6-15) in earlywood was negatively correlated with extracted specific gravity and with number of rings per inch; thus it was highest for fast-grown low-density wood. In latewood, potassium content was negatively correlated with specific gravity (best fit was with specific gravity of unextracted wood) and number of rings from the pith. It was not related to rate of growth. The equation for earlywood is relatively weak, accounting for only 17 percent of the observed variation; the equation for latewood accounted for 28 percent.

No equations were developed for phosphorus content since the abundance of this element, while greater in earlywood (40 p.p.m.) than latewood (28 p.p.m.), was unrelated to radial position, growth rate, and specific gravity in either earlywood or latewood.

Within-cell variability.—Zicherman (1970), using a low-temperature plasma technique previously described, ashed imbedded loblolly pine specimens cut 900 to 1,300 A. units thick; he found that distribution of ash in cell walls was similar to that of lignin. Ash was most heavily concentrated in the middle lamella, primary wall, and S-3 layer of the secondary wall. Delignification removed most, but not all, ash forming material from whole wood.

6-5 LITERATURE CITED

- Adams, G. A.
1964. Wood carbohydrates—review of the present status of hemicellulose chemistry. *Pulp and Pap. Mag. Can.* 65: T13-T24.
- Alston, R. E., and Turner, B. L.
1963. Biochemical systematics. 404 pp. Englewood Cliffs, N.J.: Prentice-Hall, Inc.
- Altman, P. L., and Dittmer, D. S., editors.
1964. Biology data book. 615 pp. Wash., D.C. Fed. Amer. Soc. Exp. Biol.
- Anderson, A. B.
1967. Silvichemicals from the forest. *Econ. Bot.* 21: 15-30.
- Anderson, E.
1946. The isolation of pectic substances from softwoods. *J. Biol. Chem.* 165: 233-240.
- Anthis, A.
1956. Some carbohydrate linkages in slash pine alpha-cellulose. *TAPPI* 39: 401-405.
- Aspinall, G. O.
1959. Structural chemistry of the hemicelluloses. *Advances in Carbohydr. Chem.* 14: 429-468.
- Asunmaa, S. K.
1966. The fiber wall, microfibrils, and interfaces at electron microscopic resolution. *TAPPI* 49: 319-324.
- Bailey, A. J.
1936a. Lignin in Douglas fir. *Ind. and Eng. Chem.* 8: 389-391.
- Bailey, A. J.
1936b. Structure of the middle lamella. *Pap. Ind.* 18: 379-381.
- Ball, D. H., Jones, J. K. N., Nicholson, W. H., and Painter, T. J.
1956. The structure of the hemicelluloses of loblolly pine. *TAPPI* 39: 438-443.
- Behan, M. J.
1968. Fertilization in western larch forests. *Mont. Forest Conserv. Exp. Sta. Note* 6, 28 pp.
- Berlyn, G. P., and Mark, R. E.
1965. Lignin distribution in wood cell walls. *Forest Prod. J.* 15: 140-141.
- Bishop, G. N., and Marckworth, G. D.
1933. Some factors influencing resin concentration in loblolly and slash pines. *J. Forest.* 31: 953-960.
- Bland, D. E.
1958. Chemistry of reaction wood. I. The lignins of *Eucalyptus goniocalyx* and *Pinus radiata*. *Holzfor-schung* 12: 36-43.
- Bowen, H. J. M., and Gibbons, D.
1963. Radioactivation analysis. 295 pp. Oxford, England: Clarendon Press.
- Box, B. H., and Linnartz, N. E.
1967. Record growth for loblolly pine. *Forest Farmer* 27(1): 6-8.
- Brasch, D. J., Jones, J. K. N., Painter, T. J., and Reid, P. E.
1959. Structure of some water soluble polysaccharides from wood. *Pulp and Pap. Mag. Can.* 60(11): 342-345.
- Brauns, F. E.
1952. The chemistry of lignin. 803 pp. N.Y.: Academic Press.
- Brauns, F. E., and Brauns, D. A., editors.
1960. The chemistry of lignin: Supplement volume. 804 pp. N.Y.: Academic Press.
- Bray, M. W., and Martin, J. S.
1942. Pulping Florida sand pine (*Pinus clausa*) for kraft, high-grade papers, and newsprint. *Southern Pulp and Pap. J.* 5(1): 7-14.
- Bray, M. W., Martin, J. S., and Schwartz, S. L.
1939. Sulphate pulping of southern yellow pine. II. Effect of growth variables on yield and pulp quality. *South. Pulp and Pap. J.* 2(6): 35-41.
- Bray, M. W., and Paul, B. H.
1934. Evaluation of southern pines for pulp production. III. Shortleaf pine (*Pinus echinata*). *Pap. Trade J.* 99(5): 38-41.
- Brendemuehl, R. H.
1967. Loss of topsoil slows slash pine seedling growth in Florida sandhills. *USDA Forest Serv. Res. Note SO-53*, 4 pp. South. Forest Exp. Sta., New Orleans, La.
- Browning, B. L., editor.
1963. The chemistry of wood. 689 pp. N.Y.: Interscience Pub.

- Browning, B. L.
1967. Methods of wood chemistry. Vol. 1, 384 pp. N.Y.: Interscience Pub.
- Buchanan, M. A.
1963. Extraneous components of wood. In The chemistry of wood, pp. 313-367. N.Y.: Interscience Pub.
- Buchanan, M. A., Sinnett, R. V., and Jappe, J. A.
1959. The fatty acids of some American pulpwoods. TAPPI 42: 578-583.
- Byrd, V. L.
1964. An investigation of the effect of wood chemical constituents on kraft paper properties of four selected loblolly pines. M. S. Thesis. N.C. State Univ. 113 pp.
- Byrd, V. L., Elwood, E. L., Hitchings, R. G., and Barefoot, A. C.
1965. Wood characteristics and kraft paper properties of four selected loblolly pines. II. Wood chemical constituents and their relationship to fiber morphology. Forest Prod. J. 15: 313-320.
- Campbell, W. G., and Bamford, K. F.
1939. Factors affecting the relative resistance of certain woods to hydrolysis by dilute sulphuric acid. J. Soc. Chem. Ind. 58: 180-185. London.
- Chidester, G. H., McGovern, J. N., and McNaughton, G. C.
1938. Comparison of sulphite pulps from fast-growth loblolly, shortleaf, longleaf and slash pines. Pap. Trade J. 107(4): 36-39.
- Cole, D. E., Zobel, B. J., and Roberds, J. H.
1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. TAPPI 49: 161-166.
- Côté, W. A., Jr., and Day, A. C.
1969. Wood ultrastructure of the southern yellow pines. State Univ. Coll. Forest. Syracuse Univ. Tech. Pub. 95, 70 pp.
- Côté, W. A., Jr., Day, A. C., and Timell, T. E.
1968. Studies on compression wood. VII. Distribution of lignin in normal and compression wood of tamarack (*Larix laricina* (Du Roi) K. Koch). Wood Sci. and Technol. 2: 13-37.
- Côté, W. A., Jr., Simpson, B. W., and Timell, T. E.
1966. Studies on compression wood. II. The chemical composition of wood and bark from normal and compression regions of fifteen species of gymnosperms. Svensk Papperstidn. 69(17): 547-558.
- Curran, C. E.
1936. Some relations between growth conditions, wood structure and pulping quality. Pulp and Pap. Mag. Can. 37(10): 646-650.
- Daleski, E. J.
1965. The effect of elevated temperatures on the alkaline pulping processes. TAPPI 48: 325-330.
- Danielson, R. M., and Davey, C. B.
1967. Growth response and nutrient status of loblolly pine (*Pinus taeda* L.) seedlings grown in fumigated soil. Agron. Abstr., pp. 132-133. Madison, Wis.: American Society of Agronomy.
- Duncan, D. A., and Epps, E. A., Jr.
1958. Minor mineral elements and other nutrients on forest ranges in central Louisiana. La. Agr. Exp. Sta. Bull. 516, 19 pp.
- Einspahr, D. W., Peckham, J. R., and Mathes, M. C.
1964. Base lines for judging wood quality of loblolly pine. Forest Sci. 10: 165-173.
- Ellis, E. L.
1959. The effects of environment and decay on mineral components of grand fir wood. In Marine boring and fouling organisms, pp. 477-513. D. L. Ray, ed. Seattle: Univ. Washington Press.
- Ellis, E. L.
1962. Inorganic constituents of wood. Forest Prod. J. 12: 271-274.

- Ellis, E. L.
1965. Inorganic elements in wood. *In Cellular ultrastructure of woody plants*, pp. 181-189. W. A. Côté, Jr., ed. N.Y.: Syracuse Univ. Press.
- Erdtman, H.
1959. Conifer chemistry and taxonomy of conifers. *In Biochemistry of wood*, pp. 1-27. K. Kratzl and G. Billek, eds. N.Y.: Pergamon Press.
- Fahey, D. J., and Laudrie, J. F.
1968. Kraft pulps, papers, and linerboard from southern pine thinning. USDA Forest Serv. Res. Note FPL-0182, 8 pp. Forest Prod. Lab., Madison, Wis.
- Falkehag, S. I., Marton, J., and Adler, E.
1966. Chromophores in kraft lignin. *In Lignin structure and reactions*, pp. 75-89. Wash., D.C.: American Chemical Society.
- Fisher, G. S.
1966. Variations in composition of turpentines from slash pines. *Abstr. Amer. Chem. Soc.*, D-4.
- Foreman, E. L., and Englis, D. T.
1933. Isolation and identification of a polysaccharide from southern yellow pine. *Ind. and Eng. Chem.* 23: 415-416.
- Fowells, H. A., and Krauss, R. W.
1959. The inorganic nutrition of loblolly pine and Virginia pine with special reference to nitrogen and phosphorus. *Forest Sci.* 5: 95-112.
- Goddard, R. E., and Cole, D. E.
1966. Variation in wood production of six-year-old progenies of select slash pines. *TAPPI* 49: 359-362.
- Goodall, D. W., and Gregory, F. G.
1947. Chemical composition of plants as an index of their nutritional status. *Imp. Bur. Hort. and Plant Crops Tech. Commun.* 17, 167 pp.
- Goring, D. A. I., and Timell, T. E.
1962. Molecular weight of native cellulose. *TAPPI* 45: 454-460.
- Grigsby H. C.
1967. Irrigation and fertilization of seed orchards. Southeast. Area Forest Nurserymen's Conf. Proc. 1966: 121-130. USDA Forest Serv. Southeast. Area, State and Priv. Forest.
- Hacsckaylo, J., Finn, R. F., and Vimmersted, J. P.
1969. Deficiency symptoms of some forest trees. *Ohio Agr. Res. and Develop. Center Res. Bull.* 1015, 68 pp.
- Hall, J. A., and Gisvold, O.
1935. Chemistry of slash-pine (*Pinus caribaea*, Morelet). I. Fatty constituents of the phloem. *J. Biol. Chem.* 109: 585-595.
- Hall, J. A., and Gisvold, O.
1936. Chemistry of slash-pine (*Pinus caribaea*, Morelet). II. Fats, waxes, and resins of the growing tips. *J. Biol. Chem.* 113: 487-496.
- Hamilton, J. K., Partlow, E. V., and Thompson, N. S.
1958a. The behavior of wood hemicelluloses during pulping. I. Examination of the xylose-containing hemicelluloses associated with hardwood and softwood pulps. *TAPPI* 41: 803-810.
- Hamilton, J. K., Partlow, E. V., and Thompson, N. S.
1958b. The behavior of wood hemicelluloses during pulping. II. The structure of the 4-0-methylglucuronoxylan, araboxylan, and xylan of southern pine pulps. *TAPPI* 41: 811-816.
- Hamilton, J. K., Partlow, E. V., and Thompson, N. S.
1960. The nature of a galactoglucomannan associated with wood cellulose from southern pine. *J. Amer. Chem. Soc.* 82: 451-457.
- Hamilton, J. K., and Quimby, G. R.
1957. The extractive power of lithium, sodium, and potassium hydroxide solutions for the hemicelluloses associated with wood cellulose and hemicellulose from western hemlock. *TAPPI* 40: 781-786.

- Hamilton, J. K., and Thompson, N. S.
1959. A comparison of the carbohydrates of hardwoods and softwoods. TAPPI 42: 752-760.
- Hamilton, J. R.
1963. Characteristics of tracheids produced in a gamma and gamma-neutron environment. Forest Prod. J. 13: 62-67.
- Hillis, W. E., editor.
1962. Wood extractives and their significance to the pulp and paper industries. 513 pp. N.Y.: Academic Press.
- Jones, J. K. N., and Painter, T. J.
1957. The hemicelluloses of loblolly pine (*Pinus taeda*) wood. I. The isolation of five oligosaccharide fragments. J. Chem. Soc., pp. 669-673.
- Jones, J. K. N., and Painter, T. J.
1959. The hemicelluloses of loblolly pine (*Pinus taeda*) wood. II. The constitution of hexosan and pentosan components. J. Chem. Soc., pp. 573-580.
- Karrer, W.
1958. Konstitution und Vorkommen der organischen Pflanzenstoffe. 1207 pp. Basel, Germany: Birkhäuser Verlag.
- Keller, E. L., Kingsbury, R. M., and Fahey, D. J.
1959. Boards and papers from shortleaf pine, black tupelo, and southern white oak neutral sulfite semichemical pulps. USDA Forest Serv. Forest Prod. Lab. Rep. 2141, 17 pp.
- Kitao, K., and Sato, A.
1965. [Accessory wood constituents I.] Wood Res. 34: 237-248.
- Kollman, F. F. P., and Côté, W. A., Jr.
1968. Principles of wood science and technology. I. Solid wood. 592 pp. N.Y.: Springer-Verlag New York, Inc.
- Kramer, P. J., and Kozlowski, T. T.
1960. Physiology of trees. 642 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Kurth, E. F.
1933. Distribution and nature of extractives in longleaf and shortleaf pine. Ind. and Eng. Chem. 25: 192-195.
- Lange, P. W.
1958. The distribution of chemical constituents throughout the cell wall. In Fundamentals of papermaking fibers, pp. 147-185. F. Bolam, ed. Surrey: Brit. Pap. and Boardmakers' Assoc.
- Leopold, B.
1961. Chemical composition and physical properties of wood fibers. I. Preparation of holocellulose fibers from loblolly pinewood. TAPPI 44: 230-232.
- Lewis, B. A., and Smith, F.
1957. The heterogeneity of polysaccharides as revealed by electrophoresis on glass-fiber paper. J. Amer. Chem. Soc. 79: 3929-3931.
- Lindstedt, G.
1949. Constituents of pine heartwood. XVI. The heartwood of *Pinus virginiana* Mill. Acta Chem. Scand. 3: 1381-1384.
- Lindstedt, G., and Misiorny, A.
1951. Constituents of pine heartwood. XXV. Investigation of forty-eight *Pinus* species by paper partition chromatography. Acta Chem. Scand. 5: 121-128.
- Low, A. J.
1964. Compression wood in conifers. A review of literature. I, II. Forest. Abstr. 25(3, 4): 35-41; 45-51.
- McDermott, R. E., and Fletcher, P. W.
1960. Physiological relationships of soils to forest growth: research implementation. In Southern forest soils, pp. 9-18. La. State Univ. Eighth Annu. Forest. Symp. Proc. 1959. La. State Univ. Press.
- McMillin, C. W.
1968. Chemical composition of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. Wood Sci. and Technol. 2: 233-240.
- McMillin, C. W.
1969. Ash content of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. Wood Sci. 2: 26-30.

- McMillin, C. W.
1970. Mineral content of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. *Holzforschung* 24: 152-157.
- Maki, T., and Terzi, Z-A. H.
1967. Effects of residues from burnt logging debris on tree seedling growth. *Agron. Abstr.*, p. 135. Madison, Wis.: American Society Agronomy.
- Manely, R. St. J.
1964. Fine structure of native cellulose microfibrils. *Nature* 204: 1155-1157.
- Martin, J. S.
1962. Kraft pulping of west Florida sand pine and longleaf pine. USDA Forest Serv. Forest Prod. Lab. Rep. 2248, 6 pp.
- Marton, J.
1964. On the structure of kraft lignin. *TAPPI* 47: 713-719.
- Marton, J.
1966. Lignin structure and reactions. Symposium held by Division of Cellulose, Wood, and Fiber Chemistry, 150th Meeting American Chemical Society, Atlantic City, N.J., Sept. 13-14, 1965. *Advances in Chemistry Series* 59. Washington: Amer. Chem. Soc.
- Marton, J., and Adler, E.
1963. Reactions of lignin with methanolic hydrochloric acid—a discussion of some structural questions. *TAPPI* 46: 92-98.
- Marton, J., Marton, T., and Falkehag, S. I.
1966. Alkali catalyzed reactions of formaldehyde with lignins. *In* Lignin structure and reactions, pp. 125-144. Wash., D.C.: American Chemical Society.
- Max, K. W.
1945a. A study of tall oil from green and seasoned slash pinewood. *South. Pulp and Pap. J.* 7(9): 22-24, 26, 28.
- Max, K. W.
1945b. Chemical analysis of green loblolly pine. *South. Pulp and Pap. J.* 7(8): 36.
- May, J. T., Johnson, H. H., and Gilmore, A. R.
1962. Chemical composition of southern pine seedlings. Ga. Forest Res. Council. Res. Pap. 10, 11 pp.
- Meier, H.
1961. The distribution of polysaccharides in wood fiber. *J. Polymer Sci.* 51: 11-18.
- Meier, H.
1962. Chemical and morphological aspects of the fine structure of wood. *Pure and Appl. Chem.* 5: 37-52.
- Metz, L. J., and Wells, C. G.
1965. Weight and nutrient content of the aboveground parts of some loblolly pines. USDA Forest Serv. Res. Pap. SE-17, 20 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Mirov, N. T.
1961. Composition of gum turpentine of pines. USDA Tech. Bull. 1239, 158 pp.
- Mirov, N. T.
1967. The genus *Pinus*. 602 pp. N.Y.: Ronald Press Co.
- Mitchell, R. L., Millett, M. A., Moore, W. E., and Saeman, J. F.
1956. The persistence of wood xylan and mannan through successive prehydrolysis, pulping, purification and nitration. *TAPPI* 39: 571-575.
- Most, D. S.
1957. The sorption of certain slash pine hemicellulose fractions by cellulose fibers. *TAPPI* 40: 705-712.
- Mühlethaler, K.
1965. The fine structure of the cellulose microfibril. *In* Cellular ultrastructure of woody plants, pp. 191-198. W. A. Côté, Jr., ed. Syracuse: Syracuse Univ. Press.
- Nekrasova, V. B., Agranat, A. L., and Solodkii, F. T.
1968. [Some results of the operation of an experimental-industrial arrangement for phytosterol collection.] *Les. Zh.* 11(2): 124-126.
- Necesyany, V., Jurasek, L., Sopko, R., and Bobak, M.
1965. Formation of lignified cell walls within twenty-four hours. *Nature* 206: 639.

- Nelson, R.
1960. Fractionation of hemicelluloses. TAPPI 43: 313-317.
- Nelson, R.
1961. The use of holocellulose to study cellulose supermolecular structure. J. Polymer Sci. 51: 27-56.
- Nikitin, N. I.
1966. [The chemistry of cellulose and wood.] Transl. from 1962 Russ. edition, 691 pp. N.Y.: Daniel Davey & Company, Inc.
- Orman, H. R., and Will, G. M.
1960. The nutrient content of *Pinus radiata* trees. New Zeal. J. Sci. 3: 510-522.
- Pearl, I. A.
1967. The chemistry of lignin. 339 pp. N.Y.: Marcel Dekker, Inc.
- Pillow, M. Y., and Bray, M. W.
1935. Properties and sulphate pulping characteristics of compression wood. Pap. Trade J. 101(26): 31-34.
- Posey, C. E., and Robinson, D. W.
1969. Extractives of shortleaf pine—an analysis of contributing factors and relationships. TAPPI 52: 110-115.
- Preston, R. D.
1960. Anisotropy in the microscopic and submicroscopic structure of wood. Fifth World Forest. Congr. Proc., pp. 1298-1307.
- Quijada, M. R.
1967. Variation and relationships of wood characteristics of longleaf pine in North Carolina. M. S. Thesis. N.C. State Univ., Raleigh. 91 pp.
- Ritter, G. J.
1925. Distribution of lignin in wood. Ind. and Eng. Chem. 17: 1194-1197.
- Ritter, G. J., and Fleck, L. C.
1926. Chemistry of wood. IX. Springwood and summerwood. Ind. and Eng. Chem. 18: 608-609.
- Roberts, D.
1968. Effect of wounding on the composition of slash pine: A preliminary report. Assoc. Southeast Biol. Bull. 15(2): 53.
- Rydholm, S. A.
1965. Pulping processes. 1269 pp. N.Y.: Interscience Publishers, Inc.
- Sachs, I. B.
1963. Torus of the bordered-pit membrane in conifers. Nature 198: 906-907.
- Sachs, I. B., Clark, I. T., and Pew, J. C.
1963. Investigation of lignin distribution in the cell wall of certain woods. J. Polymer Sci. (Part C, Polymer Symp.) 2: 203-212.
- Sarkanen, K. V.
1963. Wood lignins. In The chemistry of wood, pp. 249-311. N.Y.: Interscience Pub.
- Sarkanen, K. V., Chang, H., and Allan, G. G.
1967. Species variations in lignins. II. Conifer lignins. TAPPI 50: 583-587.
- Schubert, W. J.
1965. Lignin biochemistry. 131 pp. N.Y.: Academic Press.
- Simmonds, F. A., and Chidester, G. H.
1960. Sulfate and prehydrolysis-sulfate pulp for nitration relation of pulp characteristics to certain preparation variables. USDA Forest Serv. Forest Prod. Lab. Rep. 2189, 42 pp.
- Spiegelberg, H. L.
1966. The effect of hemicellulose on the mechanical properties of individual pulp fibers. TAPPI 49: 388-396.
- Stamm, A. J., and Sanders, H. T.
1966. Specific gravity of the wood substance of loblolly pine as affected by chemical composition. TAPPI 49: 397-400.
- Stanley, R. G.
1966. Biosynthesis of cellulose outside of living tree. Forest Prod. J. 16(11): 62-68.
- Stanley, R. G.
1969. Extractives of wood, bark and needles of the southern pines—a review. Forest Prod. J. 19(11): 50-56.
- Stanley, R. G., and Thomas, D. des S.
1968. Cellulose biosynthesis in a pine cambium extract. Abstr. Amer. Chem. Soc. A-92.
- Stoate, T. N.
1950. Nutrition of the pine. Australian Forest. and Timber Bur. Bull. 30, 61 pp.
- Sullivan, J. D., and Sachs, I. B.
1966. Research on cellulose morphology. Forest Prod. J. 16(9): 83-86.

- Swenson, H. A., Morak, A. J., and Kurath, S.
1961. Light scattering and ultracentrifugation studies of hemicelluloses. *J. Polymer Sci.* 51: 231-244.
- Tamm, C. O.
1964. Determination of nutrient requirements of forest stands. *In* International review of forestry research. Vol. 1, pp. 115-170. J. A. Romberger and P. Mikola, eds. N.Y.: Academic Press.
- TAPPI Forest Biology Subcommittee No. 2.
1963. Existing methods of value for small sample measurement of wood and fiber properties. *TAPPI* 46(6): 150A-156A.
- Taras, M. A., and Saucier, J. R.
1967. Influence of extractives on specific gravity of southern pine. *Forest Prod. J.* 17(9): 97-99.
- Thompson, N. S., Heller, H. H., Hankey, J. D., and Smith, O.
1966a. Investigations on the isolation and carbohydrate composition of different components of trees and wood. *Pulp and Pap. Mag. Can.* 67: T541-T551.
- Thompson, N. S., Heller, H. H., Hankey, J. D., and Smith, O.
1966b. The isolation and the carbohydrate composition of the epithelial cells of long-leaf pine (*Pinus palustris* Mill.). *TAPPI* 49: 401-405.
- Thor, E.
1964. Variation in Virginia pine. Part I. Natural variation in wood properties. *J. Forest.* 62: 258-262.
- Timell, T. E.
1957. Molecular properties of seven native wood celluloses. *TAPPI* 40: 25-29.
- Timell, T. E.
1965. Wood hemicelluloses II. *Advances in Carbohydr. Chem.* 20: 409-483.
- Timell, T. E.
1967. Recent progress in the chemistry of wood hemicellulose. *Wood Sci. and Technol.* 1: 45-70.
- USDA Forest Products Laboratory.
1964. Pulp yields for various processes and wood species. *USDA Forest Serv. Res. Note FPL-031*, 6 pp. Forest Prod. Lab., Madison, Wis.
- Van Buijtenen, J. P., Zobel, B. J., and Joranson, P. N.
1961. Variation of some wood and pulp properties in an even-aged loblolly pine stand. *TAPPI* 44: 141-144.
- Vaughn, J. M., Wise, L. E., and Borhardt, L.
1960. Crystalline glucomannan from slash pine. *J. Org. Chem.* 25: 1837-1838.
- Wahlenberg, W. G.
1960. Loblolly Pine. 603 pp. N.C.: Duke Univ. Sch. Forest.
- Wangaard, F. F., and Granados, L. A.
1967. The effect of extractives on water-vapor sorption by wood. *Wood Sci. and Technol.* 1: 253-277.
- Ward, K., Jr., and Morak, A. J.
1962. Fractional extraction and properties of hemicelluloses. *Pure and Appl. Chem.* 5: 77-89.
- Watson, A. J., and Hodder, I. G.
1954. Relationship between fibre structure and handsheet properties in *Pinus taeda*. *APPITA* 8: 290-310.
- Wehmer, C.
1929. *Die Pflanzenstoffe*. Vol. 1, ed. 2, 640 pp. Jena, Germany: Gustave Fischer.
- Wellons, J. D.
1970. Cell wall polysaccharides in southern pine wood—a review. *Wood Sci.* 2: 247-254.
- Whistler, R. L.
1960. Methods used in the characterization and proof of structure of cell-wall polysaccharides. *TAPPI* 43: 177-180.
- Whistler, R. L., BeMiller, J. N., and Walfrom, M. L., editors.
1962. *Methods in carbohydrate chemistry*. Vol. I. Analysis and preparation of sugars. 589 pp. N.Y.: Academic Press, Inc.
- Wilcox, H. E.
1940. The spectrographic analysis of white pine (*Pinus strobus* L.). M.S. Thesis. N.Y. State Coll. Forest. Syracuse Univ. 151 pp.
- Wise, L. E.
1962. Extractives of wood. *In* *Pulp and Paper Science and Technology*. Vol. 1, pp. 74-81. N.Y.: McGraw-Hill.

- Wise, L. E., and Jahn, E. C., editors.
1952. Wood chemistry. Vol. 1, ed. 2, 688 pp. N.Y.: Reinhold Publishing Corporation.
- Wise, L. E., and Ratliff, E. K.
1947. Quantitative isolation of hemicelluloses and the summative analysis of wood. *Anal. Chem.* 19: 459-462.
- Wise, L. E., and Ratliff, E. K.
1948. The distribution of mannans in the wood of slash pine and black spruce. *Arch. Biochem.* 19: 292-299.
- Young, H. E., and Carpenter, P. M.
1967. Weight, nutrient element and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. *Maine Agr. Exp. Sta. Tech. Bull.* 28, 39 pp.
- Young, H. E., and Guinn, V. P.
1966. Chemical elements in complete mature trees of seven species in Maine. *TAPPI* 49: 190-197.
- Zicherman, J. B.
1970. Characterization of loblolly pine ash residues prepared by low temperature plasma oxidation. M.S. Thesis. N.C. State Univ. 79 pp.
- Zimmerman, M. H.
1964. The formation of wood in forest trees. 562 pp. N.Y.: Academic Press, Inc.
- Zobel, B. J., and McElwee, R. L.
1958. Variations of cellulose in loblolly pine. *TAPPI* 41: 167-170.
- Zobel, B. J., Stonecypher, R., Browne, C., and Kellison, R. C.
1966. Variation and inheritance of cellulose in the southern pines. *TAPPI* 49: 383-387.
- Zobel, B., Thorbjornsen, E., and Henson, F.
1960. Geographic, site and individual tree variation in wood properties of loblolly pine. *Silvae Genet.* 9: 149-158.
- Zobel, B. J., Webb, C., and Henson, F.
1959. Core or juvenile wood of loblolly and slash pine trees. *TAPPI* 42: 345-356.

7

Specific gravity

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7

Specific gravity

Specific gravity is a simple and useful index to the suitability of wood for many important uses. It is closely correlated with the mechanical strength of wood—and is therefore a primary factor in the segregation of high-strength lumber, poles, and pilings. Specific gravity largely determines pulp yield from a given volume of wood, e.g., a cord of high-density southern pine wood will yield about twice as much kraft pulp as an equal volume of low-density wood of the same species (Mitchell and Wheeler 1959).

7-1 WOOD DENSITY AND SPECIFIC GRAVITY

Specific gravity of wood is not governed by a single factor. Length and diameter of cells, thickness of cell walls, proportion of earlywood and latewood, percent of cellulose and lignin, amount and constituents of extractives, and amount of trace metals all affect the density and specific gravity of wood.

Since wood normally contains some water, and its volume and gross weight both vary with changes in moisture content, density and specific gravity determinations are difficult. For many purposes mass and volume of samples are most conveniently measured at different moisture levels. When this is the case, values are meaningful only when the measurement conditions are identified.

It is customary to define **wood density** as the dry mass of wood substance in grams or pounds (avoirdupois) per unit of volume (in cubic centimeters or cubic feet) where volume is measured under specified conditions of moisture (i.e., green, dry, or some intermediate condition below fiber saturation point). This is in contrast to other substances whose mass and volume are always determined under identical specified conditions. The advantages of using dry mass of wood in the numerator of the wood density formula are threefold: (1) practical implications (correlation with physical and mechanical properties of wood); (2) reproducibility; and (3) ease of conversion to different moisture conditions when shrinkage information is available. Because the values for wood density vary with measurement conditions, it is essential to state moisture condition at which volume was determined.

To convert density from grams per cubic centimeter to pounds per cubic foot, the former is multiplied by 62.43. In the European literature, wood density is often expressed in kilograms per cubic meter, which is 1,000 times the value in grams per cubic centimeter.

Wood **specific gravity** is the ratio of two densities—the density of wood to the density of pure water at 4° C. In the metric system the density of water at this temperature is approximately unity (0.999973 g. per cubic centimeter) and the numerical value for specific gravity and density are identical. In the British and U. S. standard system the density of wood in pounds per cubic foot is 62.43 times the corresponding numerical value for specific gravity, since the density of water in this system is 62.43 pounds per cubic foot. The specific gravity of wood is not only dimensionless but is independent of the units used in its computation. Since it is based on density, however, it is necessary to indicate the measurement conditions; often these are oven-dry mass and green volume, because they are most easily reproducible.

“Weight” of wood (pounds per cubic foot) at specified moisture content, including both the mass of wood substance and the mass of contained water, is often required. The general formula used for calculating the weight (W) of a cubic foot of wood having a specific gravity (G) (on the basis of oven-dry mass and green volume) and a percentage moisture content (M) is:

$$W = \left(1 + \frac{M}{100}\right)(G)(62.43) \text{ pounds} \quad (7-1)$$

Thus the weight of a cubic foot of loblolly pine having a specific gravity of 0.47 (based on oven-dry mass and green volume) and a moisture content of 45 percent is:

$$W = (1.45)(0.47)(62.43) = 42.5 \text{ pounds}$$

To calculate the weight of a cubic foot of wood at a moisture content below fiber saturation, the percent volumetric shrinkage (S), between green volume and the volume at the moisture content in question must be known. The weight per cubic foot now becomes:

$$W = \left(1 + \frac{M}{100}\right)(G)(62.43) / \left(1 - \frac{S}{100}\right) \text{ pounds} \quad (7-2)$$

Thus, given that the volumetric shrinkage from green to 10-percent moisture content is 7 percent (see fig. 8-15), 1 cubic foot of loblolly pine at 10-percent moisture content will weigh:

$$W = (1.10)(0.47)(62.43) / (1 - 0.07) = 34.7 \text{ pounds}$$

Table 7-1 presents an array of data relating specific gravity and moisture content of southern pine to weight per cubic foot.

TABLE 7-1.—*Weight per cubic foot of southern pine related to wood specific gravity and moisture content*¹

Specific gravity (ovendry weight, green volume basis)	Moisture content, percent					
	0	10	20	30	50	100
	----- Pounds -----					
0.30	21.3	22.3	23.3	24.4	28.1	37.5
.35	25.2	26.3	27.3	28.4	32.8	43.7
.40	29.3	30.3	31.3	32.5	37.5	49.9
.45	33.5	34.5	35.3	36.5	42.1	56.2
.50	37.8	38.7	39.4	40.6	46.8	62.4
.55	42.3	43.0	43.6	44.6	51.5	68.7
.60	47.0	47.4	47.7	48.7	56.2	74.9
.65	51.8	51.8	51.9	52.8	60.9	81.2

¹ Based on volumetric shrinkage data from figure 8-16. It is assumed that volumetric shrinkage is linear from 28- to 0-percent moisture content.

7-2 CELL WALL DENSITY

The density of wood substance can be estimated from the proportion and specific gravities of its constituent components. Stamm and Sanders (1966) have tabulated specific gravities for the major components.

Material	Specific gravity	Component percentages of weight of extractive-free wood (see table 6-1)
		Percent
Lignin.....	1.335	27 to 30
Holocellulose.....	1.521	66 to 69
Alpha-cellulose.....	1.528	42 to 46

Cell wall density is most directly determined by measuring the volume of fluid displaced by a known mass of wood. The observed values of densities measured in this way are dependent on the medium used. There are two reasons for this observed variation. First, the displacement media vary in their ability to penetrate voids in the cell wall. Second, physical and chemical interactions between the displacement media and wood can alter the density of the media or the wood. A given value for the density of wood substance should therefore be accompanied by reference to the measurement method as well as the condition of the wood, i.e., extracted or unextracted.

Table 7-2 (assembled from Wangaard 1969) is a summary specific to southern pine.

TABLE 7-2.—*Cell wall density*

Species and density (g. per cc.)	Reference	Method
Loblolly pine		
1.540	Wangaard (1969)	Picnometric in water; extracted
1.531	Stamm (1929)	Picnometric in water; extracted
1.500	Wilfong (1966)	Picnometric with $\frac{1}{2}$ -inch cubes of unextracted latewood in a nonpolar liquid.
1.485 ¹	Wangaard (1969)	Picnometric in toluene; extracted
1.466	Stamm (1929)	Picnometric in benzene; extracted
1.463	Wilfong (1966)	Picnometric with unextracted $\frac{1}{16}$ -inch cubes of latewood in a nonpolar liquid.
1.446	Wilfong (1966)	Picnometric with unextracted $\frac{1}{32}$ -inch cubes of earlywood in a nonpolar liquid.
1.445	Stayton and Hart (1965)	Mercury porosimeter capable of penetrating voids as small as 0.06 μ m. in diameter; unextracted
1.406	Wilfong (1966)	Picnometric with $\frac{1}{16}$ -inch cubes of unextracted earlywood in a nonpolar liquid.
Longleaf pine		
1.506	Dunlap (1914)	Equilibrium suspension of thin sections of wood in water solutions of salt at different densities.
Spruce pine		
1.541	Wangaard (1969)	Picnometric in water; extracted
1.485 ¹	Wangaard (1969)	Picnometric in toluene; extracted

¹ Average of values for 1-mm. sections and for wood meal.

Kellog and Wangard (1969, p. 184) came to the following conclusions concerning cell wall density of tree species in general.

"In summary, the literature supports the following concept of cell-wall composition. The dry cell wall has a density which if measured with care is approximately 1.45 g. per cubic centimeter in displacement media ranging from helium to a silicone polymer. These displacement media must therefore penetrate the dry cell wall equally or not at all. It is our opinion that there is sufficient experimental evidence to support the latter view. If the total difference between the density of the dry cell wall and the density of wood substance determined in water is due to the presence of "voids" they could not exceed 5 percent of the wall volume. Increases in the degree to which it is felt water within the cell wall is compacted or perturbed will decrease the estimate of void volume. There is now rather convincing evidence that the water within the cell wall is compacted only slightly compared with earlier estimates and that the maximum void volume may be approximately 4 percent of the dry wall volume."

Density of the water-swollen cell wall can be determined optically by using a microscope to estimate the proportionate area of cell wall in a total cross section of wood of known density (Smith 1965). Data specific to loblolly and spruce pine have been published by Wangaard (1969).

<u>Pine species</u>	<u>Density of water-swollen cell wall</u>
	<i>G. per cc.</i>
Loblolly -----	0.999
Spruce -----	.988

7-3 EFFECT OF EXTRACTIVE CONTENT ON SPECIFIC GRAVITY

Specific gravity is frequently determined on unextracted wood. This practice results in an overestimate of the amount of wood substance present in samples of southern pine because trees of these species contain sizeable amounts of extractives (see sec. 6-3).

The magnitude of the contribution of extractives to the specific gravity of breast-height wood is shown in table 7-3. The tabulated regression equations are valid only within the range of unextracted specific gravities found in breast height cores of the trees sampled. Because there is not a close relationship between extractive content in breast-height cores and tree-average extractive content (see sec. 6-3), the regressions of table 7-3 are limited to breast-height wood. The value of the equations as prediction expressions would be improved by adding age as a second factor with unextracted gravity.

Regression expressions relating extracted tree-average specific gravity values to unextracted tree-average values are not at hand for nine out of 10 species. For spruce pine, Manwiller¹ has determined the following equation based on a 72-tree sample drawn from throughout the major commercial range.

$$\hat{Y} = 0.0713 + 0.8056 X \quad (7-1)$$

where: \hat{Y} is the extracted tree-average specific gravity, and X is the unextracted tree average (basis of oven-dry weight and green volume).

The equation accounts for 76 percent of the variation; standard error of the estimate is 0.017. Tree-average values for unextracted and extracted specific gravity were 0.425 and 0.413.

In all southern pine species studied, there are substantial between-tree and within-tree variations in extractive content (see sec. 6-3 and figs. 6-6, 6-7, 6-8). These variations in extractive content contribute to variability observed in the unextracted specific gravity of southern pine wood.

7-4 SPECIES AVERAGE VALUES

Because of the size and continuously changing nature of the populations, it is difficult, if not impossible, to get figures that truly represent tree-average values of specific gravity for each species. Table 7-4 arrays a selection of available data specific to the southern pines.

¹ Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria La., Final Report FS-SO-3201-1.1, dated May 1, 1972.

Values for the minor species are based on unextracted cores taken at breast height from trees throughout the range of the species. By regression, these cores gravities were used to predict the tree-average values listed; tree averages were calculated on the basis of a minimum top diameter of 4 inches. Values for the four major species are not based on breast-height cores, but reflect specimen gravities accumulated by the USDA Forest Products Laboratory over a long period of years.

Table 7-5 gives some indication of the variability inherent in both major and minor species; in this table, note that the average age of slash pine trees sampled was only 30 years, compared with 47 to 58 for the other three major species.

Differences between present species populations are no doubt real. While there is some indication that if loblolly, slash, and longleaf pines are grown together in natural stands the specific gravity of their outer wood will not differ significantly (Cole et al. 1966), the evidence is not conclusive.

Specific gravity of trees in southern pine plantations of the future will likely be affected by genetic manipulation as well as by species, site, and environmental factors.

7-5 WITHIN-SPECIES VARIATION

Many studies of southern pine have shown the positive correlation between specific gravity and percent of latewood (e.g., Paul 1939; Schafer 1949; Pillow 1954; Zobel and Rhodes 1955; Larson 1957; Miller 1959; Jurbergs 1963; McGinnes 1963; Harris 1967; Yao 1970).

The influence of environment and silvicultural practices on the formation of latewood and on specific gravity was discussed in section 4-3 and will not be repeated here. Because all tree populations, regardless of environmental or silvicultural conditions, can be classified according to age, growth rate, and geographic location, it is useful to consider variation within species as related to these three factors.

AGE CLASS

Within the first few rings, particularly near the ground level, specific gravity of southern pine wood has a strong positive correlation with rings from the pith. This trend is frequently confined to wood near the pith, however, and old trees do not necessarily have higher specific gravity than young trees. Manwiller's¹ study of 72 spruce pine trees drawn from throughout the major commercial range provides illustrative data; no differences between age classes proved significant regardless of rate of tree growth. His values, based on green volume and oven-dry weight, follow:

	Age class of trees, years		
	15	30	45
Unextracted tree-average gravity....	0.431	0.428	0.415
Extracted tree-average gravity.....	.416	.419	.405

TABLE 7-3.—*Relationships predicting specific gravity of extracted breast-height cores, \hat{Y} , from specific gravity of unextracted breast-height cores, X^1*

Pine species	Regression equation	Coefficient of determination r^2	Standard error of estimate S_e	Average \bar{Y}	Average \bar{X}	Comment	Extraction	Reference
Loblolly.....	$\hat{Y}=0.119+0.713X$	0.59		0.492	0.524	94 trees total from La., Miss., S.C., and Tex.	²	Taras and Saucier (1967)
Longleaf.....	$\hat{Y}=0.120+0.720X$	.61		.530	.569	143 trees total from Ala., Fla., La., Miss., S.C., and Tex.	²	Taras and Saucier (1967)
Pitch.....	$\hat{Y}=0.11241+0.68125X$	.67	0.021	.435	.474	2,000 trees throughout the range	³	Saucier and Clark (1970)
Pond.....	$\hat{Y}=0.12908+0.66027X$	.66	.023	.454	.492	554 trees throughout the range	³	Taras and Saucier (1970)
Sand (Ocala).....	$\hat{Y}=0.07015+0.76807X$	.77	.016	.407	.439	523 trees throughout the range	³	Clark and Taras (1969)
(Choctawhatchee)...	$\hat{Y}=0.11681+0.67118X$	.77	.016	.442	.485	193 trees throughout the range	³	Clark and Taras (1969)
Shortleaf.....	$\hat{Y}=0.156+0.640X$	.62		.491	.524	140 trees total from Ark., Ga., La., N.C., Tenn., and Tex.	²	Taras and Saucier (1967)

Shortleaf.....	$\hat{Y} = 0.252 + 0.381X$	.79	.011			480 trees in Okla.	⁴	Posey and Robinson (1969)
Slash (<i>elliottii</i>).....	$\hat{Y} = 0.001 + 0.943X$	.83		.513	.543	123 trees total from Ala., Fla., La., and Miss.	²	Taras and Saucier (1967)
(<i>densa</i>).....	$\hat{Y} = 0.19406 + 0.57342X$	.59		.547	.615	285 trees throughout the range	²	Clark and Taras (1970)
Spruce.....	$\hat{Y} = 0.05813 + 0.80477X$	.77	.018	.414	.443	1,152 trees throughout species range	³	Taras and Saucier (1968)
Table-Mountain.....	$\hat{Y} = 0.08523 + 0.74797X$	.76	.015	.437	.470	15 trees from each of 50 plots	³	Clark and Saucier (1969)
Virginia.....	$\hat{Y} = 0.10315 + 0.70493X$	.74	.015	.421	.451	1,200 trees	³	Clark and Wahlgren (1970)
Virginia.....	-----	-----	-----	.488	.512	195 trees total in 13 stands. 10th through 25th growth rings	⁵	Thor (1964)

¹ Specific gravities are based on oven-dry weight and green volume.

² Extracted in alcohol-benzene for 16 hours, ethanol for 6 hours, and hot water for 2 hours.

³ Extracted in alcohol-benzene for 24 hours.

⁴ Extracted in alcohol-benzene in modified ASTM Procedure D1105-50T.

⁵ Extracted in alcohol-benzene for 16 hours, then in alcohol for 6 hours.

TABLE 7-4.—*Species averages for specific gravity of the southern pines*¹

Pine species	Number of trees sampled	Mean	Standard error of mean tree value	Reference
Loblolly.....		0.47	-----	Bendtsen and Ethington (1972)
Longleaf.....		.53	-----	Bendtsen and Ethington (1972)
Pitch.....	2,000	.47	0.002	Saucier and Clark (1970)
Pond.....	554	.47	.001	Taras and Saucier (1970)
Sand				
Ocala.....	523	.42	.003	Clark and Taras (1969)
Choctawhatchee..	193	.48	.008	Clark and Taras (1969)
Shortleaf.....		.47	-----	Bendtsen and Ethington (1972)
Slash.....		.53	-----	Bendtsen and Ethington (1972)
Slash (var. <i>densa</i>)...-	285	.58	.003	Clark and Taras (1970)
Spruce.....	1,152	.43	.002	Taras and Saucier (1968)
Table-Mountain....	750	.48	.002	Clark and Saucier (1969)
Virginia.....	2,114	.45	.004	Clark and Wahlgren (1970)

¹Tree average values for unextracted wood based on oven-dry weight and green volume.

Other data have been published, however, that indicate a strong positive correlation between age of stand and tree-average specific gravity; e.g., Zobel et al. (1965, fig. 9), in an analysis of loblolly pines growing in the Coastal Plain of South Carolina, found that trees in stands 15, 30, and 45 years old had tree-average extracted specific gravities of about 0.41, 0.46, and 0.48. They explained this finding by showing that young loblolly pines contain higher proportions of corewood (i.e., juvenile wood) than older pines.

GROWTH RATE

From section 4-3 it was noted that growth rate of plantation trees, when manipulated by changing environmental or silvicultural conditions, may not be closely correlated with wood specific gravity.

In natural stands of shortleaf pine in Missouri, Ralston and McGinnes (1964) found that specific gravity of mature wood sampled at breast height was not influenced significantly by diameter growth rates from 8 to 40 rings per inch.

From a study of 40 loblolly pines aged 31 to 76 years cut on a single 160-acre tract in northeast Mississippi, Yao (1970)—after considering all

TABLE 7-5.—Average specific gravity (basis of green volume and oven-dry weight) of breast-height unextracted increment cores taken from southern pine trees throughout the Eastern and Southern States¹

Species	Sample trees	Mean age	Mean d.b.h.	Specific gravity			Extractives ²
				Mean	Range	Standard deviation	
	<i>Number</i>	<i>Years</i>	<i>Inches</i>				<i>Percent</i>
Loblolly ³	1,742	47	14.8	.51	.38-.68	.042	6.5
Longleaf.....	1,576	50	11.7	.57	.40-.75	.049	7.4
Pitch.....	2,100	59	9.9	.47	.33-.66	.046	8.9
Pond.....	654	32	10.1	.49	.35-.68	.048	8.4
Sand							
Choctawhatchee.....	243	34	9.7	.49	.39-.64	.045	9.7
Ocala.....	758	30	8.9	.45	.34-.65	.045	7.6
Shortleaf ³	2,449	58	12.2	.52	.37-.72	.049	6.7
Slash							
<i>var. elliottii</i> ⁴	931	30	11.0	.53	.41-.70	.042	5.9
<i>var. densa</i>	285	30	9.2	.62	.44-.84	.068	12.4
Spruce.....	1,222	32	11.2	.44	.33-.59	.036	6.7
Table-Mountain.....	850	50	8.4	.47	.38-.61	.033	7.6
Virginia.....	2,648	33	8.3	.46	.37-.74	.055	7.1

¹ Unpublished data provided by J. Saucier, USDA Forest Service, Southeastern Forest Experiment Station, Athens, Ga.

² The difference between the original dry weight and the dry weight after extraction, expressed as a percentage of the latter.

³ Sampled in the southern portion of the natural growing range of the species—Texas east to North Carolina.

⁴ A portion of this sample (250 trees) was from plantations in central Louisiana which is outside of the natural growing range of slash pine.

heights and radial positions—concluded that unextracted wood specific gravity was positively correlated with number of rings per inch in the range 3 to 8 rings per inch; in wood with more than 8 rings per inch, however, specific gravity was generally unrelated to growth rate.

If tree-average specific gravities were to be measured throughout natural ranges of southern pine species, it is probable that tree specific gravity would have a weak negative correlation with width of growth rings at breast height. Manwiller's¹ study of 72 spruce pines drawn from throughout the major range of the species illustrates the point. Tree-average values for specific gravity were less for fast-grown trees (less than 6 rings per inch at 1-foot level) than for slow-grown (more than 6 rings per inch).

These tree-average specific gravities were not calculated from breast-height core values, but were derived from disks (weighted by volume) cut at 8-foot intervals to a 4-inch top. Gravity determinations were based on green volume and oven-dry weight.

Condition and tree age (years)	Less than 6 rings per inch (average 4.9)	More than 6 rings per inch (average 9.0)
Unextracted tree-average gravity		
15	0.41	0.45
30	.41	.45
45	.40	.43
Extracted tree-average gravity		
15	.40	.43
30	.40	.44
45	.39	.42

Although lower in specific gravity than slow-growing trees, fast-growing spruce pine trees throughout their major range contained more volume and therefore more weight of stemwood between the 1-foot level and a 4-inch top (Manwiller¹).

Age class	Average oven-dry stem weight, unextracted, bark-free		Average volume per stem	
	Fast-growing	Slow-growing	Fast-growing	Slow-growing
<i>Years</i>	-----	<i>Pounds</i>	-----	<i>Cubic feet</i>
15	172	39	7	1
30	581	155	23	6
45	1,338	482	54	19

GEOGRAPHIC LOCATION

Saucier and Taras (1969) have reviewed regional variation in specific gravity of six of the southern pines. From their data—and that of Larson (1957), Perry and Wang (1958), Goddard and Strickland (1962), Zobel et al. (1960), Mitchell and Wheeler (1959), Wheeler and Mitchell (1962), Mitchell (1964), and the USDA Forest Service (1965)—some patterns of geographic variation can be discerned. The 1969 publication of Saucier and Taras was based on the specific gravity of breast-height unextracted increment cores.

The "Southern wood density survey", published in 1965 by the USDA Forest Service tabulated calculated tree-average values. Figures 7-1 through 7-4 show these average values for sawtimber material in trees 9 inches d.b.h. and larger. In these figures it will be observed that gravities in South Carolina and Texas were not reported. However, the publication by Saucier and Taras (1969) includes data from several hundred trees in these areas.

For loblolly pine (fig. 7-1), specific gravity values average higher in the Gulf Coastal region and Atlantic Coastal regions than in inland areas. Specific gravity values increase from north to south, particularly in the western part of the range, the Midsouth and along the Atlantic Coast, but not in the Piedmont region of North Carolina, South Carolina, and Georgia.

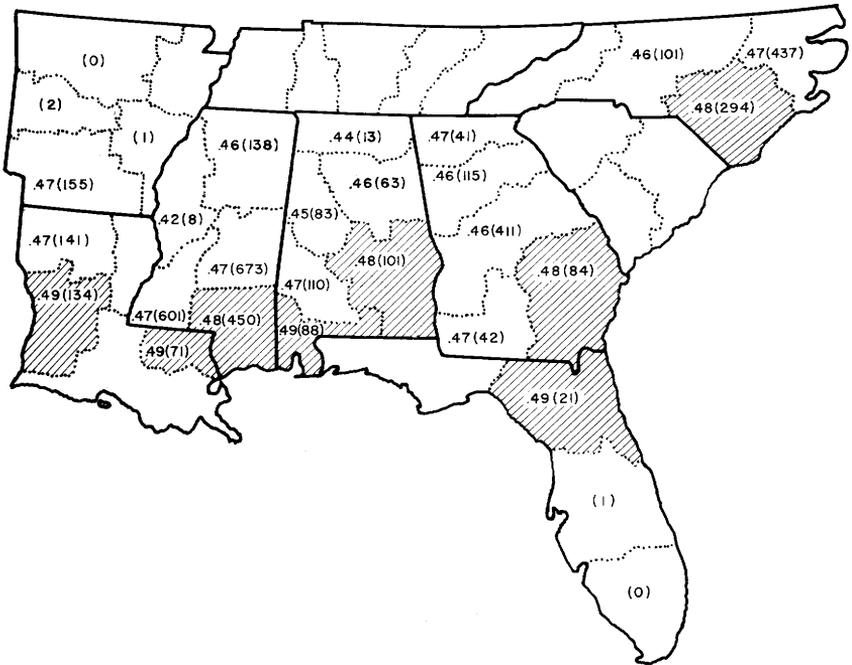


Figure 7-1.—Tree average specific gravity of loblolly pine sawtimber material in trees 9 inches d.b.h. and larger (unextracted, green volume and oven-dry weight basis); number of trees sampled shown in parentheses. Shaded areas exceeded species average of 0.47. (Drawing after USDA Forest Service 1965.)

For longleaf pine (fig. 7-2) specific gravity values appear highest in north Florida. Gravities increase from north to south in Texas, the Mid-south and along the Atlantic Coast from North Carolina to Florida.

For shortleaf pine (fig. 7-3), no overall north-south or east-west trends were evident. However, data from Saucier and Taras (1969) indicated that gravities increased from north to south in east Texas and in a region extending due south from eastern Kentucky to north-central Georgia.

For slash pine, specific gravity values are highest in Florida. The observed trend of increasing specific gravity from north to south in Florida reflects an increasing proportion of the relatively dense south Florida slash pine in the sample because no attempt was made to separate var. *elliottii* and var. *densa* Little and Dorman (fig. 7-4). Data from Saucier and Taras (1969) indicate that specific gravity values increase from north to south in Alabama; in their data an east-west trend was also discernible, i.e., gravity increased from Louisiana in the west to Florida in the east. Larson (1957), Perry and Wang (1958), and Goddard and Strickland (1962) observed a similar trend.

Of the minor species, pitch, pond, Virginia, and spruce pines have fairly extensive ranges; it appears, however, that only pitch pine (and possibly spruce pine), vary in specific gravity with geographic location.

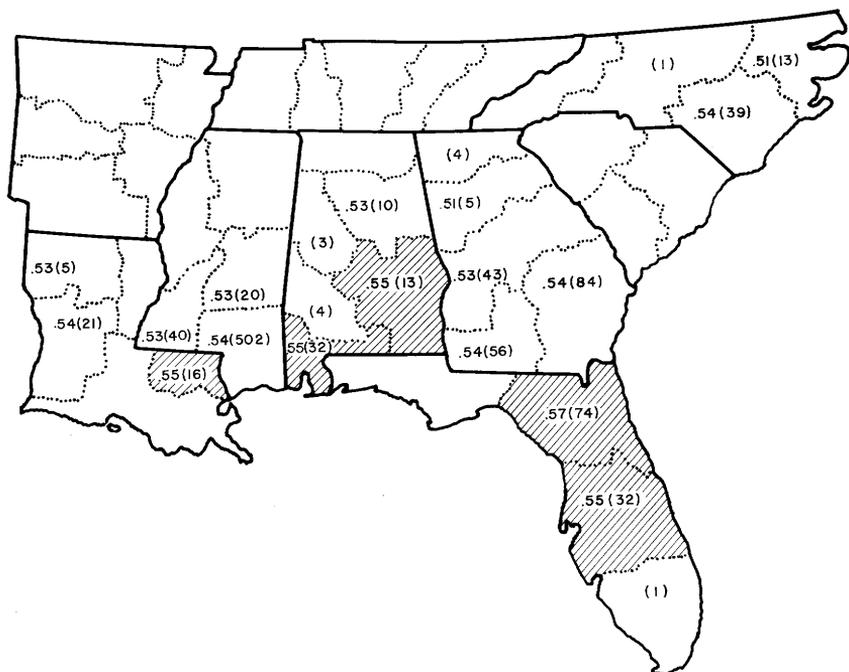


Figure 7-2.—Tree average specific gravity of longleaf pine sawtimber material in trees 9 inches d.b.h. and larger (unextracted, green volume and oven-dry weight basis); number of trees sampled shown in parentheses. Shaded areas averaged in excess of 0.54. (Drawing after USDA Forest Service 1965.)

Saucier and Clark (1970, table 4) reported that the average unextracted breast-height increment core specific gravity of pitch pine in North Carolina, South Carolina and Tennessee was 11.1 percent greater than the average in New England and New York; after extractives were removed, specific gravity of increment cores from the northeast region was still significantly below that in all other regions.

There appear to be no distinct north-south or east-west trends in specific gravity of spruce pine; plots sampled near the Coast had the highest specific gravity whereas inland plots were lower (Taras and Saucier 1968).

No geographic trends in specific gravity have been observed in pond pine (McElwee and Zobel 1963; Taras and Saucier 1970), sand pine (Clark and Taras 1969), Table-Mountain pine (Clark and Saucier 1969), or Virginia pine (Thor 1964; Clark and Wahlgren 1970).

7-6 WITHIN-TREE VARIATION

Specific gravity in stem wood varies across each annual ring, between adjacent rings, with radial position in the stem, and with height above the ground.

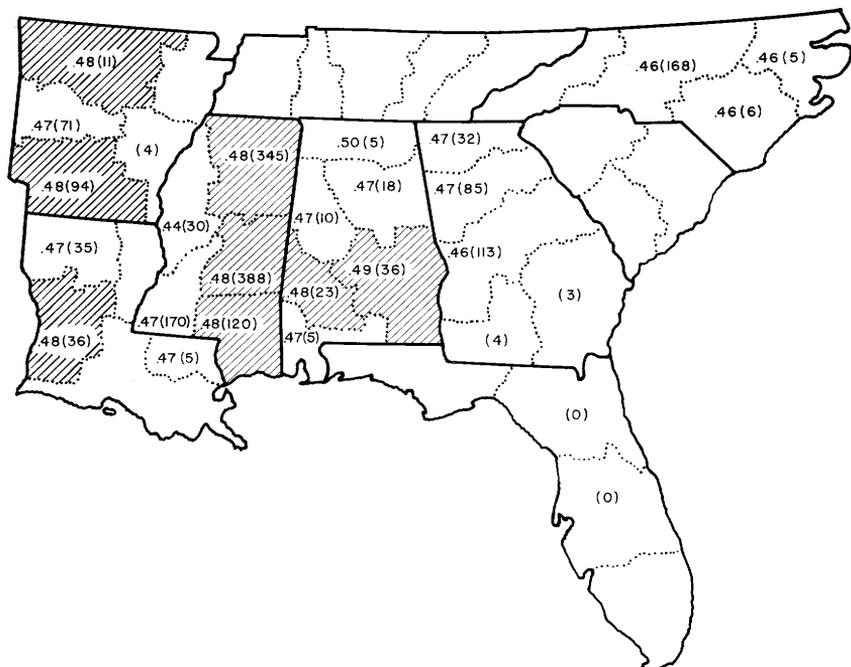


Figure 7-3.—Tree average specific gravity of shortleaf pine sawtimber material in trees 9 inches d.b.h. and larger (unextracted, green volume and oven-dry weight basis); number of trees sampled shown in parentheses. Shaded areas exceeded species average of 0.47. (Drawing after USDA Forest Service 1965.)

WITHIN ANNUAL INCREMENT

Latewood in the southern pines is two to three times as dense as earlywood. Some selected values (not represented as tree or species averages) are shown in table 7-6. All except the value for spruce pine (determined optically) and the Taras values for slash pines are for unextracted wood. Because of variation in gravity across increments, valid averages for earlywood and latewood can be achieved only if they are separated with precision. Weighted tree averages require sampling to account for variation with height and radial position in the stem.

Data published by Paul (1939), based on two- and three-tree samples of the major species, illustrate distinct specific gravity differences between earlywood and latewood, and the broad range of values in latewood (fig. 7-5). To make these determinations, specimens measuring $\frac{1}{2}$ -inch in the tangential direction and about 1 inch in length were separated into earlywood and latewood with a hand-held knife. Some of the overlap shown (fig. 7-5) between earlywood and latewood specific gravity probably resulted from less than perfect separation.

Ifju (1969) and Biblis (1969, p. 18) have illustrated in more detail the variation in specific gravity across single annual increments. Ifju's data

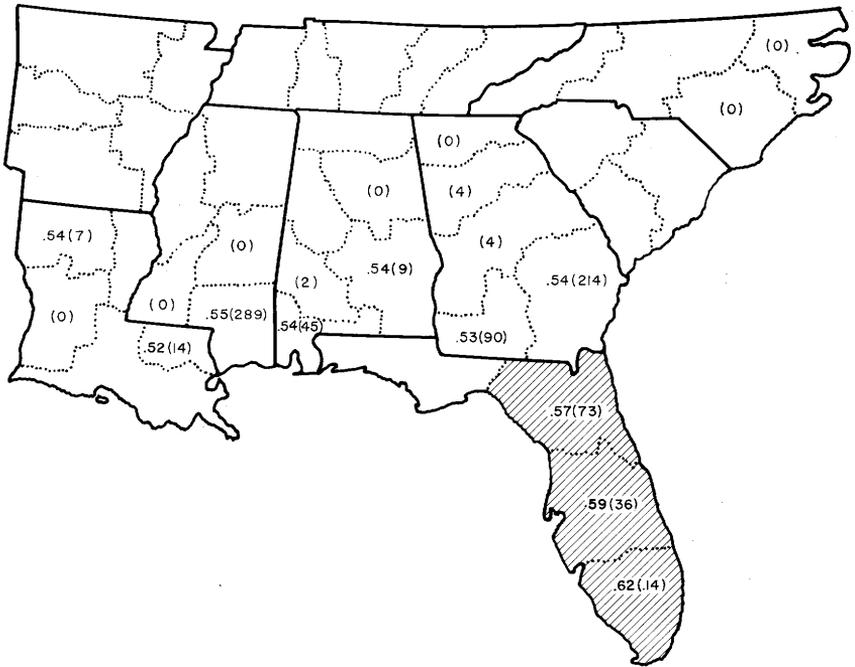


Figure 7-4.—Tree average specific gravity of slash pine sawtimber material in trees 9 inches d.b.h. and larger (unextracted, green volume and oven-dry weight basis); number of trees sampled shown in parentheses. Standard areas averaged in excess of 0.56. (Drawing after USDA Forest Service 1965.)

(based on single-tree samples of six species) are shown in figure 7-6; these regressions are of the form:

$$\hat{Y} = a + b \arctan \left(\frac{x+s}{10} - 10 \right) \quad (7-4)$$

where:

- Y = specific gravity at point of interest
- a is a constant
- b is a regression coefficient
- x = percent of distance across the increment
- s = percent latewood

In general, the equations accounted for 53 to 83 percent of the variation, with a standard error of the estimate of 0.09 to 0.14. The Virginia pine values are based on 60 observations; 120 to 215 observations established each of the other five equations.

There is a voluminous literature on the variations in latewood volume in southern pine trees. Section 4-3 discusses the physiological aspects of

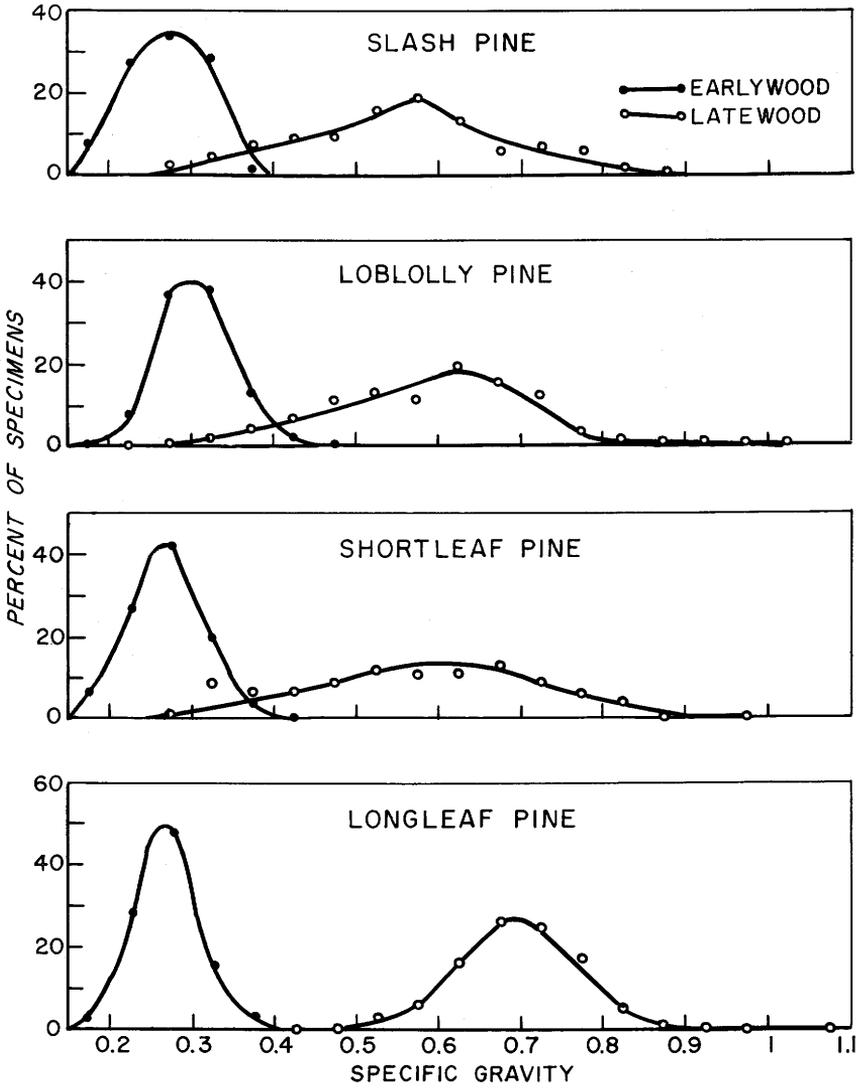


Figure 7-5.—Distribution of specific gravity among samples of unextracted earlywood and latewood of the major southern pines; green volume, oven-dry weight basis. (Drawing after Paul 1939.)

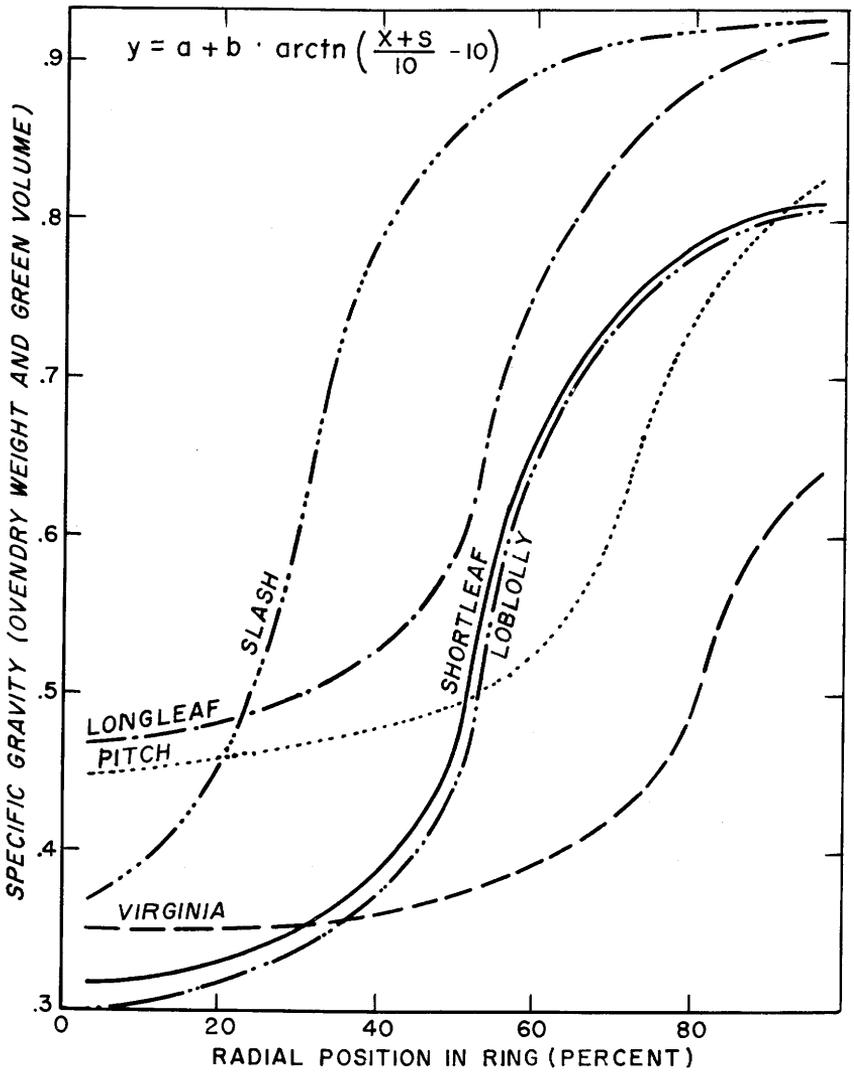


Figure 7-6.—Intra-increment specific gravity patterns observed in six southern pine trees. Based on 60 to 215 samples from a single tree of each species. (Drawing after Ifju 1969.)

TABLE 7-6.—*Specific gravity of earlywood and latewood of the southern pines; unextracted green volume, oven-dry weight basis (except as noted)*

Pine species	Trees	Early-wood	Late-wood	Comments	Reference
	<i>Number</i>				
Loblolly-----	3	0.31	0.63	¹	Paul (1939)
	1	.25	.65	²	Biblis (1969)
	1	.30	.80	²	Ifju (1969)
	40	.33	.78	O.D. vol.	Yao (1970)
	60	.32	.67	³	Goggans (1964)
	128	.29	.63	³	Goggans (1964)
	1	.34	.85	^{1,4}	Woodson & Koch (1969)
	-----	.30	.85	-----	Pillow & Luxford (1937)
Longleaf-----	2	.28	.69	⁴	Paul (1939)
	1	.47	.92	²	Ifju (1969)
Pitch-----	1	.45	.83	²	Ifju (1969)
Pond-----	1	.29	.64	^{1,6}	Koch ⁵
Sand					
Choctawhatchee---	1	.35	.66	^{1,7}	Koch ⁵
Ocala-----	1	.27	.58	^{1,8}	Koch ⁵
Shortleaf-----	2	.27	.60	¹	Paul (1939)
	1	.32	.81	²	Ifju (1969)
Slash-----	2	.28	.57	¹	Paul (1939)
	1	.37	.93	²	Ifju (1969)
	3	.30	.70	⁹	Taras (1965)
Spruce-----	72	.38	.69	¹⁰	Manwiller (text footnote ²)
Table-Mountain----	1	.30	.59	^{1,11}	Koch ⁵
Virginia-----	1	.35	.64	²	Ifju (1969)

¹ Average across entire increment of earlywood (or latewood).

² Value estimated from graph; gravities shown are for first-formed earlywood and last-formed latewood (see figure 7-6).

³ Seven- and 8-year-old trees.

⁴ Basis of oven-dry weight and oven-dry volume. Earlywood ranged from 0.29 to 0.42 with standard deviation of 0.036; latewood ranged from 0.77 to 0.96 with standard deviation of 0.046.

⁵ Unpublished data from USDA Forest Serv. study FS-SO-3201-5.8.

⁶ Weighted average from 83 observations of 67-year-old tree; earlywood range 0.20 to 0.38 with standard deviation of 0.041. Latewood range from 0.42 to 0.78 with standard deviation of 0.063.

⁷ Weighted average from 71 observations of 57-year-old tree; earlywood range 0.27 to 0.47 with standard deviation of 0.046. Latewood range from 0.43 to 0.88 with standard deviation of 0.086.

⁸ Weighted average from 37 observations of 58-year-old tree; earlywood range 0.19 to 0.34 with standard deviation of 0.031. Latewood range from 0.40 to 0.79 with standard deviation of 0.098.

⁹ Extracted wood. See figs. 7-7 through 7-9.

¹⁰ Each value is an average of 648 sample points representing a range of tree ages, radial positions, and heights; trees sampled throughout major range (extracted basis). See fig. 7-11.

¹¹ Weighted average from 21 observations of 50-year-old tree; earlywood range 0.23 to 0.41 with standard deviation of 0.047. Latewood range from 0.40 to 0.68 with standard deviation of 0.070.

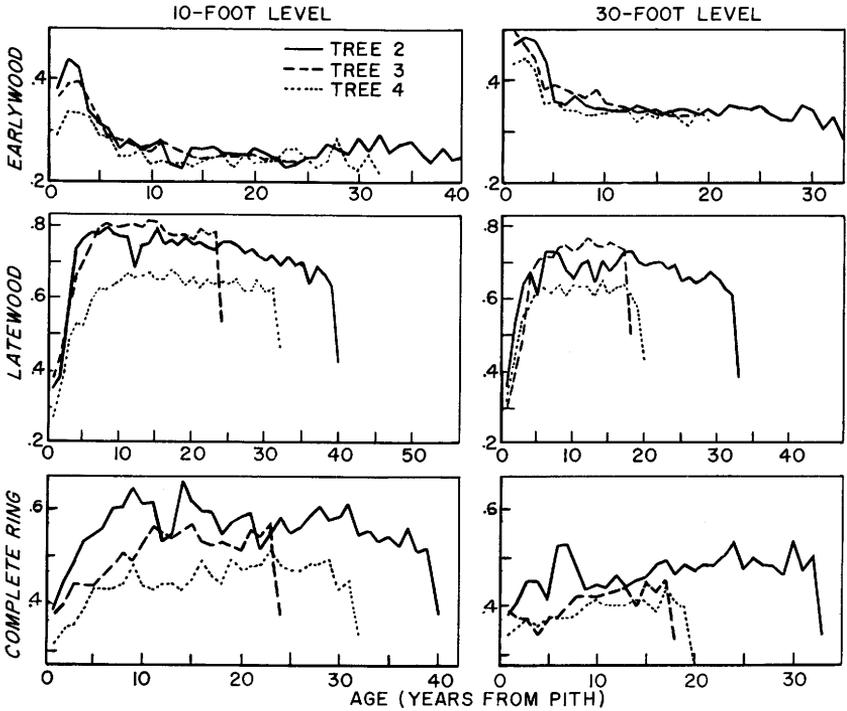


Figure 7-7.—Radial variation of specific gravity (after extraction, oven-dry weight and green volume basis) in earlywood, latewood, and complete growth rings of slash pine at two height levels. Latewood adjacent to bark had lower specific gravity because cell wall thickening was not complete. (Drawing after Taras 1965, pp. 51, 56, 60.)

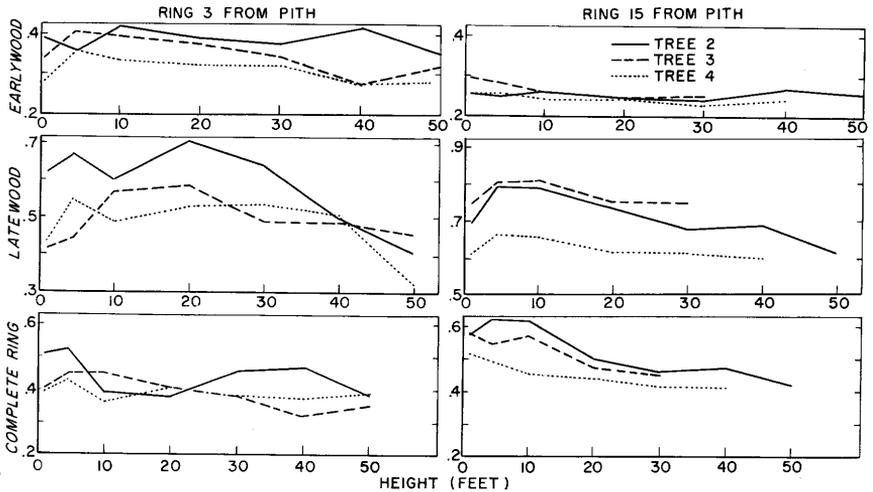


Figure 7-8.—Variation of specific gravity (after extraction, oven-dry weight and green volume basis) with height in earlywood, latewood, and the entire growth increment of the third and 15th rings from the pith of slash pine. (Drawing after Taras 1965, pp. 73, 76, 78.)

latewood formation. For the interested reader, following are a few references specific to southern pines.

<u>Pine species</u>	<u>References</u>	
Loblolly.....	Pew and Knechtes (1939) Young (1952) Pillow (1954) Zobel and Rhodes (1955, 1956) Yandle (1956) Zobel (1956) Van Buijtenen (1958) Zobel and McElwee (1958) Echols (1960) Zahner (1959, 1962) Zobel et al. (1959, 1960, 1961a, 1961b)	Smith and Wilsie (1961) Van Buijtenen et al. (1961) Goggans (1962) Paul (1963, p. 53-67) Posey (1964) Geyer and Gilmore (1965) Hamilton and Mathews (1965) McMillin (1968) Smith (1968) Biblis (1969) Ifju (1969) Yao (1970)
Longleaf.....	Marts (1950, 1951) Paul and Marts (1954)	Paul (1963, p. 53-67)
Shortleaf.....	McGinnes (1963) Paul (1963, p. 53-67)	Hamilton and Mathews (1965) Ralston and McGinnes (1964)
Slash.....	Larson (1957) Perry and Wang (1958) Dadswell and Nichols (1959) Miller (1959) Zobel et al. (1959)	Williams and Hamilton (1961) Walker and Youngberg (1962) Taras (1965) White and Saucier (1965)

Percentage of latewood is readily measured, but because of sampling expense few species averages are published. Manwiller¹ found that in 72 spruce pines sampled throughout the major commercial range of the species, latewood percentages varied with tree growth rate (but not with tree age classes of 15, 30, 45 years) as follows:

<u>Growth rate 1 foot above ground level</u>	<u>Tree-average latewood content</u>
<i>Rings per inch</i>	<i>Percent</i>
Less than 6	25.4
More than 6	30.8
Average	28.1

WITH POSITION IN TREE

The specific gravity of stemwood is a function of the densities of earlywood and latewood and the relative proportion of each in the wood. All three of these factors vary with radial distance from the pith and height in the tree. Taras' (1965) three-tree sample provided data specific to the southern pine of greatest density (slash pine) by individual growth incre-

² Manwiller, F. G. Variation of transverse cellular dimensions and specific gravity in stems of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201.8 dated May 1, 1972.

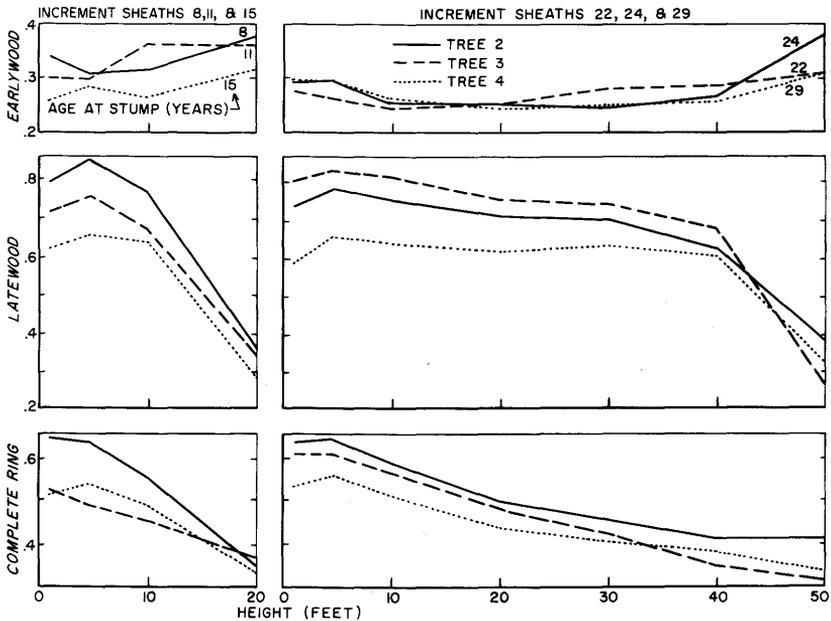


Figure 7-9.—Variation of specific gravity (after extraction, oven-dry weight and green volume basis) with height for earlywood, latewood, and the entire growth increment, in selected increment sheaths of slash pine. (Drawing after Taras 1965, pp. 81, 84, 86.)

ments at 6 height levels (figs. 7-7 through 7-10). Manwiller's² study of 72 spruce pine trees gives information on the species of least density (fig. 7-11). In both of these studies, specific gravity is given for extracted wood on the basis of green volume and oven-dry weight. The following observations, while specific to slash and spruce pines, probably apply to the other southern pines as well, e.g., Smith's³ unpublished data on loblolly pine, Hiller's (1964) data on latewood of slash and loblolly pines, and Yao's (1970) study of loblolly pine tend to confirm these patterns.

The specific gravity of earlywood is negatively correlated with number of rings from the pith (figs. 7-7 and 7-11); in contrast, latewood specific gravity shows positive correlation with age during the first 10 years or so (figs. 7-7 and 7-11). Specific gravity of the combined earlywood and latewood increases sharply with radial distance from the pith until ring 5 to 10; it may increase slowly to about ring 30 (fig. 7-7). In other trees, specific gravity changes relatively little beyond age 10 or 15.

When rings of the same age with respect to the pith are compared, earlywood specific gravity shows minor changes with height in the tree (figs. 7-8 and 7-11); the specific gravity of earlywood is highest near the

³ Smith, D. Pattern of variation of wood structure and properties within trees of southern pine and the influence of environmental factors on their patterns. Presented at the symposium on wood and wood fiber quality in relation to the southern pulp and paper industry. At North Carolina State University, Raleigh, N.C., November 14-16, 1962.

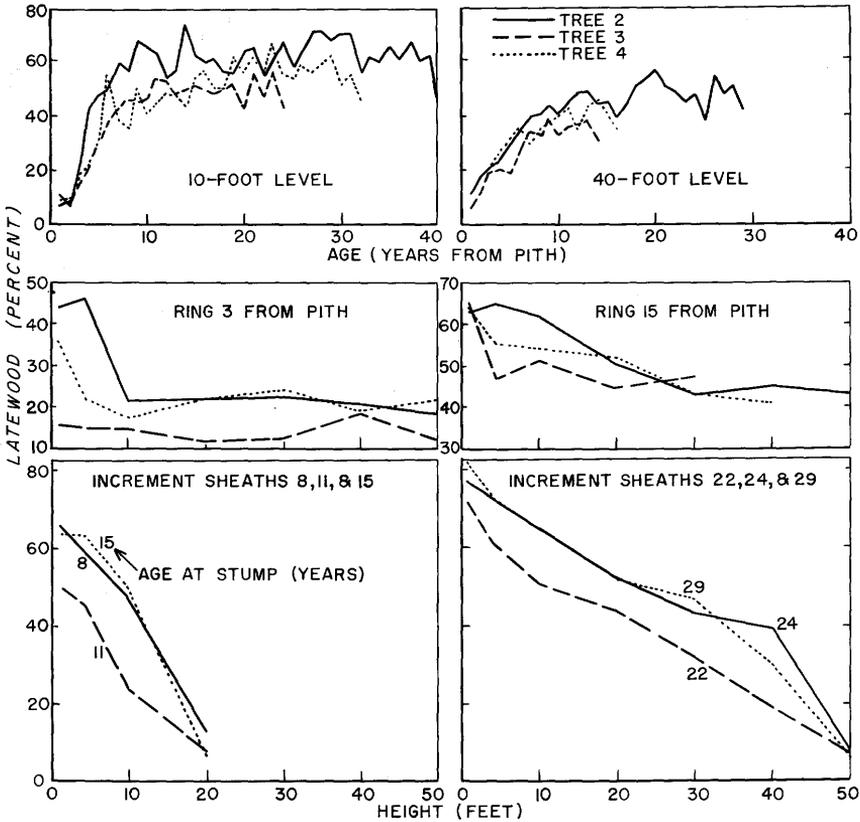


Figure 7-10.—Variation in percentage of latewood in slash pine in relation to height and radial position in the tree, and age of ring at stump. (Top) With radial position at two height levels. (Middle) With height at two radial positions. (Bottom) With height within selected growth increment sheaths. (Drawing after Taras 1965, pp. 92, 99, 101.)

base of the tree. Latewood in the first ring of slash pine shows no discernible trends with height in the tree; specific gravity of latewood 5 and 15 years from the pith (fig. 7-8), however, reaches a maximum at about 10 to 20 feet above ground level and then decreases slowly with additional height (Taras 1965). Manwiller's² data show that the specific gravity of spruce pine latewood (when measured at a constant number of rings from the pith) also is negatively correlated with height above ground level (fig. 7-11).

Specific gravity of entire slash pine rings is negatively correlated with height if sampled at a constant number of rings from the pith (fig. 7-8).

The Taras (1965) data on slash pine also show that within a given increment sheath, the specific gravity of earlywood is positively correlated with height once a certain minimum is reached. The minimum occurs about breast height in sheaths 20 feet high, about 10 feet in sheaths 30 feet high, and about 20 feet in sheaths 40 to 50 feet high (fig. 7-9).

For latewood increment sheaths in slash pine, Taras (1965) shows that

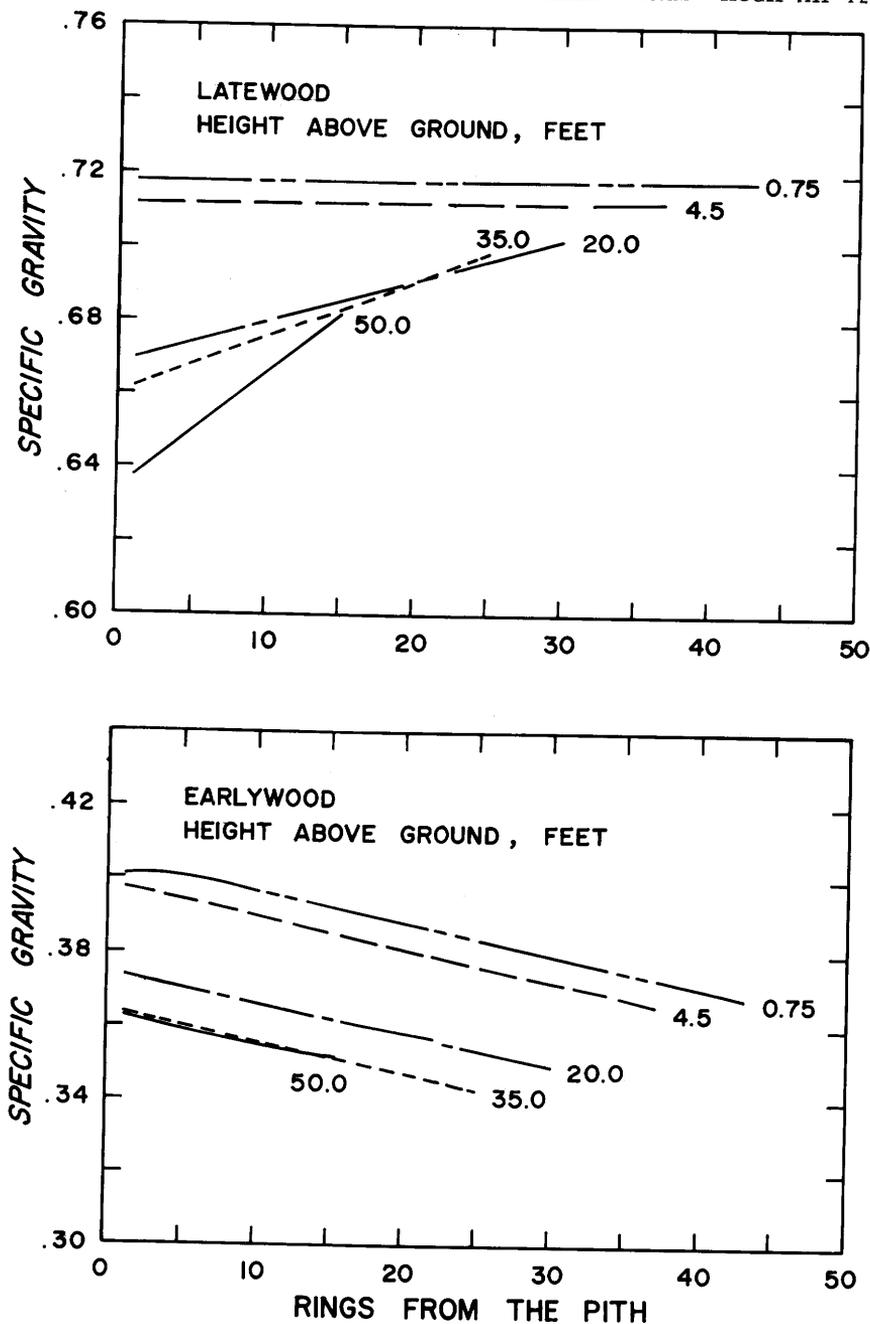


Figure 7-11.—Extracted specific gravity (basis of oven-dry weight and green volume) of spruce pine earlywood and latewood as related to height above ground and number of rings from the pith. These curves, established by sampling 72 trees at three heights and three radial positions, are based on regression equations that account for only a limited proportion of the observed variation, i.e., 9 percent for earlywood and 17 percent for latewood. (Drawing after Manwiller².)

specific gravity is relatively high at ground level; it increases to a maximum at breast height and thereafter decreases (fig. 7-9).

For an entire increment sheath, the specific gravity is nearly constant to breast height (probably maximum at breast height) and then decreases with height (fig. 7-9).

Figure 7-10 shows percentage of latewood as a function of both height in the tree and years from the pith. In entire cross sections of slash pine, Taras (1965) found that percentage of latewood decreased with height; the largest proportion of latewood was found near the base of the tree. He also found a negative correlation when percentage of latewood at a constant number of rings from the pith was plotted against height; also, within a given increment sheath, there was a strong negative correlation between percentage of latewood and height (fig. 7-10).

The findings of Taras (1965) on within-tree variation of percentage of latewood are probably typical of the major southern pine species. In Manwiller's¹ study of spruce pine, however, he did not find that percentage of latewood was a strong function of height in tree or radial position.

7-7 METHODS FOR COMPUTING AND ESTIMATING SPECIFIC GRAVITY

It is not the purpose of this text to dwell on methodology; however, the interested reader may wish to pursue the subject. Some references follow:

To measure small pieces of wood

Paul and Baudendistel (1943)	USDA Forest Products Laboratory
Heinrichs (1954)	(1956)
Smith (1954, 1961, 1965)	Browning (1967, ch. 18)
	Wangaard (1969)

To measure logs, fitches, and bolts

Pillow (1951)	Pronin (1968)
---------------	---------------

To estimate tree specific gravity from breast-height increment cores

<u>Pine species</u>	<u>Reference</u>
Loblolly.....	Wahlgren and Fassnacht (1959) Gilmore et al. (1961) Christopher and Wahlgren (1964) USDA Forest Service (1965) Burkhart and Beckwith (1970) Wahlgren and Yandle (1970)
Longleaf.....	Wahlgren and Fassnacht (1959) Taras and Wahlgren (1963) USDA Forest Service (1965)
Pitch.....	Saucier and Clark (1970)
Pond.....	Taras and Saucier (1970)
Sand.....	Clark and Taras (1969)
Shortleaf.....	Wahlgren and Fassnacht (1959) Gilmore et al. (1961) Christopher and Wahlgren (1964) USDA Forest Service (1965)

<u>Pine species</u>	<u>Reference</u>
Slash.....	Wahlgren and Fassnacht (1959) Taras and Wahlgren (1963) USDA Forest Service (1965) Clark and Taras (1970)
Spruce.....	Taras and Saucier (1968)
Table- Mountain---	Clark and Saucier (1969)
Virginia.....	Clark and Wahlgren (1970) Smith and Wahlgren (1970)

To estimate average specific gravity of an entire species or large block of timber

- By random sample: Bendtsen (1968)
 By random sample stratified according to age and growth rate: Manwiller¹
 By random sample of breast-height increment cores: Taras and Saucier (1968)

7-8 LITERATURE CITED

- Bendtsen, B. A.
 1968. Mechanical properties and specific gravity of a randomly selected sample of spruce pine. USDA Forest Serv. Res. Pap. FPL-92, 8 pp. Forest Prod. Lab., Madison, Wis.
- Bendtsen, B. A., and Ethington, R. L.
 1972. Properties of major southern pines: Part II—Structural properties and specific gravity. USDA Forest Serv. Res. Pap. FPL 177.
- Biblis, E. J.
 1969. Transitional variation and relationships among properties within loblolly pine growth rings. Wood Sci. and Technol. 3: 14-24.
- Browning, B. L.
 1967. Methods of wood chemistry. Vol. 1, 384 pp. N.Y.: Interscience Pub.
- Burkhart, H. E., and Beckwith, J. R.
 1970. Specific gravity prediction and dry-weight yield estimation. TAPPI 54: 603-604.
- Christopher, J. F., and Wahlgren, H. E.
 1964. Estimating specific gravity of south Arkansas pine. USDA Forest Serv. Res. Pap. SO-14, 10 pp. South. Forest Exp. Sta., New Orleans, La.
- Clark, A., III, and Saucier, J. R.
 1969. Wood density surveys of the minor species of yellow pine in the Eastern United States. III. Table-Mountain pine (*Pinus pungens* Lamb.). USDA Forest Serv. Res. Pap. SE-52, 12 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Clark, A., III, and Taras, M. A.
 1969. Wood density surveys of the minor species of yellow pine in the Eastern United States. II. Sand pine (*Pinus clausa* (Chapm.) Vasey). USDA Forest Serv. Res. Pap. SE-51, 14 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Clark, A. A., III, and Taras, M. A.
 1970. Wood density surveys of the minor species of yellow pine in the Eastern United States. Part VII—South Florida slash pine (*Pinus elliottii* var. *densa* Little & Dorman). USDA Forest Serv. Res. Pap. SE-66, 11 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Clark, A., and Wahlgren, H. E.
 1970. Wood density surveys of the minor species of yellow pine in the Eastern United States. V. Virginia pine (*Pinus virginiana* Mill.). USDA Forest Serv. Res. Pap. SE-64, 11 pp. Southeast. Forest Exp. Sta., Asheville, N.C.

- Cole, D. E., Zobel, B. J., and Roberds, J. H.
1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. TAPPI 49: 161-166.
- Dadswell, H. E., and Nicholls, J. W. P.
1959. Assessment of wood qualities for tree breeding. I. CSIRO Div. Forest Prod. Tech. Pap. 4, 16 pp.
- Dunlap, F.
1914. Density of wood substance and porosity of wood. J. Agr. Res. 2: 423-428.
- Echols, R. M.
1960. Effects of growing space on wood specific gravity in loblolly pine. Soc. Amer. Forest. Proc. 1959: 140-143.
- Geyer, W. A., and Gilmore, A. R.
1965. Effect of spacing on wood specific gravity of loblolly pine in southern Illinois. Ill. Agr. Exp. Sta. Forest. Note 113, 5 pp.
- Gilmore, A. R., Metcalf, G. E., and Boggess, W. R.
1961. Specific gravity of shortleaf pine and loblolly pine in southern Illinois. J. Forest. 59: 894-896.
- Goddard, R. E., and Strickland, R. K.
1962. Geographic variation in wood specific gravity of slash pine. TAPPI 45: 606-608.
- Goggans, J. F.
1962. The correlation, variation, and inheritance of wood properties in loblolly pine [*Pinus taeda* L.]. N.C. State Coll. Sch. Forest. Tech. Rep. 14, 155 pp.
- Goggans, J. F.
1964. Correlation and heritability of certain wood properties in loblolly pine (*Pinus taeda* L.). TAPPI 47: 318-322.
- Hamilton, J. R., and Mathews, R. M.
1965. Wood characteristics of planted loblolly and shortleaf pine. Ga. Forest Res. Pap. 27, 5 pp. Ga. Forest Res. Council.
- Harris, J. M.
1967. Latewood, earlywood, and wood density. Fourteenth IUFRO Congr., Vol. 9, Sect. 41, pp. 56-59. München.
- Heinrichs, J. F.
1954. Rapid specific gravity determinations. J. Forest Prod. Res. Soc. 4: 68.
- Hiller, C. H.
1964. Correlation of fibril angle with wall thickness of tracheids in summerwood of slash and loblolly pine. TAPPI 47: 125-128.
- Ifju, G.
1969. Within-growth-ring variation in some physical properties of southern pine wood. Wood Sci. 2: 11-19.
- Jurbergs, K. A.
1963. Determining fiber length, fibrillar angle, and springwood - summerwood ratio in slash pine. Forest Sci. 9: 181-187.
- Kellogg, R. M., and Wangaard, F. F.
1969. Variation in the cell-wall density of wood. Wood and Fiber 1: 180-204.
- Larson, P. R.
1957. Effect of environment on the percentage of summerwood and specific gravity of slash pine. Yale Univ. Sch. Forest. Bull. 63, 89 pp.
- Marts, R. O.
1950. Wood quality of bud-pruned longleaf pine. South. Lumberman 181(2273): 197-199.
- Marts, R. O.
1951. Influence of crown reduction on springwood and summerwood distribution in longleaf pine. J. Forest. 49: 183-189.
- McElwee, R. L., and Zobel, B. J.
1963. Some wood and growth characteristics of pond pine. Forest Genet. Workshop Proc. 1962: 19-25. Macon, Ga.
- McGinnes, E. A.
1963. Growth-quality evaluation of Missouri-grown shortleaf pine (*Pinus echinata* Mill.). Mo. Agr. Exp. Sta. Res. Bull. 841, 59 pp.
- McMillin, C. W.
1968. Morphological characteristics of loblolly pine wood as related to specific gravity, growth rate, and distance from the pith. Wood Sci. and Technol. 2: 166-176.
- Miller, S. R., Jr.
1959. Variation in inherent wood characteristics in slash pine. Fifth South. Conf. on Forest Tree Impr. Proc. 1959: 97-106.

- Mitchell, H. L.
1964. Patterns of variation in specific gravity of southern pines and other coniferous species. TAPPI 47: 276-283.
- Mitchell, H. L., and Wheeler, P. R.
1959. Wood quality of Mississippi's pine resources. USDA Forest Serv. Forest Prod. Lab. Rep. 2143, 20 pp.
- Paul, B. H.
1939. Variation in the specific gravity of the springwood and summerwood of four species of southern pines. J. Forest. 37: 478-482.
- Paul, B. H.
1963. The application of silviculture in controlling the specific gravity of wood. USDA Tech. Bull. 1288, 97 pp.
- Paul, B. H., and Baudendistel, M. E.
1943. A field method of determining specific gravity by use of increment cores or auger chips. USDA Forest Serv. Forest Prod. Lab. Rep. 1587, 7 pp.
- Panshin, A. J., DeZeeuw, C., and Brown, H. P.
1964. Textbook of wood technology. 643 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Paul, B. H., and Marts, R. O.
1954. Controlling the proportions of summerwood in longleaf pine. USDA Forest Serv. Forest Prod. Lab. Note 1988, 6 pp.
- Perry, T. O., and Wang, C. W.
1958. Variation in the specific gravity of slash pinewood and its genetic and silvicultural implications. TAPPI 41: 178-180.
- Pew, J. C., and Knechtges, R. G.
1939. Cross-section dimensions of fibers in relation to paper-making properties of loblolly pine. South. Pulp and Pap. J. 2(4): 7-9.
- Pillow, M. Y., and Luxford, R. F.
1937. Structure, occurrence, properties of compression wood. USDA Tech. Bull. 546, 32 pp.
- Pillow, M. Y.
1951. Simplified procedure for determining oven-dry specific gravity of fitches and bolts. USDA Forest Serv. Forest Prod. Lab. Rep. 1790, 8 pp.
- Pillow, M. Y.
1954. Specific gravity relative to characteristics of annual rings in loblolly pine. USDA Forest Serv. Forest Prod. Lab. Rep. 1989, 23 pp.
- Posey, C. E.
1964. The effects of fertilization upon wood properties of loblolly pine (*Pinus taeda* L.). N.C. State Univ. Sch. Forest. Tech. Rep. 22, 62 pp.
- Posey, C. E., and Robinson, D. W.
1969. Extractives of shortleaf pine—an analysis of contributing factors and relationships. TAPPI 52: 110-115.
- Pronin, D.
1966. Methods for estimating specific gravity of logs. USDA Forest Serv. Res. Note FPL-0110, 9 pp. Forest Prod. Lab., Madison, Wis.
- Ralston, R. A., and McGinnes, E. A., Jr.
1964. Shortleaf pine wood density unaffected by ring growth. South. Lumberman 208(2592): 17-19.
- Saucier, J. R., and Clark, A.
1970. Wood density surveys of the minor species of yellow pine in the Eastern United States. USDA Forest Serv. Res. Pap. SE-63, 16 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Saucier, J. R., and Taras, M. A.
1969. Regional variation in specific gravity of seven pines in the Southern United States. USDA Forest Serv. Res. Pap. SE-45, 16 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Schafer, E. R.
1949. The influence of volume of summerwood and rate of growth on the specific gravity of southern pine pulpwood. Southern Pulp and Pap. Manufacturer 12(10A): 166-168.
- Smith, D. M.
1954. Maximum moisture content method for determining specific gravity of small wood samples. USDA Forest Serv. Forest Prod. Lab. Rep. 2014, 8 pp.

- Smith, D.
1961. Method of determining specific gravity of wood chips. USDA Forest Serv. Forest Prod. Lab. Rep. 2209, 8 pp.
- Smith, D. M.
1965. Rapid measurement of tracheid cross-sectional dimensions of conifers: its application to specific gravity determinations. Forest Prod. J. 15: 325-334.
- Smith, D. M.
1968. Wood quality of loblolly pine after thinning. USDA Forest Serv. Res. Pap. FPL-89, 10 pp. Forest Prod. Lab., Madison, Wis.
- Smith, D. M., and Wahlgren, H. E.
1971. Half a core gives better results in core-to-tree specific gravity relationships. TAPPI 54: 60-62.
- Smith, D. M., and Wilsie, M.
1961. Some anatomical responses of loblolly pine to soil-water deficiencies. TAPPI 44: 179-185.
- Stamm, A. J.
1929. Density of wood substance, adsorption by wood, and permeability of wood. J. Phys. Chem. 33: 398-414.
- Stamm, A. J., and Sanders, H. T.
1966. Specific gravity of the wood substance of loblolly pine as affected by chemical composition. TAPPI 49: 397-400.
- Stayton, C. L., and Hart, C. A.
1965. Determining pore-size distribution in softwoods with a mercury porosimeter. Forest Prod. J. 15: 435-440.
- Taras, M. A.
1965. Some wood properties of slash pine (*Pinus elliotii* Engelm.) and their relationship to age and height within the stem. Ph.D. Thesis. Univ. N.C. Raleigh. 157 pp.
- Taras, M. A., and Saucier, J. R.
1967. Influence of extractives on specific gravity of southern pine. Forest Prod. J. 17(9): 97-99.
- Taras, M. A., and Saucier, J. R.
1968. Wood density surveys of the minor species of yellow pine in the Eastern United States. I. Spruce pine (*Pinus glabra* Walt.). USDA Forest Serv. Res. Pap. SE-34, 15 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Taras, M. A., and Saucier, J. R.
1970. Wood density surveys of the minor species of yellow pine in the Eastern United States. VI. Pond pine (*Pinus serotina* Michx.). USDA Forest Serv. Res. Pap. SE-65, 12 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Taras, M. A., and Wahlgren, H. E.
1963. A comparison of increment core sampling methods for estimating tree specific gravity. USDA Forest Serv. Res. Pap. SE-7, 16 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Thor., E.
1964. Variation in Virginia pine. Part I. Natural variation in wood properties. J. Forest. 62: 258-262.
- USDA Forest Products Laboratory.
1955. Wood handbook. USDA Agr. Handbook 72, 528 pp.
- USDA Forest Products Laboratory.
1956. Methods of determining the specific gravity of wood. USDA Forest Serv. Forest Prod. Lab. Tech. Note B-14, 6 pp.
- USDA Forest Service.
1965. 1965 Status report. Southern wood density survey. USDA Forest Serv. Res. Pap. FPL-26, 38 pp. Forest Prod. Lab., Madison, Wis.
- Van Buijtenen, J. P.
1958. Experimental control of environmental factors and their effect upon some aspects of wood anatomy in loblolly pine. TAPPI 41: 175-178.
- Van Buijtenen, J. P., Zobel, B. J., and Joranson, P. N.
1961. Variation of some wood and pulp properties in an even-aged loblolly pine stand. TAPPI 44: 141-144.
- Wahlgren, H. E., and Fassnacht, D. L.
1959. Estimating tree specific gravity from a single increment core. USDA Forest Serv. Forest Prod. Lab. Rep. 2146, 9 pp.

- Wahlgren, H. E., and Yandle, D. O.
1970. Development of a model for estimating tree specific gravity of loblolly pine. *Wood Sci.* 2: 129-135.
- Walker, L. C., and Youngberg, C. T.
1962. Response of slash pine to nitrogen and phosphorus fertilization. *Soil Sci. Soc. Amer. Proc.* 26: 399-401.
- Wangaard, F. F.
1969. Cell-wall density of wood with particular reference to the southern pines. *Wood Sci.* 1: 222-226.
- Wheeler, P. R., and Mitchell, H. L.
1962. Specific gravity variation in Mississippi pines. USDA Forest Serv. Forest Prod. Lab. Rep. 2250, 10 pp.
- White, J. F., and Saucier, J. R.
1966. A comparison of the specific gravity of two slash pine varieties grown in south Florida. *TAPPI* 49: 230-232.
- Wilfong, J. G.
1966. Specific gravity of wood substance. *Forest Prod. J.* 16(1): 55-61.
- Williams, R. F., and Hamilton, J. R.
1961. The effect of fertilization on four wood properties of slash pine. *J. Forest.* 59: 662-665.
- Woodson, G. E., and Koch, P.
1970. Tool forces and chip formation in orthogonal cutting of loblolly pine. USDA Forest Serv. Res. Pap. SO-52, 25 pp. South. Forest Exp. Sta., New Orleans, La.
- Yandle, D. O.
1956. Statistical evaluation of the effect of age on specific gravity in loblolly pine. USDA Forest Serv. Forest Prod. Lab. Rep. 2049, 4 pp.
- Yao, J.
1970. Influence of growth rate on specific gravity and other selected properties of loblolly pine. *Wood Sci. and Technol.* 4: 163-175.
- Young, H. E.
1952. Differential time of change from earlywood to latewood along the bole of young loblolly pine trees. *J. Forest.* 50: 614-615.
- Zahner, R.
1959. Fertilizer trials with loblolly pine in southern Arkansas. *J. Forest.* 57: 812-816.
- Zahner, R.
1962. Terminal growth and wood formation by juvenile loblolly pine under two soil moisture regimes. *Forest Sci.* 8: 345-352.
- Zobel, B. J.
1956. Genetic, growth, and environmental factors affecting specific gravity of loblolly pine. *Forest Prod. J.* 6: 442-447.
- Zobel, B. J., and McElwee, R. L.
1958. Natural variation in wood specific gravity of loblolly pine, and an analysis of contributing factors. *TAPPI* 41: 158-161. *Pages 12, 14, 16.*
- Zobel, B. J., Goggans, J. F., Maki, T. E., and Henson, F.
1961a. Some effects of fertilizers on wood properties of loblolly pine. *TAPPI* 44: 186-192.
- Zobel, B., McElwee, R. L., and Browne, C.
1961. Interrelationship of wood properties of loblolly pine. Sixth South. Forest Tree Impr. Conf. Proc. 1961: 142-163.
- Zobel, B., Ralston, J., and Roberds, J. H.
1965. Wood yields from loblolly pine stands of different age, site, and stand density. N.C. State Univ. School of Forestry Tech. Rep. 26, 23 pp.
- Zobel, B. J., and Rhodes, R. R.
1955. Relationship of wood specific gravity in loblolly pine to growth and environmental factors. *Tex. Forest Serv. Tech. Rep.* 11, 32 pp.
- Zobel, B., and Rhodes, R.
1956. Specific gravity estimations of mature loblolly pine from juvenile wood and seedling limb sections. *Forest Sci.* 2: 107-112.
- Zobel, B., Thorbjornsen, E., and Henson, F.
1960. Geographic, site and individual tree variation in wood properties of loblolly pine. *Silvae Genet.* 9: 149-158.
- Zobel, B. J., Webb, C., and Henson, F.
1959. Core or juvenile wood of loblolly and slash pine trees. *TAPPI* 42: 345-356.

8

Wood-water relationships

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8

Wood-water relationships

Living southern pines commonly contain about 1 pound of water for each pound of dry wood. In use, wood generally serves best if most of this water is removed because many of the desirable properties of wood are negatively correlated with its moisture content. Some utilization processes require that water solutions of various chemicals be made to penetrate wood. For these reasons, it is desirable to know the location of water in wood and the manner of its movement.

Moisture content is usually expressed as a percentage of the oven-dry weight of wood.

Percentage moisture content

$$= \frac{(\text{weight of wood with moisture} - \text{oven-dry weight of wood})}{\text{oven-dry weight of wood}} (100) \quad (8-1)$$

The oven-dry weight of wood is measured after drying it to a constant weight in an oven held at 101° to 105° C.

There are numerous methods of measuring and computing moisture content. The interested reader will find techniques described in the following references.

<u>Method</u>	<u>Reference</u>
Ovendrying -----	Browning (1967, p. 61) American Society for Testing and Materials (1968, p. 682)
Vacuum drying -----	Browning (1967, p. 62) Loos and Robinson (1968)
Distillation -----	Browning (1967, p. 62) American Society for Testing and Materials (1968, p. 689)
Karl Fischer titration -----	Browning (1967, p. 65) Loos and Robinson (1968)
Electric moisture meter -----	James (1963, 1965, 1968) American Society for Testing and Materials (1968, p. 683)
Probe -----	Duff (1966) Hill and Munkittrick (1970)

<u>Method</u>	<u>Reference</u>
Electric hygrometer -----	American Society for Testing and Materials (1968, p. 693)
Microwave absorption -----	Lowery and Kotok (1967) Busker (1968) Lundstrom (1970)
Nuclear magnetic resonance -----	Wall (1958) Swanson et al. (1962) Bersenev et al. (1963)
Nuclear radiation -----	Kajanne and Hollming (1958) Loos (1961, 1965) Gibson and Rusten (1964)
Infrared backscatter gage -----	Beutler (1965)

8-1 MOISTURE CONTENT IN LIVING TREES

The water content of wood in southern pine trees varies among species, within species, and within trees.

VARIATION AMONG SPECIES

Because of the difficulty in sampling entire species populations, comparative information is scarce. Choong (1969b) has summarized available data. Comparisons among species are meaningful only if made for trees of the same age. Miller (1959), Quijada (1967), Zobel et al. (1968), and Schroeder and Phillips (1972) have provided data that permit evaluation by age class. Table 8-1 shows estimated tree-average values at age 30 for six of the 10 southern pine species. In arriving at this tabulation, moisture determinations based on breast-height increment cores were given less credence than weighted evaluations of entire stems based on disks taken at several heights.

TABLE 8-1.—*Moisture content of wood in stems of 30-year-old living pine trees¹*

<u>Pine species</u>	<u>Moisture content ²</u>
	<i>Percent</i>
Loblolly -----	110
Longleaf -----	100
Shortleaf -----	110
Slash -----	90
Spruce -----	120
Virginia -----	100

¹ Species-average values estimated from a survey of the literature. There are no published data on the moisture contents of pitch, pond, sand, or Table-Mountain pines.

² Defined by equation 8-1.

VARIATION WITHIN SPECIES

The moisture content of standing southern pines has an inverse correlation with tree age, i.e., young trees have higher moisture contents than older trees (Lindgren 1949; Quijada 1967; Zobel et al. 1968). Contributing to this relationship is the fact that juvenile wood—if heartwood has not yet formed—characteristically has a much higher moisture content than mature wood. Young trees have a greater proportion of their volume in juvenile wood than older trees. Figure 8-1 illustrates the tree age-moisture content relationship for loblolly pine. Data from Zobel et al. (1968) suggest that tree-average moisture contents in Virginia pine are lower and vary less with tree age than those in loblolly and shortleaf (fig. 8-2). Lindgren (1949) found that moisture content in slash pine decreased

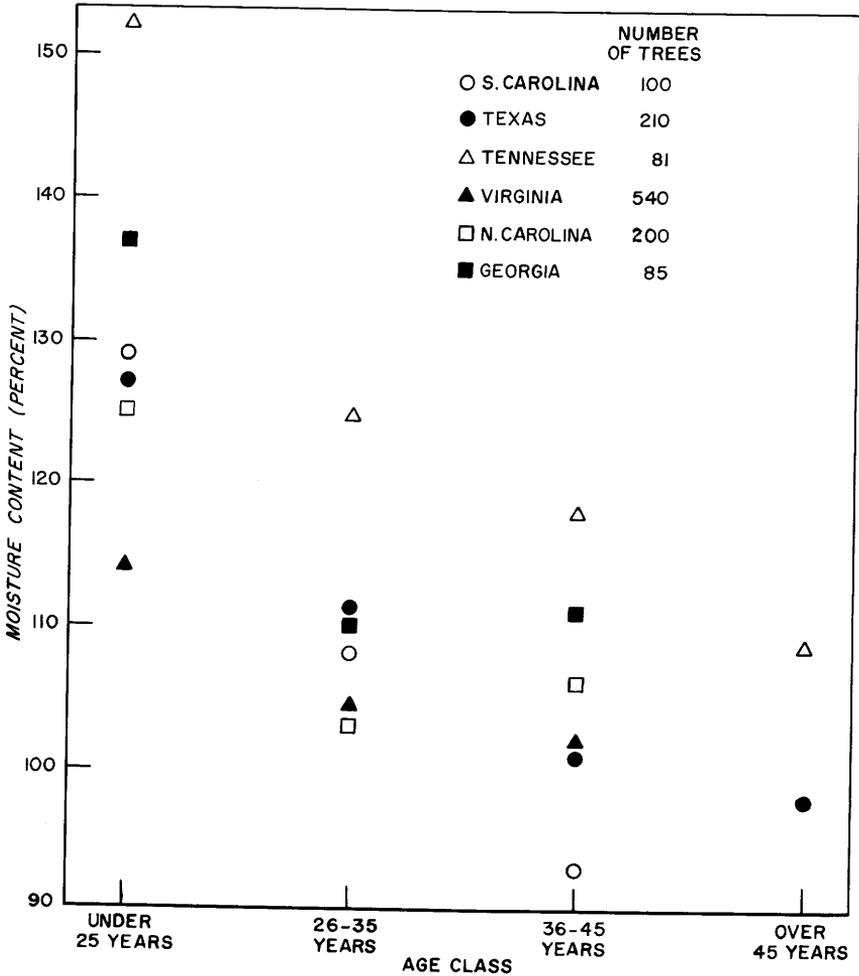


Figure 8-1.—Tree-average moisture content of loblolly pine stems for stands of four age classes growing in six geographic locations. Trees growing in Tennessee had the highest moisture content. (Drawing after Zobel et al. 1968.)

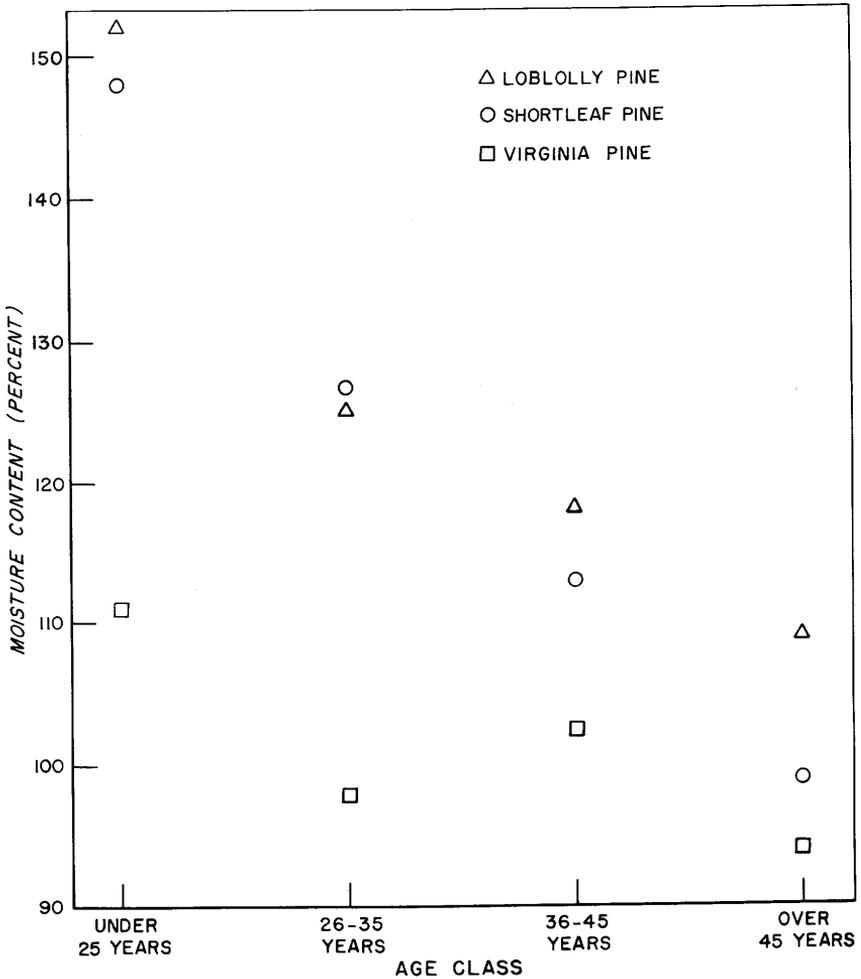


Figure 8-2.—Relationship of age class to tree-average moisture content of three species growing together in a mixed stand in Tennessee. Virginia pine had relatively low moisture content, and the slope of its moisture content-tree age relationship was relatively flat. (Drawing after Zobel et al. 1968.)

as age of bolt increased. Zobel et al. (1968) observed that three samples totaling 46 longleaf pines aged 10 to 40 years averaged 105-, 106-, and 116-percent moisture content, whereas 80 trees aged 30 to 60 years averaged only 97-percent moisture content. Quijada (1967) found that 48 North Carolina longleaf pines aged 30 to 34 years had a tree-average moisture content of 99 percent (range 68 to 123), whereas 36 longleaf pines aged 45 to 53 years averaged only 83-percent moisture content (range 73 to 97).

Moisture content has also been found to have an inverse correlation with tree specific gravity (Lindgren 1949; Miller 1959; Cole et al. 1966;

Choong et al. 1970). Wood attains its maximum possible moisture content when all spaces in the walls and lumens are filled with liquid water. Because the volume of these voids is negatively correlated with wood specific gravity it follows that the maximum possible moisture content for dense wood is less than that for less dense wood. The data following are from Panshin et al. (1964, p. 170).

Wood specific gravity based on weight and volume when ovendry	Maximum possible moisture content based on void volume
	<i>Percent</i>
0.85	50
.60	100
.46	150
.37	200

Although his specific gravities are based on green volume, Miller's (1959) data on moisture content in living slash pines (fig. 8-3) show that standing trees normally have less water content than these maximum percentages. Miller did not find a significant relationship between **growth rate** and percent moisture content.

The evidence is not conclusive concerning variation in tree-average moisture content with **season of the year**. Peck (1953), Miller (1959), Schroeder and Phillips (1972), and R. M. Echols (in a 1958 unpublished

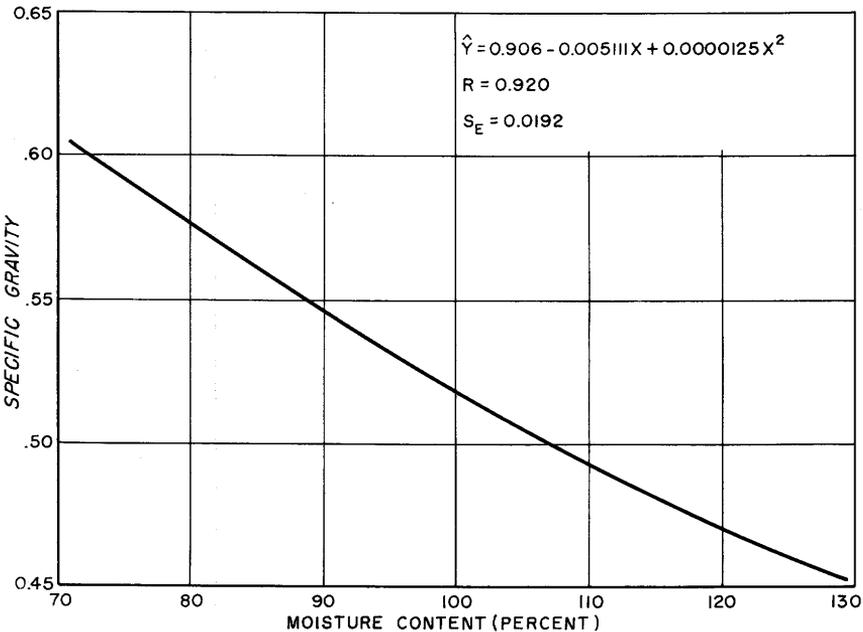


Figure 8-3.—Relationship between specific gravity (Y) of slash pine wood (basis of green volume and ovendry weight) and moisture content (X). Data based on samples from 96 trees averaging 32 years of age, cut near Savannah, Ga. (Drawing after Miller 1959.)

report titled "Monthly variation in moisture in the stems of living pine trees") all concluded that the southern pines do not significantly change moisture content with changing seasons of the year. However, Choong (1969b) and Choong and Fogg (1970) did find seasonal differences in breast-height 10-mm. increment cores extracted from loblolly, shortleaf, slash, and spruce pines; cores taken during midwinter had substantially higher moisture contents than cores taken in early summer.

Zobel et al. (1968) found considerable variation in tree-average moisture content with **geographic location**. Loblolly pines cut in Tennessee had higher moisture contents than loblolly pines from other geographic regions; those from Virginia tended to be low in moisture (fig. 8-1). The authors also concluded that ". . . loblolly from the mountains and Georgia Coastal Plain had somewhat higher moisture content than that from the Piedmont. Shortleaf from the mountain valleys had more moisture than shortleaf from ridges and high ground."

Finally, it appears that there are **genetic differences** that cause variations in moisture content among trees of the same species. Figure 8-4 illustrates between-tree differences in loblolly pines of 25- and 30-year age classes. Zobel et al. (1968) found large tree-to-tree variation among individuals of the same species and age growing on the same site; they reported that these differences "were found to hold by family" in progeny tests. In a later unpublished report by B. Zobel, R. Kellison, and Martha

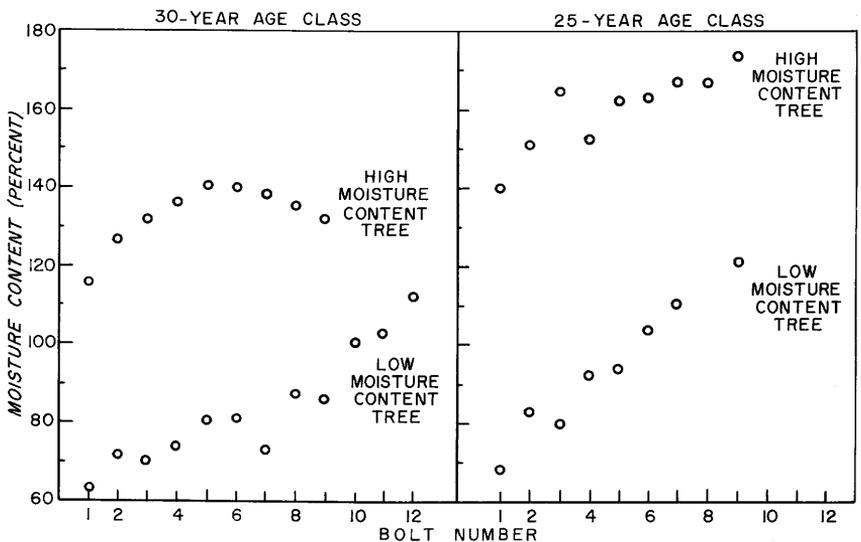


Figure 8-4.—Moisture content in loblolly pines can vary significantly between trees of the same age. Data from these four trees cut in Texas illustrate the tendency of trees of high moisture content to have high moisture content in all parts of the stem; conversely, trees of low moisture content had low moisture content in all parts. Bolts were numbered from ground level; they measured 5 feet 3 inches in length. (Drawing after Zobel et al. 1968.)

Matthias titled "Genetic improvement in forest trees—growth rate and wood characteristics in young loblolly pine", inheritance by family was reported in trees 7½ years old. They found that parents having a low moisture content produced progeny also having low moisture content.

VARIATION WITHIN TREES

Moisture content in trees varies with radial position and with height above the ground. Some of the contributing factors have been identified.

Heartwood has a much lower moisture content than sapwood. Peck (1953) published values for the moisture content of **heartwood**.

<u>Pine species</u>	<u>Moisture content</u>
	<i>Percent</i>
Loblolly -----	33
Loblolly -----	47-59
Longleaf -----	31
Shortleaf -----	32

Choong (1969b) reported that the heartwood of spruce pine and shortleaf pine sampled at breast height contained 30- to 40-percent moisture. Pine wood with a high content of extractives commonly has relatively low moisture content. Zobel et al. (1968) observed that it is not uncommon for resinous heartwood to contain less than 20-percent moisture, while sapwood from the same height in the tree is near 90 percent. It is evident that sapwood in 30-year-old trees must average 100-percent moisture content or more to give the tree average values shown in table 8-1.

Because of the relationship between moisture content and specific gravity (fig. 8-3), **latewood** in living pine sapwood should have a lower percentage of moisture than **earlywood**. Miller's (1959) observations appear to confirm such a relationship in slash pine (fig. 8-5).

The dominant factor affecting moisture variation within stems of living pine trees seems to be the high moisture content of **juvenile wood** (prior to heartwood formation) compared to **mature wood**. Zobel et al. (1968) have shown that juvenile wood of young loblolly pines has substantially more moisture per unit of dry wood weight than mature wood of the same species (fig. 8-6). In older trees, after formation of heartwood, the relationship may be reversed; Quijada (1967) has shown that North Carolina longleaf pines have lower moisture content in corewood than in outer wood (fig. 8-7). This confirmed findings of Cole et al. (1966) that loblolly and slash pine had a slightly higher moisture content in corewood than outerwood, while the reverse was true for longleaf.

Moisture content in southern pine trees is positively correlated with **height above ground**. Upper pine logs always contain a higher percentage of moisture than butt logs (figs. 8-4, 8-6, 8-7). Zobel et al. (1968) have shown that moisture contents at breast height are closely correlated with tree-average values. The relationships are particularly good when data are taken from wedges cut from cross-sectional disks; breast-height in-

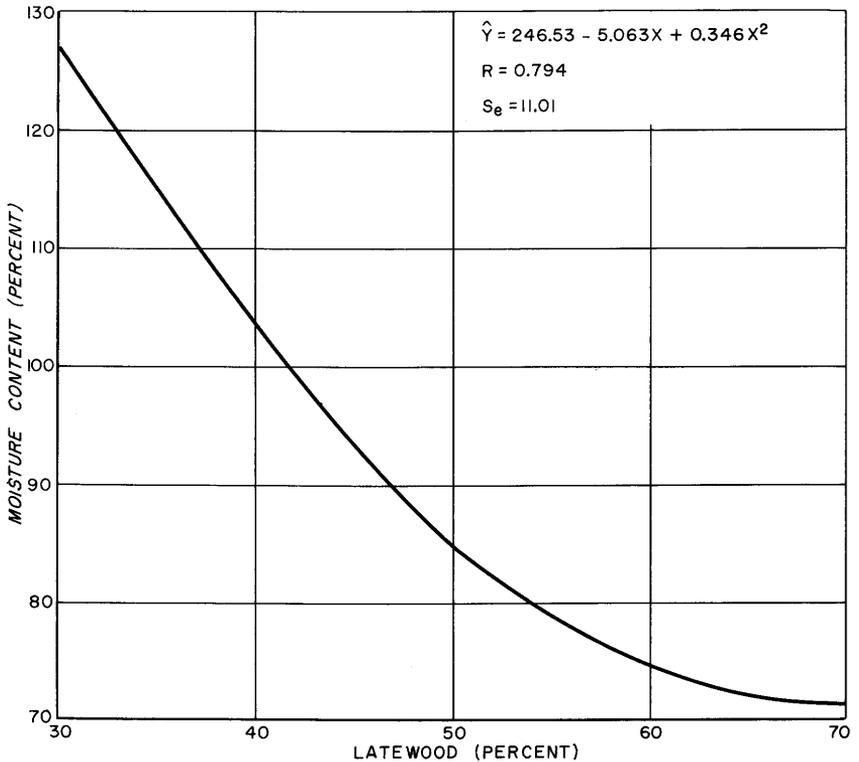


Figure 8-5.—Relationship between percent moisture content (Y) and percent latewood (X) in 96 slash pine trees cut near Savannah, Ga. The trees averaged 32 years of age. (Drawing after Miller 1959.)

crement cores afford acceptable estimates. These authors present regressions applicable to loblolly, longleaf, and slash pines from various geographic locations. Quijada (1967) has also developed a regression equation predicting tree average moisture content of longleaf pine from breast-height values.

In a study of ten loblolly pines, 7 to 21 years old, growing in the Piedmont section of North Carolina, Metz and Wells (1965) observed that stemwood moisture content was greatest in the upper crown and lowest below the crown. Branch wood had a lower moisture content than stemwood.

<u>Tree part</u>	<u>Moisture content</u>
	<i>Percent</i>
Stemwood	
Upper 1/3 crown -----	151
Mid 1/3 crown -----	149
Lower 1/3 crown -----	145
Below crown -----	131
Branches	
Live -----	108
Dead -----	49

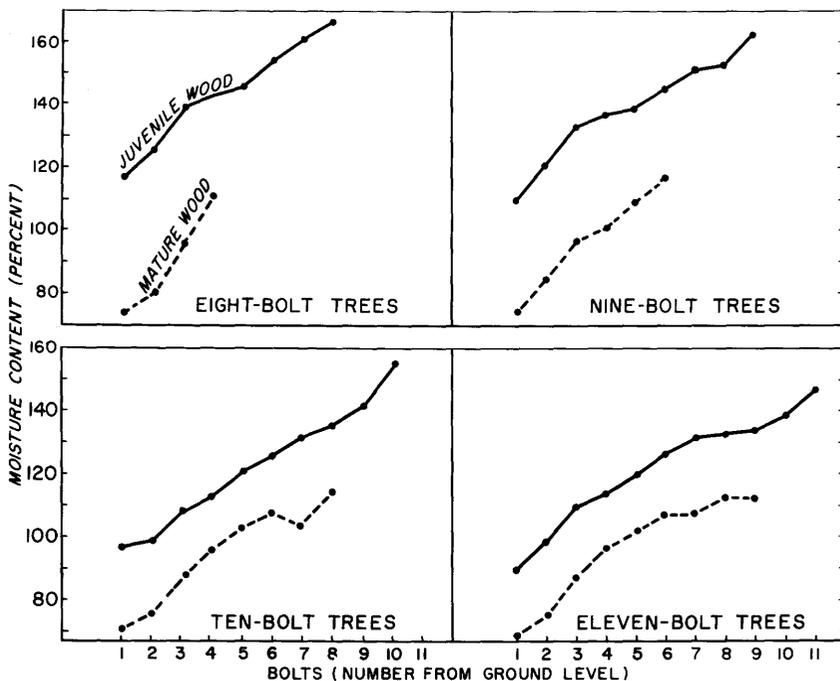


Figure 8-6.—Percent moisture content was positively correlated with height above ground in 166 loblolly pines cut from natural stands in the North Carolina Coastal Plains. Bolts were numbered from ground level and measured 5 feet 3 inches in length. (Drawing after Zobel et al. 1968.)

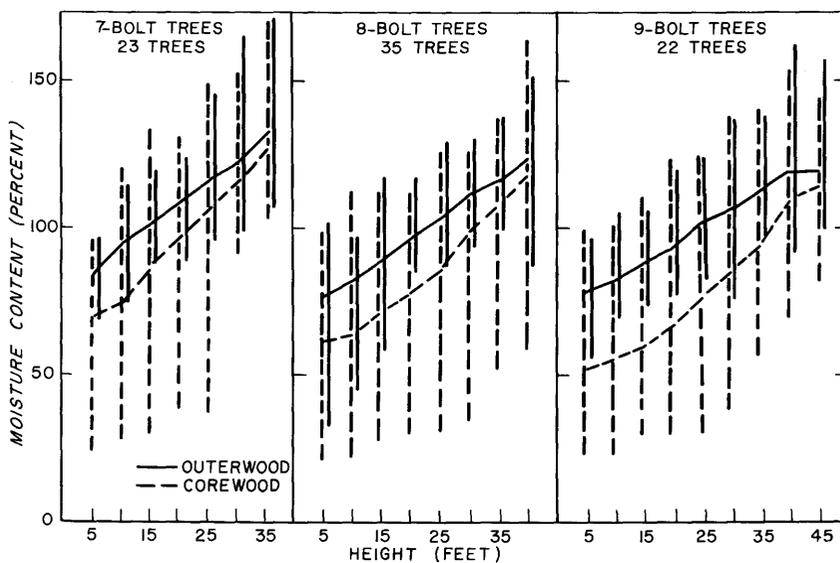


Figure 8-7.—In North Carolina longleaf pine, corewood (rings 0 to 11) had lower moisture content than outerwood, particularly in the lower portion of stems from tall trees. Ranges in values are shown by vertical lines. (Drawing after Quijada 1967.)

8-2 FIBER SATURATION POINT

Wood is a **hygroscopic** material; it readily takes up and retains moisture when exposed to water vapor or liquid water. Water is held by wood in three ways. **Water vapor** is present in the air within cell lumens, **free water** may be enclosed as a liquid within the lumens, and **bound water** is adsorbed by the cell wall polymers. Water vapor and free water do not form close associations with the wood substance. Bound water, however, is more closely bonded to the cell wall structure; three mechanisms are noted by Wangaard and Granados (1967, p. 255) in their review of the concept of adsorption.

- Formation of a monolayer of water molecules (Langmuir sorption) held by hydrogen bonds at polar sites on molecular surfaces in the noncrystalline regions of the cell wall. **Monomolecular adsorption** predominates at low relative humidities.
- Attraction of polymolecular water held in solid solution or as multilayers on the first-formed monolayer. **Polymolecular adsorption** predominates in the intermediate and higher ranges of relative humidity.
- **Capillary condensation** (expressed by the Kelvin equation relating the condensation of water vapor to relative vapor pressure and capillary size). The extent of capillary condensation is limited by volume of voids in the cell wall. As noted in section 7-2 the maximum void may be approximately 4 percent of the dry wall volume.

As wet wood dries, the free water leaves the lumens before the bound water. The moisture content at which the cell walls are still saturated but the free water is gone from cell cavities is defined as the **fiber saturation point** (Tiemann 1906, p. 82). As wood dries from its natural green moisture content, it does not commence to shrink until the fiber saturation point is reached. Similarly, from the green condition to the fiber saturation point the strength of wood is constant; below the fiber saturation point most strength properties are negatively correlated with moisture content.

While 30 percent is commonly accepted as the fiber saturation point of wood, values vary considerably between and within species (Spalt 1958). The variation is caused by differences in chemical composition, crystallinity of the cellulose, compactness of the cell wall, specific gravity, and extractive content. Values determined may also vary according to the experimental procedure used, e.g., extrapolation to 100-percent relative humidity of sorption data on equilibrium moisture content, observation of shrinkage initiation with loss of moisture, correlation of strength or electrical properties with moisture content, or analysis by the polymer exclusion technique. Stamm (1971) has reviewed nine methods for determining the fiber saturation point in wood and wood products.

The spectrum of reported values for the 10 southern pine species has been reviewed by Choong (1969a, b). He shows that research based on shrinkage measurements has yielded values for fiber saturation point that, for the most part, fall within the range from 25- to 30-percent moisture content in extracted woods (or woods with low extractives content).

Feist and Tarkow (1967) have pointed out the weaknesses inherent in estimation of fiber saturation point by measuring a unidirectional property such as tangential shrinkage, strength, or electrical conductivity with incremental removal of water from green wood. They devised a method that measures a bulk property, rather than a unidirectional property, through examination of a waterlogged specimen rather than a partially dried (and perhaps dimensionally altered) specimen. Their method calls for soaking green wood in a solution of polyethylene glycol of a molecular size too large to penetrate the cell walls. The polyethylene glycol does, however, diffuse into the free water contained in the lumen. The wood is then removed from the solution, and all the water and polyethylene glycol are extracted. The weight of the water taken from the lumen is determined by assuming that it contained all of the polyethylene glycol that entered the tracheid and was therefore of the same concentration as the treating solution. The weight of the water removed from the tracheid wall—which they call nonsolvent water—can thus be determined, and this weight is used to calculate the fiber saturation point.

Feist and Tarkow (1967) observed that earlywood of never-dried green slash pine had a higher fiber saturation point (41 percent) than latewood (35 percent).

These values for never-dried green slash pine are substantially higher than those determined from shrinkage observations (Nearn 1955; Higgins 1957; Choong 1969a, b) of once-dried southern pine. The difference is perhaps explained by Feist and Tarkow's (1967) additional finding that, in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) never-dried green wood has a higher fiber saturation point (40 percent) than once-dried wood (31 percent).

There appears to be a relationship between the specific gravity of wood and its fiber saturation point that would partially explain the difference observed between earlywood and latewood. Feist and Tarkow (1967) conclude from their work with polyethylene glycol that below about 0.35 specific gravity, the fiber saturation point is negatively correlated with density, whereas above 0.35 the fiber saturation point of wood low in extractives is more or less constant; Kellogg and Wangaard's (1969) data also show a negative correlation between specific gravity and moisture content at fiber saturation (fig. 8-8).

Specimens of southern pine wood that have a large extractive content may display an abnormally low fiber saturation point (Nearn 1955; Higgins 1957; Wangaard 1957; Spalt 1958; Wangaard and Granados 1967; Feist and Tarkow 1967; Choong 1969a). Apparently, extractives bulk the cell wall and thus preclude water from occupying the same space.

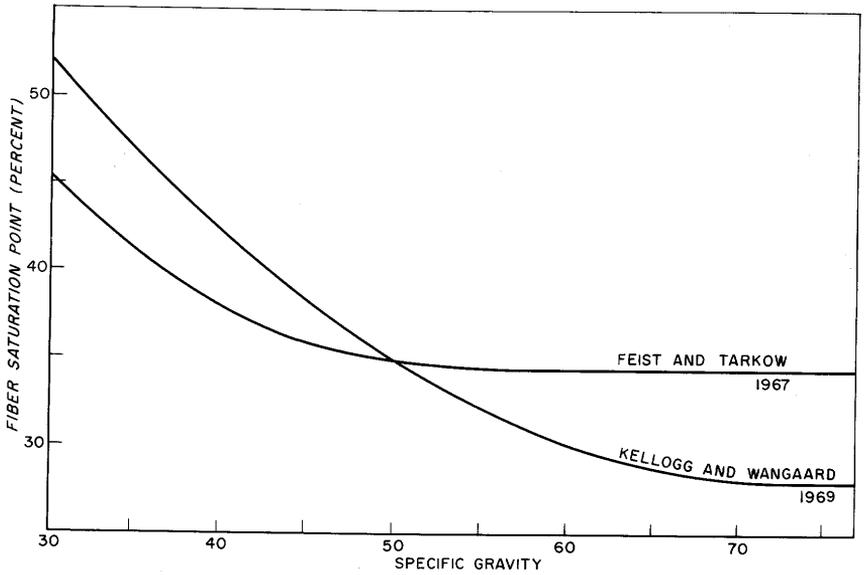


Figure 8-8.—Relation of fiber saturation point to wood specific gravity—basis of oven-dry volume and weight. (Drawing after Kellogg and Wangaard 1969.)

The polymer exclusion method gives evidence that wood cellulose has much higher saturation points than solid wood. Figure 8-9 compares solid wood with cellophane (virtually pure cellulose) and with holocellulose.

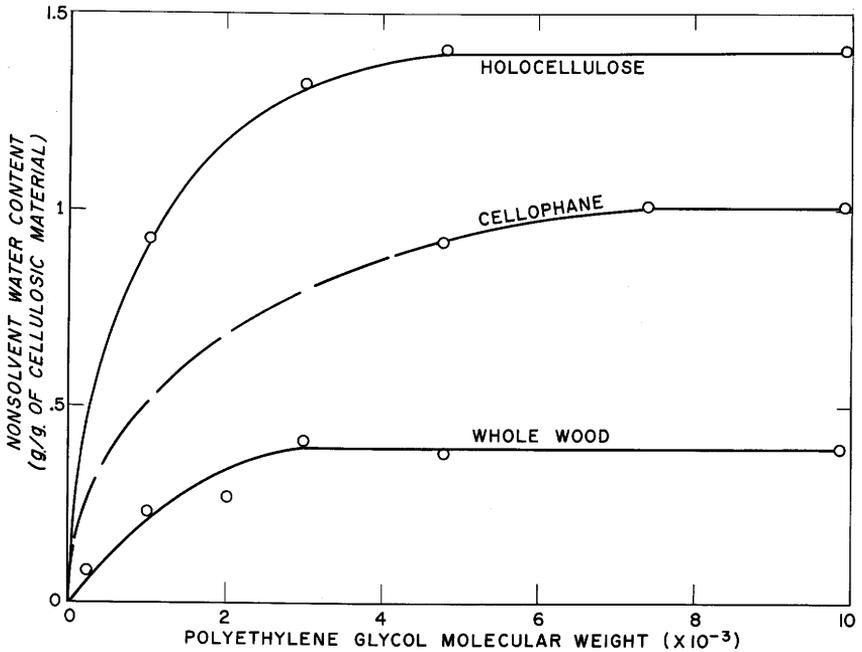


Figure 8-9.—Fiber saturation point of hard maple wood, cellulose in the form of cellophane, and holocellulose. (Drawing after USDA Forest Products Laboratory 1967, p. 8.)

8-3 EQUILIBRIUM MOISTURE CONTENT

The weight of water vapor contained in a unit volume of space is called **absolute humidity**; it is usually expressed as the number of grains of moisture per cubic foot (7,000 grains = 1 pound avoirdupois). The capacity of air to hold water increases greatly at higher temperatures. Air containing the total number of grains of water that it can hold at its temperature is **saturated**.

Temperature	Absolute humidity (i.e., weight of moisture in saturated air at normal atmospheric pressure)
°F.	<i>Grains per cubic foot</i>
20 -----	1.2
60 -----	5.8
100 -----	20.0
140 -----	56.9
180 -----	139.3
200 -----	208.1
212 -----	261.1

Wood reaches an **equilibrium moisture content** (e.m.c.) if held in air at constant **relative humidity** and temperature. Relative humidity is defined as the vapor pressure exerted by the amount of water vapor actually in the air, expressed as a percentage of the vapor pressure at saturation. Dry air has 0-percent relative humidity, while saturated air is at 100 percent. Relative humidity is usually determined from simultaneous readings on two thermometers, one of which has its bulb wetted by a wick in water. The reading of this **wet bulb** is depressed by evaporation.

SORPTION HYSTERESIS

For any condition of relative humidity and temperature, the equilibrium moisture content attained during **desorption** (drying from water-swollen condition) is greater than the e.m.c. attained during **adsorption** from the dry condition. Figure 8-10 illustrates an adsorption-desorption hysteresis loop for spruce (*Picea* sp.). Not all researchers have been able to observe that the hysteresis loop is closed at the upper end as illustrated (Wangaard and Granados 1967). Browning (1967, p. 317) states that a closed hysteresis loop is obtained only when desorption data are observed after adsorption data. It is believed that in the original green condition, the available polar hydroxyl groups in cell wall polymers are almost entirely satisfied by bound water. In dry wood which has lost its bound water, however, shrinkage brings the polar hydroxyl groups close enough together to satisfy each other; this results in diminished adsorption when rewetted.

The ratio between e.m.c. during adsorption and e.m.c. during desorption

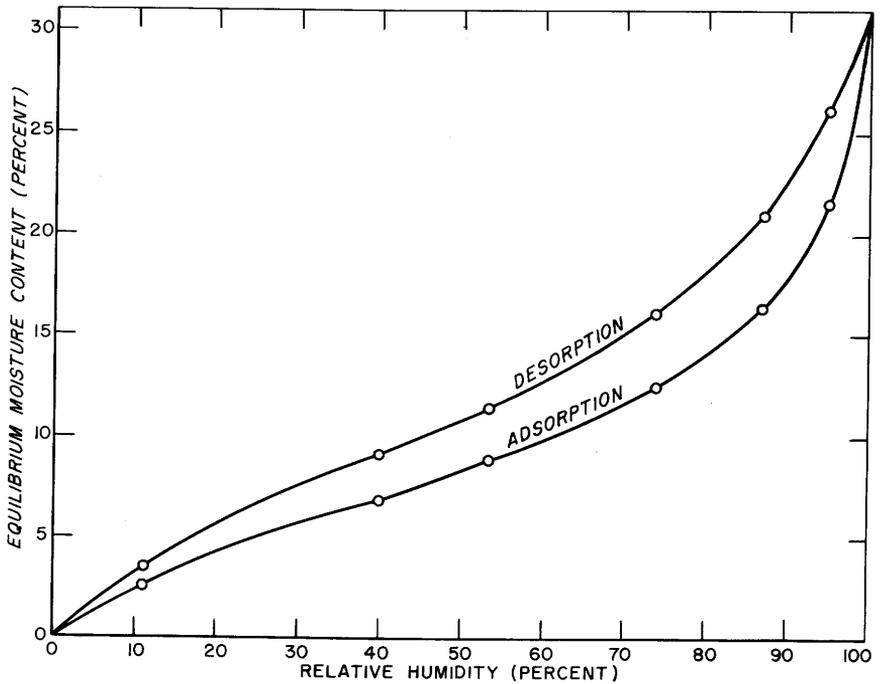


Figure 8-10.—Adsorption and desorption of water by spruce at 25° C. with changes in relative humidity. (Drawing after Alfred J. Stamm 1964, p. 146, *WOOD AND CELLULOSE SCIENCE*, Copyright © 1964, The Ronald Press Company, New York.)

has been measured for southern pine. Choong's ratios were obtained on unextracted wood at 20° C. and 85-percent relative humidity. Seborg's data were also taken at 20° C.

Specimen	Adsorption: desorption ratio	Reference
Loblolly pine kraft pulp		Seborg (1937)
Unbeaten	0.85	
Highly beaten .....	.86	
Unbeaten, 90 percent earlywood .....	.87	
Unbeaten, 90 percent latewood .....	.87	
Loblolly pine pulp (sulfite)		Seborg (1937)
Unbeaten, 100 percent earlywood .....	.86	
Unbeaten, 100 percent latewood .....	.88	
Loblolly pine		Choong (1969a)
Corewood .....	.77	
Mature wood .....	.77	

Longleaf pine.....		Choong (1969a)
Corewood.....	.77	
Mature wood.....	.77	
Pitch pine (mixed wood).....	.82	Choong (1969a)
Pond pine (mixed wood).....	.87	Choong (1969a)
Sand pine (mixed wood).....	.81	Choong (1969a)
Shortleaf pine.....		Choong (1969a)
Corewood.....	.77	
Mature wood.....	.80	
Slash pine.....		Choong (1969a)
Corewood.....	.73	
Mature wood.....	.80	
Spruce pine (mixed wood).....	.88	Choong (1969a)
Table-Mountain pine		
(mixed wood).....	.92	Choong (1969a)
Virginia pine (mixed wood)...	.86	Choong (1969a)

Choong's (1969a) data show a range in adsorption: desorption ratios from 0.73 to 0.80 for the four major species and from 0.81 to 0.92 for samples drawn from single trees of the minor species. These values fall close to the values reported by Spalt (1958) for eight softwoods and eight hardwoods (range 0.79 to 0.85). Ratios determined by Wangaard and Granados (1967) for nine unextracted hardwoods ranged from 0.74 to 0.82. Values reported by Spalt, as well as Wangaard and Granados, were obtained from ratios of the entire areas under the adsorption and desorption curves.

The equilibrium moisture content of extracted wood is higher than that of unextracted wood at relative humidities above 50 percent (Nearn 1955; Anderson 1961; Wangaard and Granados 1967). Nearn's values for southern pine are listed below. Specific gravity was 0.52 unextracted and 0.51 after cold-water extraction (basis of oven-dry weight and oven-dry volume).

Nominal relative humidity	Specimen condition	Equilibrium moisture content at about 70° F.
<i>Percent</i>		<i>Percent</i>
66.0	Unextracted	13.4
	Leached in cold water	14.3
84.0	Unextracted	17.3
	Leached in cold water	18.7
92.9	Unextracted	21.2
	Leached in cold water	23.4

EFFECT OF STRESS ON EQUILIBRIUM MOISTURE CONTENT

Simpson and Skaar (1968ab), in experiments with red oak (*Quercus rubra* L.) have shown that the e.m.c. of wood is decreased by a transverse compressive stress. The reduction in e.m.c. per unit of compressive stress increased with increasing moisture content and also appeared to increase with increasing stress levels. Stresses imposed ranged from 420 to 1,200

p.s.i.; wood under the maximum stress had an e.m.c. 0.44 percentage point below that of unstressed wood. Bello (1968) drew similar conclusions from his observation of five hardwoods.

Libby and Haygreen (1967) demonstrated on Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) that a transverse tensile stress slightly increased the e.m.c. of wood; when stressed at 60 percent of ultimate strength, wood had an e.m.c. less than 0.2 percentage point higher than when unstressed.

EFFECT OF TEMPERATURE ON EQUILIBRIUM MOISTURE CONTENT

At all relative humidities, the e.m.c. of wood is correlated with temperature; in the range from 25° to 100° C. an increase in temperature reduces e.m.c. (fig. 8-11).

Dry wood heated to 200° or 300° C. for a short time, or 100° C. for a prolonged period, will experience a permanent decrease in both hygroscopicity and tendency to shrink and swell (Stamm et al. 1946; Stamm 1956).

Steaming or boiling wood that has been through several desorption-adsorption cycles tends to restore its hygroscopic characteristics to those of never-dried green wood (Urquhart and Eckersall 1932; Seborg et al. 1938).

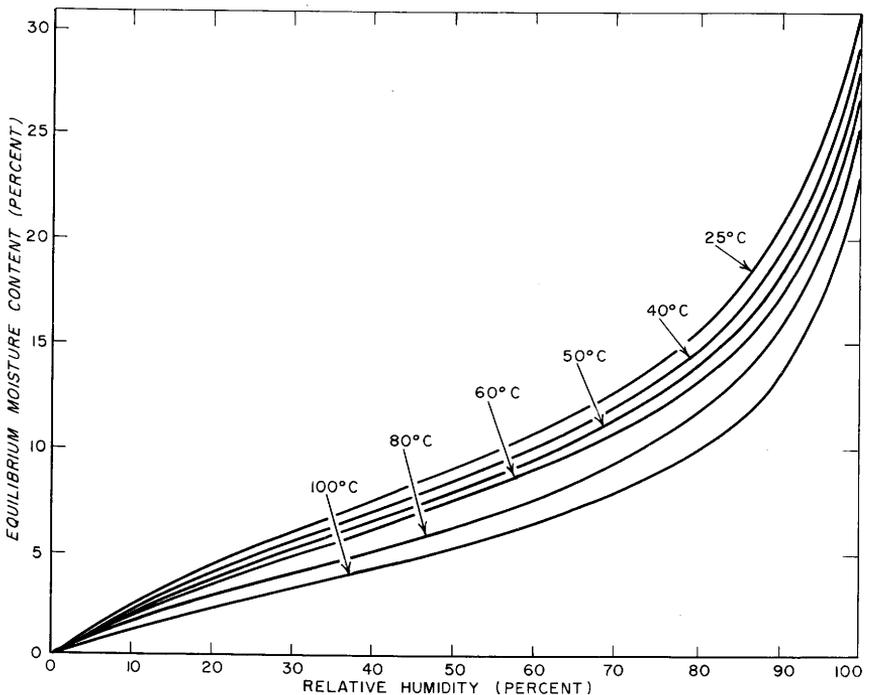


Figure 8-11.—Effect of temperature on the equilibrium moisture content of a large Sitka spruce specimen during desorption. (Drawing after Alfred J. Stamm 1964, p. 152, *WOOD AND CELLULOSE SCIENCE*, Copyright © 1964, The Ronald Press Company, New York.)

WORKING VALUES FOR EQUILIBRIUM MOISTURE CONTENT

It has been shown that the fiber saturation point varies with extractive content and specific gravity (fig. 8-8), and that equilibrium moisture content varies with temperature (fig. 8-11), extractive content, direction of sorption (fig. 8-10), temperature history of the specimen, and stress in the wood.

For most purposes, however, it is convenient to assume that all wood in the normal range of atmospheric pressures attains the same e.m.c. under similar conditions of relative humidity and temperature. Table 8-2, arranged with dry-bulb temperatures and wet-bulb depressions, provides useful approximations in the temperature range from 30° to 210° F. The e.m.c. for given conditions appears below the related relative humidity in the pair of lines to the right of the selected dry-bulb temperature.

EQUILIBRIUM MOISTURE CONTENT AT LOW TEMPERATURES

The limited data available (none for southern pine) indicate that e.m.c. patterns at temperatures below the freezing point of water differ somewhat from those shown in figure 8-11.

Hedlin (1967), in observations of 12 different species, found that moisture contents reached at 10° F. were substantially lower than those reached at the same relative humidity at 70° F.

For wood of Sitka spruce and Douglas-fir, Schmidt (1967) found that at -20° C., sorption curves deviated considerably from the sigmoid shape shown in figure 8-10. The sorption isotherms were more or less linear from 10-percent relative humidity to vapor saturation, yielding a fiber saturation point of about 21-percent moisture content—a value much lower than one would expect from extrapolating the trend shown in figure 8-11.

EQUILIBRIUM MOISTURE CONTENT ABOVE 212° F.

Wood can be placed in a retort filled with steam, to the complete exclusion of air, and the steam in this retort heated above atmospheric pressure to above the boiling point of water. Under such circumstances, the e.m.c. of wood is negatively correlated with the temperature, e.g., the e.m.c. will be about 20 percent at 212° F. and approximately 5 percent at 240° F. (fig. 8-12).

If air is admitted to the retort so that the steam is no longer saturated, then the e.m.c. of wood is determined by the dry-bulb temperature and

TABLE 8-2.—Continued

105	96	93	90	87	83	80	77	74	71	69	66	63	60	58	55	53	50	48	46	44	42	40	37	35	34	31	29	28	26	24	20	17	14	11	8	-----	-----	
	21.4	19.0	17.5	16.2	15.1	14.0	13.2	12.6	11.9	11.3	10.8	10.3	9.8	9.4	9.0	8.7	8.3	7.9	7.6	7.3	6.9	6.7	6.4	6.1	5.7	5.4	5.2	4.8	4.6	4.2	3.6	3.1	2.4	1.8	-----	-----		
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50	48	46	44	42	40	38	36	34	32	30	28	26	23	20	17	14	11	4	-----	-----
	21.4	19.0	17.5	16.2	15.1	14.1	13.3	12.6	12.0	11.4	10.8	10.4	9.9	9.5	9.2	8.8	8.4	8.1	7.7	7.5	7.2	6.8	6.6	6.3	6.0	5.7	5.4	5.2	4.8	4.5	4.0	3.5	3.0	2.5	1.1	-----	-----	
115	97	93	90	88	85	82	79	76	74	71	68	66	63	61	58	56	54	52	50	48	45	43	41	40	38	36	34	32	31	29	26	23	20	17	14	8	2	
	21.4	19.0	17.5	16.2	15.1	14.1	13.4	12.7	12.1	11.5	10.9	10.4	10.0	9.6	9.3	8.9	8.6	8.2	7.8	7.6	7.3	7.0	6.7	6.5	6.2	5.9	5.6	5.4	5.2	4.7	4.3	3.9	3.4	2.9	1.7	0.4		
120	97	94	91	88	85	82	80	77	74	72	69	67	65	62	60	58	55	53	51	49	47	45	43	41	40	38	36	34	33	31	28	25	22	19	17	5		
	21.3	19.0	17.4	16.2	15.1	14.1	13.4	12.7	12.1	11.5	11.0	10.5	10.0	9.7	9.4	9.0	8.7	8.3	7.9	7.7	7.4	7.2	6.8	6.6	6.3	6.1	5.8	5.6	5.4	5.0	4.6	4.2	3.7	3.3	2.3	1.1		
125	97	94	91	88	86	83	80	77	75	73	70	68	65	63	61	59	57	55	53	51	48	47	45	43	41	39	38	36	35	33	30	27	24	22	19	13	8	
	21.2	18.9	17.3	16.1	15.0	14.0	13.4	12.7	12.1	11.5	11.0	10.5	10.0	9.7	9.4	9.0	8.7	8.3	8.0	7.7	7.5	7.2	7.0	6.7	6.5	6.2	6.0	5.8	5.6	5.2	4.8	4.4	4.0	3.6	2.7	1.6		
130	97	94	91	89	86	83	81	78	76	73	71	69	67	64	62	60	58	56	54	52	50	48	47	45	43	41	40	38	37	35	32	29	26	24	21	15	10	
	21.0	18.8	17.2	16.0	14.9	14.0	13.4	12.7	12.1	11.5	11.0	10.5	10.0	9.7	9.4	9.0	8.7	8.3	8.0	7.8	7.6	7.3	7.0	6.8	6.6	6.4	6.1	5.9	5.6	5.3	4.9	4.6	4.2	3.8	3.0	2.0		
140	97	95	92	89	87	84	82	79	77	75	73	70	68	66	64	62	60	58	56	54	53	51	49	47	46	44	43	41	40	38	35	32	30	27	25	19	14	
	20.7	18.6	16.9	15.8	14.8	13.8	13.2	12.5	11.9	11.4	10.9	10.4	10.0	9.6	9.4	9.0	8.7	8.4	8.0	7.8	7.6	7.3	7.1	6.9	6.6	6.4	6.2	6.0	5.8	5.4	5.1	4.8	4.4	4.1	3.4	2.6		
150	98	95	92	90	87	85	82	80	78	76	74	72	70	68	66	64	62	60	58	57	55	53	51	49	48	46	45	43	42	41	38	36	33	30	28	23	18	
	20.2	18.4	16.6	15.4	14.5	13.7	13.0	12.4	11.8	11.2	10.8	10.3	9.9	9.5	9.2	8.9	8.6	8.3	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.4	5.2	4.9	4.5	4.2	3.6	2.9		
160	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	64	62	60	58	57	55	53	52	50	49	47	46	44	43	41	38	35	33	31	25	21	
	19.8	18.1	16.2	15.2	14.2	13.4	12.7	12.1	11.5	11.0	10.6	10.1	9.7	9.4	9.1	8.8	8.5	8.2	7.9	7.7	7.4	7.2	7.0	6.8	6.7	6.4	6.2	6.0	5.8	5.5	5.2	4.9	4.6	4.3	3.7	3.2		
170	98	95	93	91	89	86	84	82	80	78	76	74	72	70	69	67	65	63	62	60	59	57	55	53	52	51	49	48	47	45	43	40	38	35	33	28	24	
	19.4	17.7	15.8	14.8	13.9	13.2	12.4	11.8	11.3	10.8	10.4	9.9	9.6	9.2	9.0	8.6	8.4	8.0	7.8	7.6	7.3	7.2	6.9	6.7	6.6	6.4	6.2	6.0	5.7	5.5	5.2	4.9	4.6	4.4	3.7	3.2		
180	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	67	65	63	62	60	58	57	55	54	52	51	50	48	47	45	42	40	38	35	30	26	
	18.9	17.3	15.5	14.5	13.7	12.9	12.2	11.6	11.1	10.6	10.1	9.7	9.4	9.0	8.8	8.4	8.1	7.8	7.6	7.4	7.2	7.0	6.8	6.5	6.4	6.2	6.0	5.8	5.7	5.4	5.2	4.8	4.6	4.4	3.8	3.3		
190	98	96	94	92	90	88	85	84	82	80	78	76	75	73	71	69	68	66	65	63	62	60	58	57	56	54	53	51	50	49	46	44	42	39	37	32	28	
	18.5	16.9	15.2	14.2	13.4	12.7	12.0	11.4	10.9	10.5	10.0	9.6	9.2	8.9	8.6	8.2	7.9	7.7	7.4	7.2	7.0	6.8	6.6	6.4	6.2	6.0	5.9	5.7	5.5	5.3	5.0	4.8	4.5	4.4	3.8	3.3		
200	98	96	94	92	90	88	86	84	82	80	78	77	75	74	72	70	69	67	66	64	63	61	60	58	57	55	54	53	52	51	48	46	43	41	39	34	30	
	18.1	16.4	14.9	14.0	13.2	12.4	11.8	11.2	10.8	10.5	9.8	9.4	9.1	8.8	8.4	8.1	7.7	7.5	7.2	7.0	6.9	6.6	6.4	6.2	6.0	5.9	5.7	5.6	5.4	5.2	4.9	4.7	4.5	4.3	3.8	3.3		
210	98	96	94	92	90	88	86	85	83	81	79	78	76	75	73	71	70	68	67	65	64	63	61	60	59	57	56	54	53	52	50	47	45	43	41	36	32	
	17.7	16.0	14.6	13.8	13.0	12.2	11.7	11.1	10.6	10.0	9.7	9.2	9.0	8.7	8.5	8.0	7.6	7.4	7.1	6.9	6.8	6.5	6.3	6.1	5.9	5.8	5.5	5.4	5.3	5.1	4.8	4.6	4.4	4.2	3.7	3.2		

1 Relative humidity values in roman type.

2 Equilibrium moisture content values in italic type.

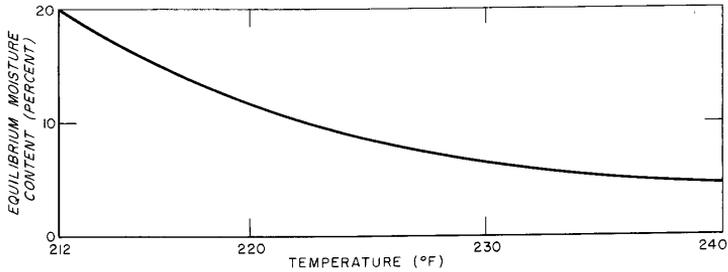


Figure 8-12.—Equilibrium moisture content of wood in superheated steam at atmospheric pressure. (Drawing after Kauman 1956.)

the relative humidity. At temperatures above the boiling point of water—as at lower temperatures—the relative vapor pressure is:

$$\left(\frac{\text{partial pressure of water vapor in the atmosphere at dry-bulb temperature, } t}{\text{pressure of saturated water vapor at the same dry-bulb temperature, } t} \right);$$

relative humidity is this value multiplied by 100. The partial pressure of water vapor in an air-vapor mixture at any dry-bulb temperature (whether above or below 212° F.) is the vapor pressure at the prevailing wet-bulb temperature. For example, at a dry-bulb temperature of 240° F. and a wet-bulb temperature of 160° F., the partial water vapor pressure is 4.739 p.s.i. absolute, and the pressure of saturated water vapor is 24.97 p.s.i. Therefore, the relative vapor pressure is 0.19, and the relative humidity is 19 percent.

In 1926 the USDA Forest Products Laboratory prepared curves which, when mathematically extrapolated, provided e.m.c. data to 248° F. (USDA Forest Products Laboratory 1957). Kauman (1956, p. 330) has provided graphs showing the e.m.c. for wood in steam-air mixtures above the boiling point of water; from these curves (based on data of A. J. Stamm, W. K. Loughborough, and R. Keylwerth) the Forest Products Laboratories of Canada have published the e.m.c. data shown in table 8-3.

EQUILIBRIUM MOISTURE CONTENT OF RECONSTITUTED WOOD

Particleboards, hardboards, and high-pressure decorative laminates are commonly used in the relatively narrow temperature range from 60° to 90° F. Their moisture contents change, however, with variations in relative humidity. As with solid wood, e.m.c. values observed during desorption are higher than during adsorption. Because of resins, waxes, and other additives incorporated in these products, and because of the high temperatures they experience during pressing, their e.m.c. values are characteristically lower than those of solid wood. Heebink (1966) has published some average e.m.c. values that are useful even though it is recognized that the e.m.c. of these products varies considerably with brand, resin

content, pressing cycle, and raw material. Comparative data on solid wood are taken from table 8-2.

Percent relative humidity at 70° F.	Equilibrium moisture content			
	Solid wood	Particleboard	Tempered hardboard	Decorative laminate
	----- Percent -----			
30	6.0	6.6	4.0	3.0
42	8.0	7.5	4.6	3.3
65	12.0	9.3	6.9	5.1
80	16.1	11.6	9.5	6.6
90	20.6	16.6	10.8	9.1

TABLE 8-3.—*Relationship of equilibrium moisture content to temperature and relative humidity of air-steam mixtures at atmospheric pressure and above 212° F. (data from Ladell 1957)¹*

Wet-bulb Temperature (°F.)	Dry-bulb Temperature—(°F.)										
	260	255	250	245	240	235	230	225	220	215	212
212	42 3.1	45 3.4	49 3.8	53 4.2	59 5.0	65 5.8	70 6.9	77 8.7	85 11.3	94 15.5	100 19.5
210	40 2.9	43 3.3	47 3.6	51 4.0	56 4.7	61 5.4	67 6.3	74 8.0	82 10.4	90 14.0	98 17.0
205	36 2.7	39 3.0	43 3.4	47 3.8	51 4.2	55 4.7	61 5.5	67 6.6	74 8.3	82 10.7	88 13.0
200	32 2.4	36 2.8	39 3.1	42 3.4	46 3.8	51 4.3	55 4.9	62 5.8	67 6.9	74 8.7	79 10.0
195	30 2.2	32 2.5	35 2.8	38 3.1	42 3.5	46 3.9	51 4.5	56 5.1	61 5.9	66 7.0	69 7.6
190	26 2.0	28 2.2	30 2.4	34 2.8	37 3.1	40 3.4	44 3.8	48 4.3	52 5.0	58 5.7	61 6.2
185	23 1.8	25 2.0	28 2.2	30 2.5	32 2.7	35 3.0	39 3.4	42 3.7	47 4.3	52 5.0	55 5.4
180	20 1.6	22 1.8	24 2.0	27 2.3	29 2.5	31 2.7	35 3.1	38 3.4	42 3.9	47 4.5	50 4.9
175	19 1.5	20 1.6	22 1.8	24 2.0	26 2.2	29 2.5	32 2.8	35 3.2	38 3.5	43 4.0	45 4.4
170	17 1.3	18 1.5	20 1.7	22 1.9	24 2.1	26 2.3	28 2.5	31 2.8	34 3.2	38 3.5	40 3.8
165	15 1.2	16 1.3	17 1.4	19 1.6	21 1.9	23 2.1	25 2.3	28 2.6	31 2.9	34 3.3	36 3.5
160	13 1.0	14 1.2	16 1.3	17 1.5	19 1.7	21 1.9	23 2.1	25 2.3	27 2.6	30 2.9	32 3.1

¹ In body of table, the upper figure is percent relative humidity, and the lower is percent e.m.c.

MOISTURE CONTENT OF WOOD IN USE

To reduce adverse effects of shrinking and swelling in use, wood should be put in place at a moisture content in equilibrium with the atmosphere in which it serves. For example, wood to be submerged in marine use can be pressure treated and installed at 30-percent moisture content or higher.

On the other hand, southern pine dimension lumber in unheated structures, sheathing boards, and exterior trim for houses should be installed at a moisture content corresponding to the e.m.c. for average outside conditions, e.g., approximately 9 percent for the dry southwestern States and 12 percent for the rest of the United States.

Structural lumber for southern homes without air conditioning will probably serve best if dried to 10-percent moisture content (Hopkins 1960); for air-conditioned southern houses, 9-percent moisture content at time of installation may be best.

Because exterior siding is exposed to the sun—and reflections from the sun—siding temperature frequently exceeds 110° F., with resultant low e.m.c.; McMillin (1969) has shown that well-nailed southern pine tongue and groove siding installed in central Louisiana will neither show gaps due to shrinkage nor buckle due to swelling if it is installed at a moisture content of 9 percent. Probably, this moisture content is appropriate for the major market area of southern pine; in the dry States of the Southwest, the moisture content at installation might better be 7 percent.

Increasingly in the major market areas for southern pine, houses and commercial structures are air conditioned the year around to about 75° F. and 25- to 50-percent relative humidity. Table 8-2 shows that wood placed in such atmospheres will reach an e.m.c. of 5 to 9 percent.

Some pieces of southern pine dimension lumber develop considerable warp as their moisture contents are reduced from the content at which shipped to the content they eventually reach in a heated and air-conditioned house. If 2 by 4 wall studs, for example, could be put in place at 9- or 10-percent moisture content (rather than 15 percent), the incidence of cracked plaster walls caused by developing crook would be reduced.

Wood in uncooled basements in winter-heated houses in the Southeast may fluctuate from a high of 14- or 15-percent moisture content in summer to a low of 6 percent in winter (Taras 1967).

Beams laminated from southern pine are installed throughout most of the United States. Studies by Hann et al. (1970) indicate that the year-round national average moisture content for laminated timbers in protected exterior exposure is 9 percent; for interior exposure, 8 percent.

Southern pine plywood is commonly below 9-percent moisture content when shipped and at installation is normally close to the e.m.c. it reaches in most applications. Reconstituted products such as particleboard, fiberboard, and decorative laminates have lower e.m.c. values than solid wood. For these products it is more meaningful to specify that they be equilibrated

in the conditions of relative humidity and temperature at which they will serve, rather than to specify moisture content at time of application.

8-4 SHRINKING AND SWELLING

As southern pine dries from fiber saturation to oven-dry, it shrinks in external dimensions; conversely, when dry wood is wetted, it swells. Because southern pine lumber sometimes does not shrink uniformly throughout its length and cross section, boards may warp when moisture content changes. Some knowledge of the cause of shrinkage and the nature of its variation is necessary to insure the successful use of wood.

It will be recalled from section 8-2 that water is adsorbed as a monolayer of water molecules at polar sites in the non-crystalline regions where the long threadlike cellulose molecules are imperfectly oriented. Also, water is adsorbed as polymolecular water held in solid solution on the surface of the cellulose crystallites or as multilayers on the first-formed monolayer. In zones of low crystallinity, water may also be adsorbed onto hemicellulose molecules surrounding elementary fibrils. When wood dries as water evaporates, resulting surface tension forces between water and cellulose tend to draw the imperfectly aligned cellulose molecules of the less crystalline regions into closer proximity and more nearly parallel orientation (Campbell 1933).

On drying, cell walls diminish in thickness; however, lumens appear to change but little in diameter. Therefore, the external radial and tangential dimensions of a block of wood must diminish as it dries. If the lumen diameters do not change, it also follows that volumetric shrinkage of a piece of wood during unrestrained oven-drying should be about equal to the volume of water adsorbed by the cell walls at fiber saturation (Stamm 1935).

External dimensional changes during desorption or adsorption are usually expressed as a percentage of the swollen or green dimension.

$$\text{Shrinkage, percent} = \frac{\text{change in dimension from swollen size}}{\text{swollen dimension}} (100) \quad (8-2)$$

Southern pine shrinks more tangentially than radially (fig. 8-13); longitudinal shrinkage in normal wood is usually slight (fig. 8-14, curves 1 and 2). While volumetric shrinkage of southern pine dried from fiber saturation to oven-dry varies considerably (figs. 8-15, 8-16), it is commonly 11 or 12 percent (Peck 1960; Choong 1969b).

FACTORS AFFECTING SHRINKAGE

The percent shrinkage observed between green and oven-dry conditions is correlated with specific gravity, extractive content, chemical constituents,

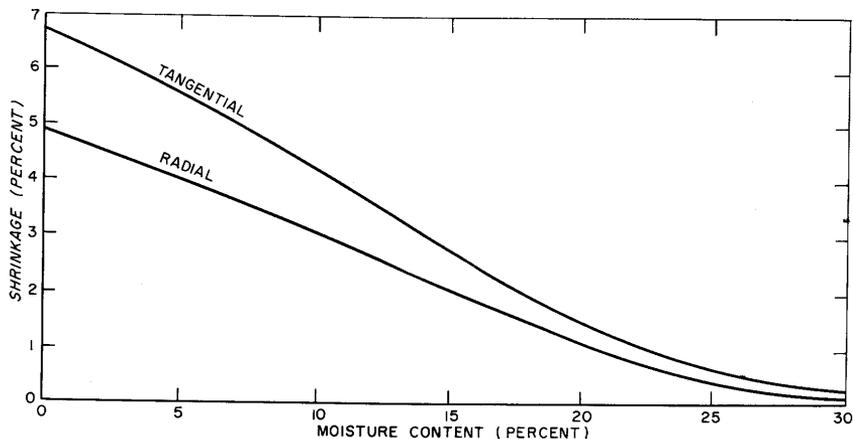


Figure 8-13.—Typical relationship between moisture content and radial and tangential shrinkage of southern pine wood. (Drawing after Peck 1947.)

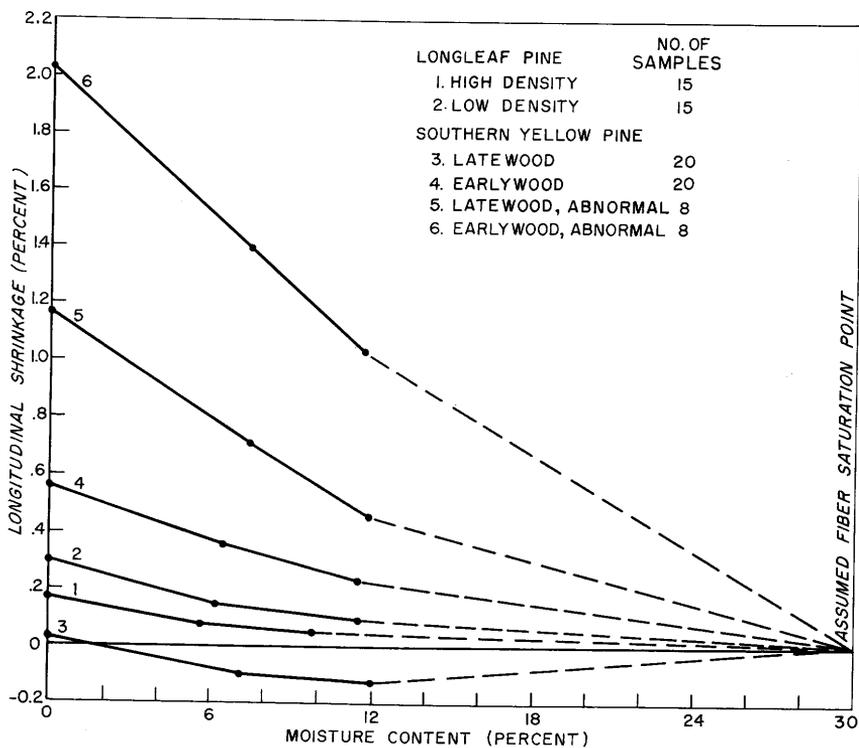


Figure 8-14.—Relationship of longitudinal shrinkage and moisture content when southern pine wood is dried from fiber saturation. Curves 1 and 2 are typical of normal wood. (Drawing after Koehler 1931.)

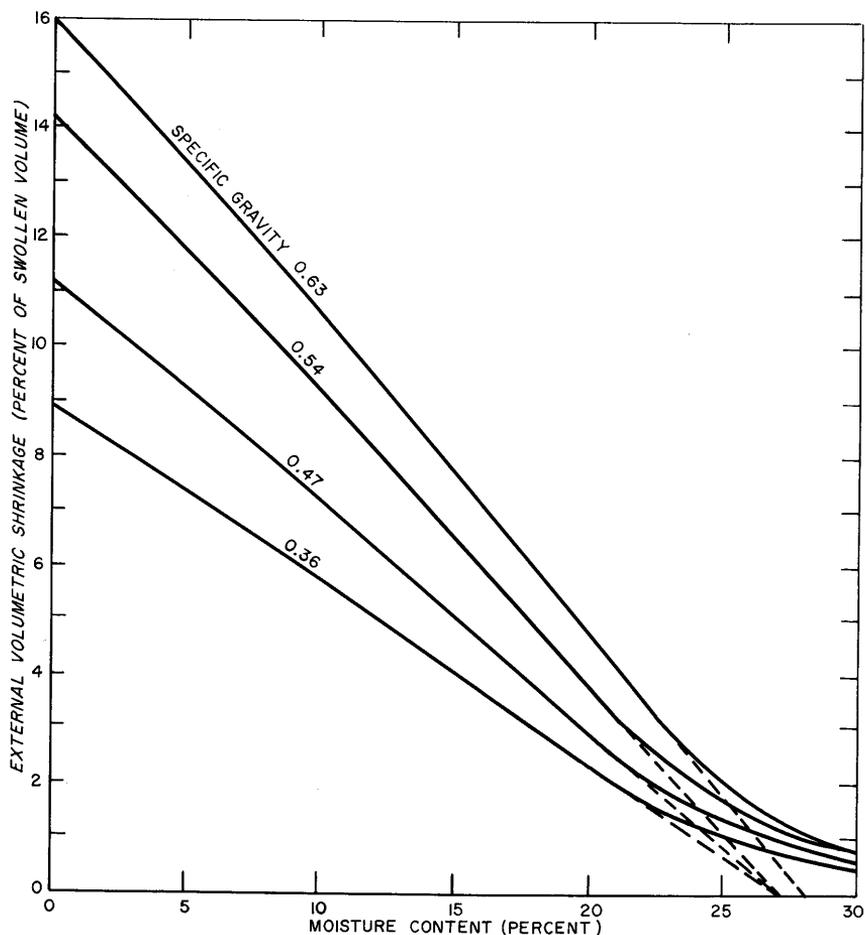


Figure 8-15.—Shrinkage of external volume in $\frac{7}{8}$ -inch-thick loblolly pine boards as related to moisture content and specific gravity based on oven-dry weight and swollen volume. (Drawing after Peck 1928.)

position in the tree, fibril angle, degree of restraint, and past temperature history.

Specific gravity.—When dried, southern pine wood of high density shows more volumetric shrinkage than wood of low density. The relationship can be expressed approximately in terms of specific gravity based on oven-dry weight and green volume (Stamm 1935).

Percent volumetric shrinkage

$$= (\text{percent moisture content at fiber saturation}) (\text{specific gravity}) \quad (8-3)$$

Volumetric shrinkage is approximately linear between about 22-percent moisture content and the oven-dry condition; Peck's (1928) data illustrate this relationship as well as the effects of specific gravity on volumetric shrinkage (fig. 8-15). As wood dries from the green condition, the outer surface

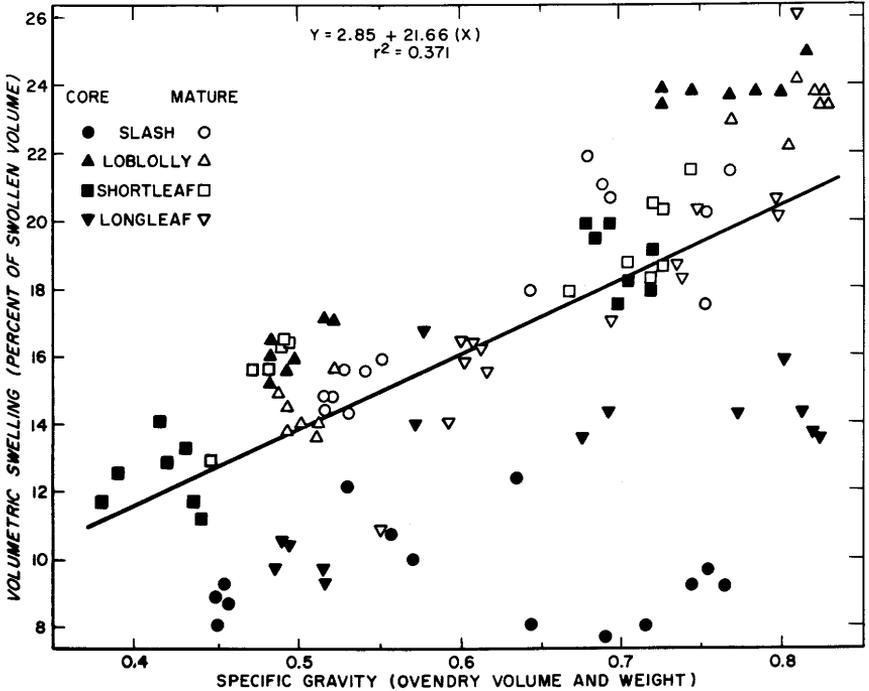


Figure 8-16.—Relationship of volumetric swelling (ovendry to swollen condition) to unextracted specific gravity. Specimens were 1 inch square and measured ½-inch along the grain. (Drawing after Choong and Barnes 1968.)

often reaches a level where shrinkage occurs before the average moisture content falls below the fiber saturation point. This results in the curved lines above 22-percent moisture content in figure 8-15.

Choong and Barnes (1968) have related specific gravity to volumetric swelling in unextracted specimens of corewood and mature wood taken from the four major southern pine species; their regression expression accounted for 37 percent of the variation in volumetric shrinkage (fig. 8-16).

Yao (1969) observed shrinkage in thirty-six 1-inch-square specimens (measuring 4 inches along the grain) removed from each of 28 loblolly pines grown in northeast Mississippi—1,008 specimens in all. They were cut from three radial positions on the four cardinal azimuths at each of three heights (breast height, 30 percent, and 50 percent of tree height). The trees ranged from 32 to 55 years of age. In contrast with volumetric, radial, and tangential shrinkage, longitudinal shrinkage was negatively correlated with specific gravity (fig. 8-17).

Specimens of equal specific gravity, but from different trees, showed a substantial variation in shrinkage from the green condition to ovendry. Therefore, while the simple correlation between unextracted specific gravity (ovendry weight and green volume basis) and shrinkage was significant, it accounted for not more than 11 percent of the variation in shrinkage when all 1,008 specimens were evaluated.

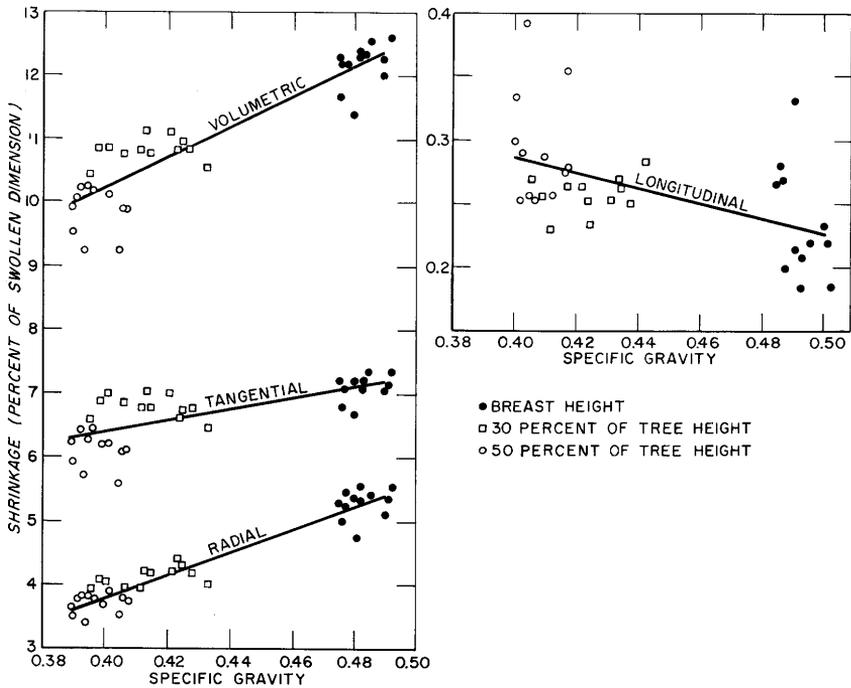


Figure 8-17.—Relationship of specific gravity (basis of green volume and oven-dry weight) to shrinkage from green to oven-dry condition. Each of the 36 points defining each curve is an average for the same azimuth, radial location, and height in 28 loblolly pine trees. (Drawing after Yao 1969.)

Type shrinkage	r	r^2
Volumetric	0.32	0.11
Tangential	.16	.04
Radial	.26	.07
Longitudinal	-.10	.01

Within single trees, however, volumetric shrinkage was more highly correlated with specific gravity, the r^2 exceeding 0.5 in the two trees studied.

Further, if the tree-to-tree variation was eliminated by averaging the specific gravity and shrinkage values of all 28 trees at each of the 36 sample positions, then the correlation coefficients were additionally improved. Yao's (1969) regression equations derived from these average shrinkage values (36 points define each curve of figure 8-17) are as follows:

Equation	r	r^2
$V = 0.48 + 23.75G$	0.91	0.83
$T = 2.79 + 8.78G$	.74	.54
$R = -3.45 + 17.67G$	.96	.93
$L = 0.526 - 0.599G$	-.51	.26

where V, T, R, and L are volumetric, tangential, radial, and longitudinal shrinkages (percent), respectively, and G is unextracted specific gravity (basis of ovendry weight and green volume).

If the regression expressions are extrapolated above 0.72 specific gravity, radial shrinkage is indicated to exceed tangential shrinkage. To test the validity of the latter point, Yao (1969) examined the radial and tangential shrinkage (from green to ovendry) of 160 specimens of loblolly earlywood and an equal number of latewood specimens; specific gravities were 0.26 and 0.65 (green volume and ovendry weight).

<u>Direction</u>	<u>Earlywood shrinkage</u>	<u>Latewood shrinkage</u>
	----- Percent -----	
Tangential -----	5.0	7.1
Radial -----	2.6	8.3

The greater radial than tangential shrinkage of the high-gravity latewood appears to support Yao's regression equaitons.

A regression equation developed by Choong and Barnes (1968) from specimens of the four major species indicated that the ratio of radial to tangential swelling does not become unity until the unextracted specific-gravity (ovendry volume and weight) reaches 0.96 (fig. 8-18); when the Choong and Barnes' value of 0.96 is converted to a green volume basis it is 0.73, in close agreement with Yao.

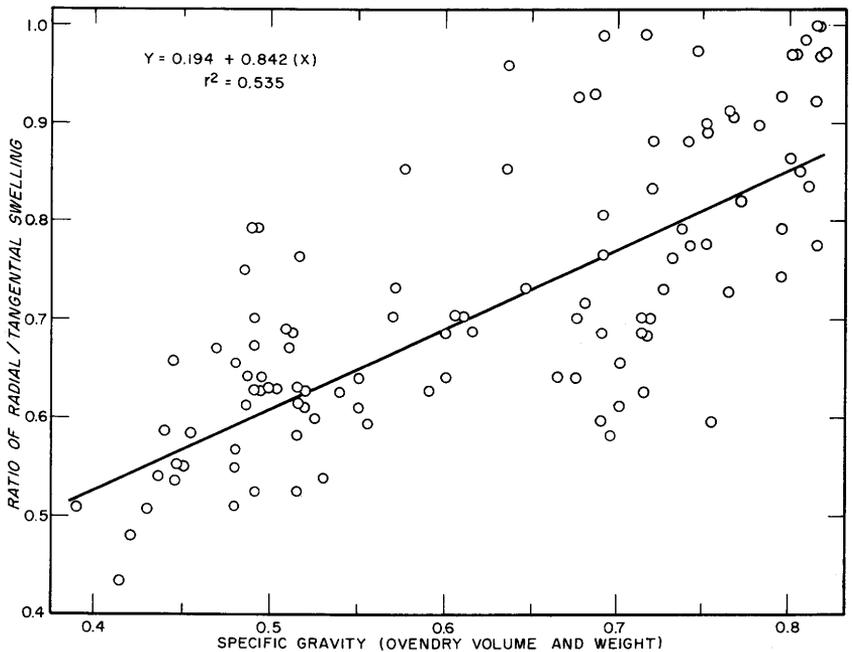


Figure 8-18.—Relationship of the ratio of radial to tangential swelling (Y) to specific gravity (X) of the four major southern pine species. (Drawing after Choong and Barnes 1968.)

Extractives.—The fiber saturation point in southern pine is reduced by the presence of extractives (Nearn 1955) as is the volumetric shrinkage (Choong 1969a).

Choong's data indicate that for corewood of the four major species, there is no correlation between shrinkage and specific gravity until most of the extractives have been removed. When data were pooled for all 10 species (corewood as well as mature wood) Choong noted that correlation for unextracted wood was low ($r^2 = 0.21$); extraction with hot water improved the correlation somewhat ($r^2 = 0.31$), and further extraction with organic solvents raised the r^2 value to 0.59 (fig. 8-19).

In all, Choong measured the volumetric shrinkage from swollen to oven-dry in 406 specimens drawn from the 10 species. The averaged values show that hot water extraction increased shrinkage 1.0 percentage points and extraction in hot water and organic solvents increased shrinkage 1.5 percentage points.

	<u>Volumetric shrinkage</u>
	<i>Percent</i>
Unextracted -----	11.7
Extracted in hot water -----	12.7
Extracted in hot water and organic solvents -----	13.2

Chemical constituents.—It is believed that water does not enter the highly crystalline parts of the cellulose elementary fibril but instead moves into less-ordered parts of the cell wall. It is possible, then, that southern pine high in hemicellulose tends to swell more than wood having a low level of hemicellulose. There are, however, no published data specific to southern pine that illustrate this concept.

Kelsey (1963, p. 32) has published a figure containing data from a variety of species that shows a linear negative correlation between lignin content and volumetric shrinkage.

<u>Lignin content</u>	<u>Volumetric shrinkage (green to oven-dry)</u>
-----	<i>Percent</i> -----
16	15
32	10

Heartwood versus sapwood.—Because of the high extractive content in heartwood of some species of southern pine, shrinkage may be less in heartwood than in sapwood located an equal number of rings from the pith. However, corewood that has made the transition to heartwood of relatively low extractive content may shrink more than mature sapwood (fig. 8-20).

In Manwiller's¹ study of 72 spruce pines, he found that sapwood speci-

¹ Manwiller, F. G. Variation of transverse cellular dimensions and specific gravity in stems of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.8 dated May 1, 1972.

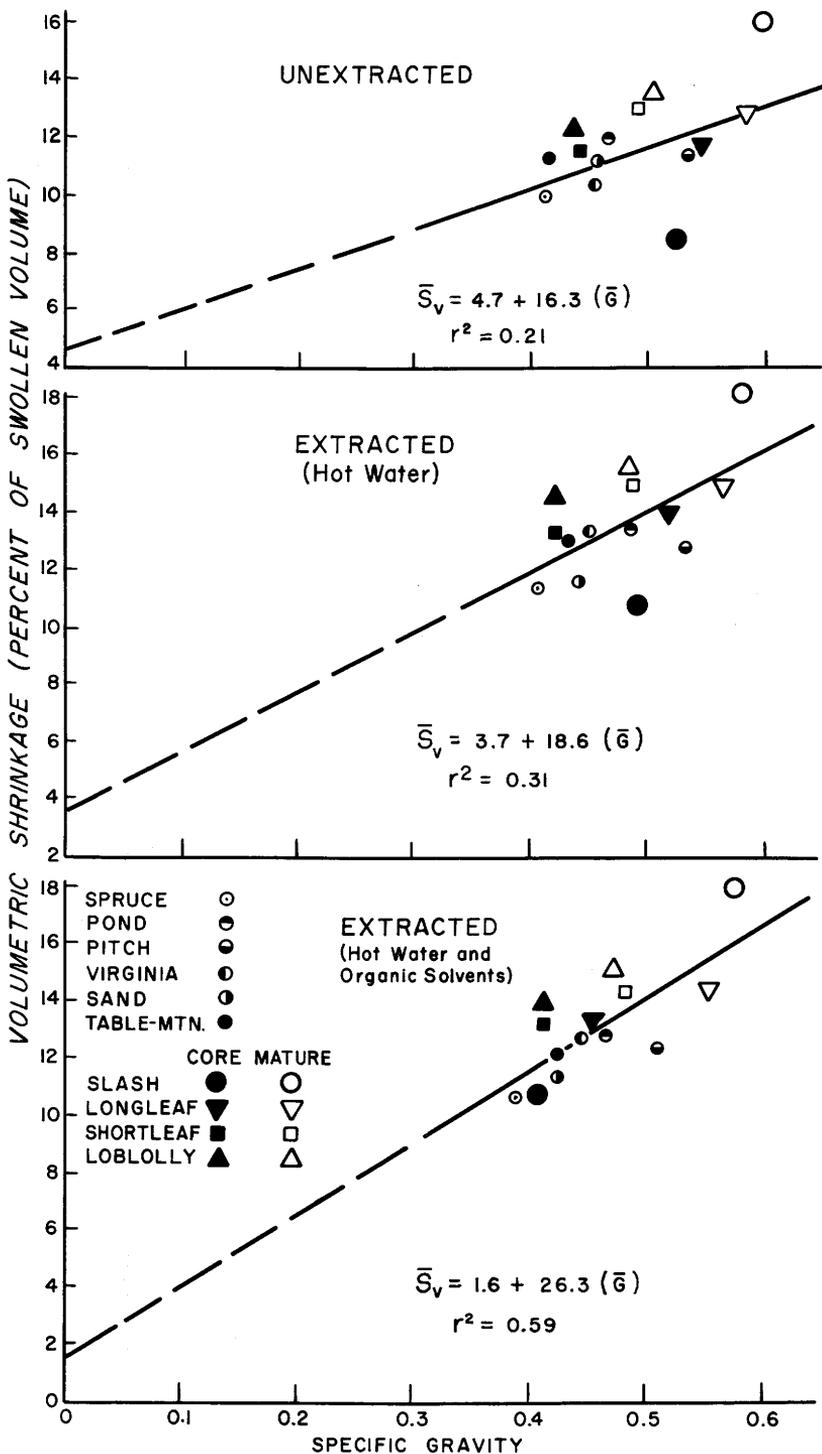


Figure 8-19.—Relationship of volumetric shrinkage (fiber saturation to oven-dry) to specific gravity (oven-dry weight and green volume) for unextracted and extracted southern pine wood. (Drawing after Choong 1969a.)

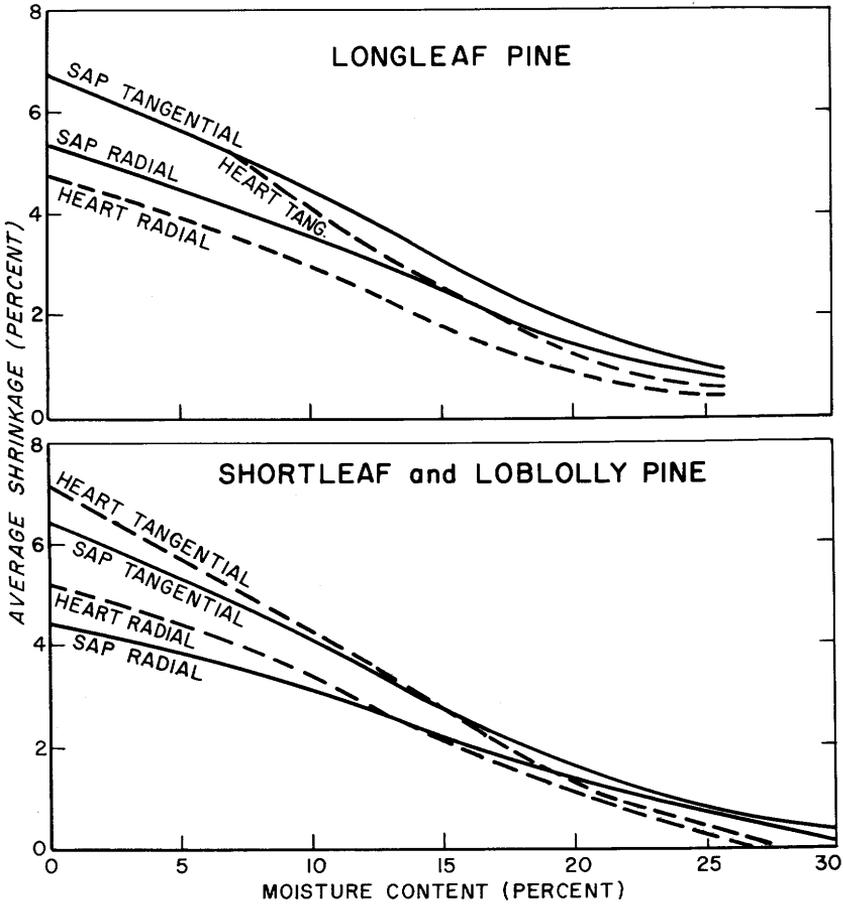


Figure 8-20.—Average shrinkage (percent of swollen dimension) with decrease in moisture content of 1- by 6-inch green southern pine boards. (Drawing after Teesdale 1930.)

mens showed less longitudinal shrinkage than heartwood when overdried from the swollen condition. In spruce pine, heartwood does not have a large content of extractives and most heartwood of this species lies within the zone of juvenile wood.

Type of wood	Longitudinal shrinkage		Observations
	Percent		Number
Earlywood			
Heartwood -----	0.54		29
Sapwood -----	.49		619
Latewood			
Heartwood -----	.29		29
Sapwood -----	.26		619

Fibril angle.—Shrinking (and swelling) movement is predominantly at right angles to the alignment axis of the cellulose molecules and of the elementary fibrils and microfibrils into which they are aggregated (fig.

6-2). The concept of imperfectly aligned cellulose molecules and elementary fibrils drawing into closer proximity when drying appears to offer a partial explanation of why longitudinal shrinkage is usually much less than radial or tangential shrinkage.

While it is generally agreed that fibril angle is significantly correlated with longitudinal shrinkage, the correlation is weak, and the experimental evidence is conflicting. Some recent workers have concluded that fibril angle is only indirectly related to variation in longitudinal shrinkage (Dadswell and Nicholls 1959; Boutelje 1962).

Koehler (1931) observed that some specimens of normal wood were longer at 12-percent moisture content than when green. Welch (1932), Cockrell (1943), and Kelsey (1963) all reported nonlinear relationships between longitudinal shrinkage and moisture content.

Pearson and Gilmore (1971) measured longitudinal shrinkage in 500 pieces of loblolly pine juvenile and mature wood taken from a range of heights in 19 trees; the specimens measured $1\frac{1}{4}$ by $1\frac{1}{4}$ inches in cross section and 17 inches long. The changes in longitudinal dimensions on drying from green to 12-percent moisture content were very variable, particularly in the butt log specimens. Approximately 75 percent of all the specimens exhibited an elongation at 12 percent when compared with the green dimensions. Juvenile wood tended to shrink in drying from green to 12-percent moisture content whereas mature wood tended to elongate, but the changes were generally small except in butt log material. Excluding butt log specimens, the average shrinkage was 0.001 percent for juvenile wood and the average elongation was 0.013 percent for mature wood. The average changes in length for butt log material were 0.096-percent shrinkage for the juvenile wood and 0.067-percent elongation for the mature wood, the maximum shrinkage being 0.57 percent and the maximum elongation 0.30 percent.

Barber and Meylan (1964) explained the anisotropic shrinkage of wood in terms of a model containing reinforcing microfibrils in a plastic matrix. Their theory indicated that the relationship between microfibril angle and shrinkage is unlikely to be linear, and depends not only on the angle but also on the ratio of the elastic moduli of the microfibrils and the matrix, and on the swelling properties of the matrix alone.

According to their theory, negative longitudinal shrinkage would be expected when the microfibril angle is 20° to 30° and when the elastic modulus of the microfibril is 20 or more times greater than the elastic modulus of the matrix. In wood, the elastic modulus of the matrix is reduced when moisture content is high. As wood dries, the matrix becomes more rigid and longitudinal shrinkage changes from negative to positive.

Research by Harris and Meylan (1965) on Monterey pinus (*Pinus radiata* D. Don) supports the theory of Barber and Meylan. Their results showed that minimum longitudinal shrinkage, which may be negative, occurs in wood with a fibril angle of approximately 25° and that longi-

tudinal shrinkage increases rapidly as fibril angle exceeds 25°. They suggest that the influence of the S_1 and middle lamella layers of the cell wall, which were ignored in the Barber-Meylan theory, exert a secondary effect on shrinkage. Their experimental data—summarized in figure 8-21—show that in 7-year-old trees tangential shrinkage decreases, while longitudinal shrinkage changes curvilinearly with increasing fibril angle. At comparable fibril angles, tangential shrinkage in latewood exceeded that in earlywood; longitudinal shrinkage was slightly greater in earlywood. Compression wood resembled earlywood in tangential shrinkage, but its longitudinal shrinkage at high fibril angles was much greater. The authors reported that fibril angles in compression wood were all within the range observed in normal wood.

In mature wood longitudinal shrinkage was less, and tangential shrinkage greater, than in corewood; at a fibril angle of 20°, longitudinal shrinkage of mature wood was negative (fig. 8-21 top).

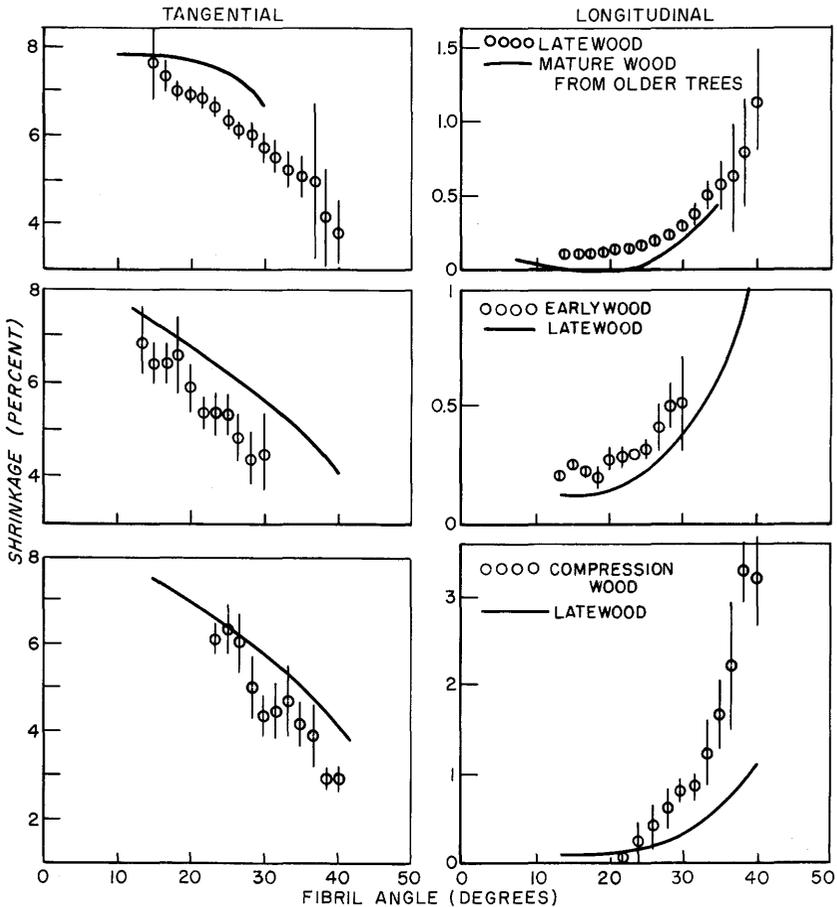


Figure 8-21.—Relationship between shrinkage (green to oven-dry) and fibril angle in latewood, earlywood, and compression wood from 7-year-old Monterey pine. Vertical lines indicate two standard errors about the mean. (Drawing after Harris and Meylan 1965.)

Further support of the reinforced matrix theory appears in Meyland's (1968) observations of shrinkage in earlywood and latewood of Jeffrey pine (*Pinus Jeffreyi* Grev. & Balf.). He found that the longitudinal and tangential shrinkage were equal when the fibril angle was 49° ; longitudinal shrinkage increased sharply with an increase in fibril angles above 30° (fig. 8-22).

In the work of Barber and Meylan (1964), Harris and Meylan (1965), and Meylan (1968), fibril angles were measured in the tangential wall

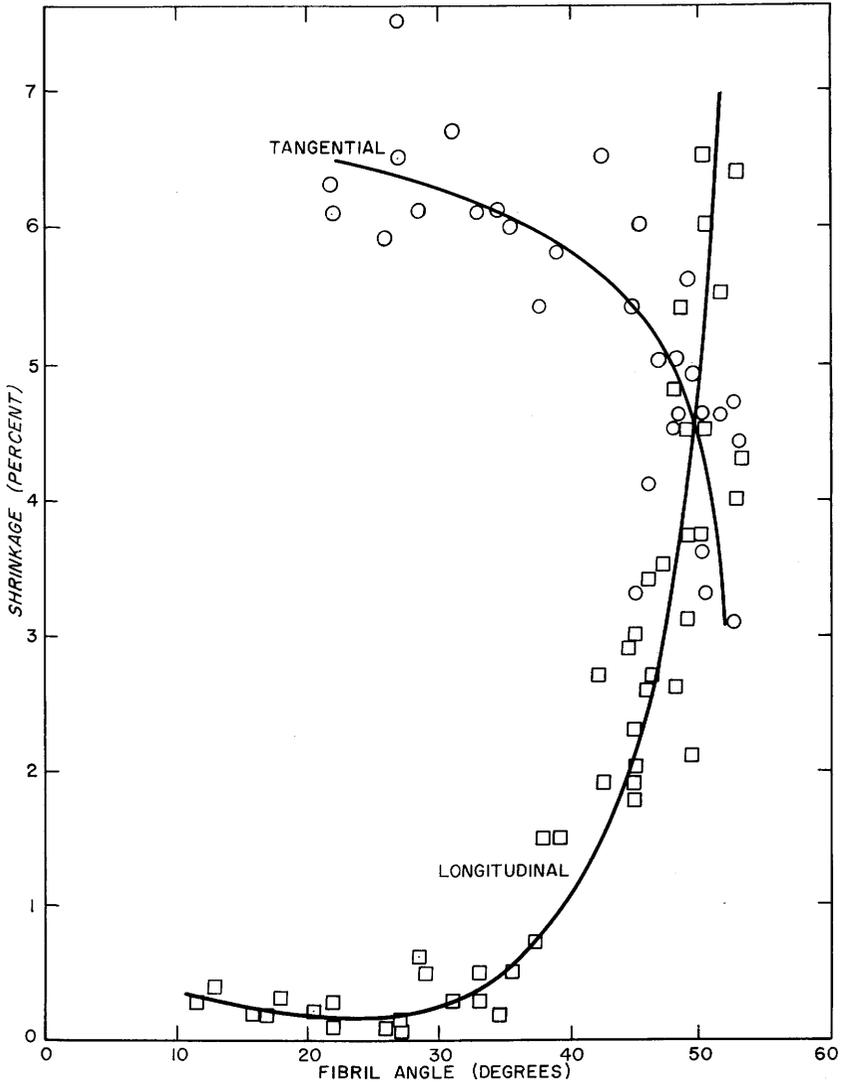


Figure 8-22.—Relationship of longitudinal and tangential shrinkage to fibril angle in Jeffrey pine. (Drawing after Meylan 1968.)

by X-ray diffraction techniques. Fibril angles are greater in the tangential wall than in the radial wall (Kelsey 1963).

By a technique of staining with iodine crystals, Wooten et al. (1967) measured fibril angles in the S_2 layer of radial walls of compression wood in 2-year-old slash pine. They found that longitudinal shrinkage of microtome sections was correlated with fibril angle in the S_2 layer, but the slope of the curve was very steep, i.e., longitudinal shrinkage increased from 1.06 to 8.60 percent, while fibril angle increased only 3° . They concluded that factors other than the fibril angle of the S_2 layer were involved in longitudinal shrinkage of compression wood and proposed that the abnormally thick S_1 layer (with its large fibril angles) adds to the shrinkage.

In observations of 1,296 micro-specimens of spruce pine earlywood and latewood, Manwiller¹ did not find a strong correlation between fibril angle and longitudinal shrinkage; in this study he used polarized light to measure fibril angle of wood closely adjacent to the micro-specimens. Perhaps better correlation would have been attained had fibril angles within the shrinkage specimens—rather than within wood adjacent to them—been measured.

Growth rate.—Classification of lumber according to fibril angle as a possible means of identifying boards prone to develop excessive longitudinal shrinkage is difficult.

Pillow et al. (1953), Hiller (1954), and McMillin² all found that there is some tendency for fast-grown wood of the southern pines—particularly earlywood from dense lumber—to have higher fibril angles than wood of slow growth. Manwiller¹, in his study of spruce pine, observed that fibril angles in earlywood of fast-grown trees were significantly larger than those in earlywood from slow-grown trees. Latewood fibril angles, however, were not significantly related to tree growth rate (by analysis of variance).

High fibril angles in fast-grown wood could possibly explain the positive correlation observed by Koehler (1938) between ring width and longitudinal shrinkage; he found that in both loblolly pine (fig. 8-23) and slash pine, wood of fast growth (i.e., with wide rings) had more longitudinal shrinkage than wood of slow growth.

The evidence is not conclusive, however. Yao (1969, p. 37) found no significant correlation between rings per inch growth rate and longitudinal shrinkage in southern pine wood. Nor did Dadswell and Nicholls (1959) observe a significant correlation between ring width and longitudinal shrinkage in latewood of slash pine (*var. elliottii*) taken 24 to 30 inches from ground level. In his study of spruce pine, Manwiller¹ was also unsuccessful in finding such a correlation.

Earlywood versus latewood.—Earlywood shrinks more longitudinally

² McMillin, C. W. Fibril angle of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.23 dated September 7, 1969.

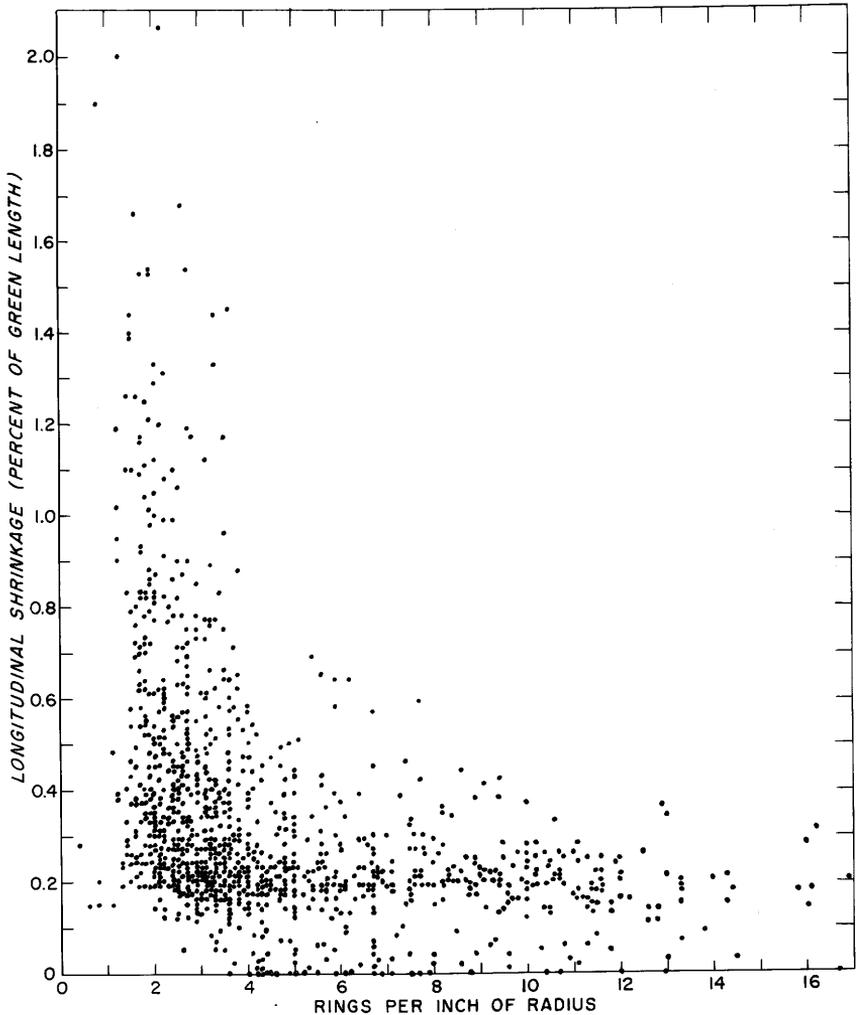


Figure 8-23.—Relationship of longitudinal shrinkage of loblolly pine to number of growth rings per inch of radius. (Drawing after Koehler 1938.)

than latewood (figs. 8-14, curves 3 and 4; 8-21). Tangential shrinkage of earlywood, however, is less than that of latewood (fig. 8-21). Harris and Meylan (1965), and also Manwiller¹, observed that the greater longitudinal shrinkage of earlywood is not explainable solely in terms of fibril angle, i.e., even at equal fibril angles earlywood from Monterey pine and spruce pine shrinks more longitudinally than latewood.

The difference in shrinkage between earlywood and latewood is of more than academic interest, since it causes earlywood slivers to loosen and pull away from the surface of flat-sawn boards. Curvature and undulations in dry rotary-peeled southern pine veneer can frequently be traced to the presence of earlywood on one face and latewood on the other.

Fiber length.—In wood taken from slash pine (*var. elliottii*) at 20 to 30 inches from ground level, Dadswell and Nicholls (1959) found a within-tree negative correlation ($r = -0.425$) between fiber length and longitudinal shrinkage.

In spruce pine wood (1,296 sample points), Manwiller¹ did not observe such a correlation.

Restraint.—When wood is externally restrained during swelling, the lumens are reduced in size as the cell walls get thicker; on redrying to the original moisture content, it shrinks permanently to a smaller volume. If the wood is then restrained to the smaller dimension, reswollen and redried, it will shrink to a yet smaller dimension.

No information specific to southern pine has been published. However, data on other species (Kollmann and Côté 1968, p. 215) indicate that repeatedly restraining wood in the radial direction through a series of wetting and drying cycles will finally result in more than 60 percent shrinkage in the radial direction; this radial shrinkage will be accompanied by a tangential swelling of about 35 percent. If the restraint is applied tangentially, the final tangential shrinkage will be in excess of 50 percent and will be accompanied by a radial swelling of about 25 percent.

WITHIN-TREE VARIATION

From the preceding section it was seen that heartwood (because of its extractive content) may shrink less than sapwood, and that earlywood has greater longitudinal shrinkage but less tangential shrinkage than latewood. There are other within-tree variations that have practical implications.

Radial position.—Lumber cut from a tree stem is usually not perfectly oriented to yield true flat or vertical grain boards. Figure 8-24 summarizes the manner of shrinkage to be expected in flats, squares, and rounds cut from various radial locations. Lumber cut not truly parallel to the grain can be expected to have greater longitudinal shrinkage than normal because it will contain a component of transverse shrinkage.

Because volumetric shrinkage is positively correlated with specific gravity (figs. 8-15, 8-16, 8-17) and negatively correlated with extractive content (fig. 8-19), volumetric shrinkage should be positively correlated with distance from the pith. Choong (1969a) observed such a positive correlation in four southern pines (fig. 8-25).

Possibly because fibril angles near the pith are large, longitudinal shrinkage should be greatest in the juvenile core, but fairly uniform in mature wood. Dadswell and Nicholls (1959) found this to be true in samples of slash pine (fig. 8-26). Variability in radial distribution of extractives may sometimes confound this relationship.

Height above ground.—In a study of loblolly pine wood, Yao (1969) observed that volumetric, radial, and tangential shrinkage decreased with increasing height above ground, but longitudinal shrinkage was positively correlated with height (fig. 8-27). This is not surprising because

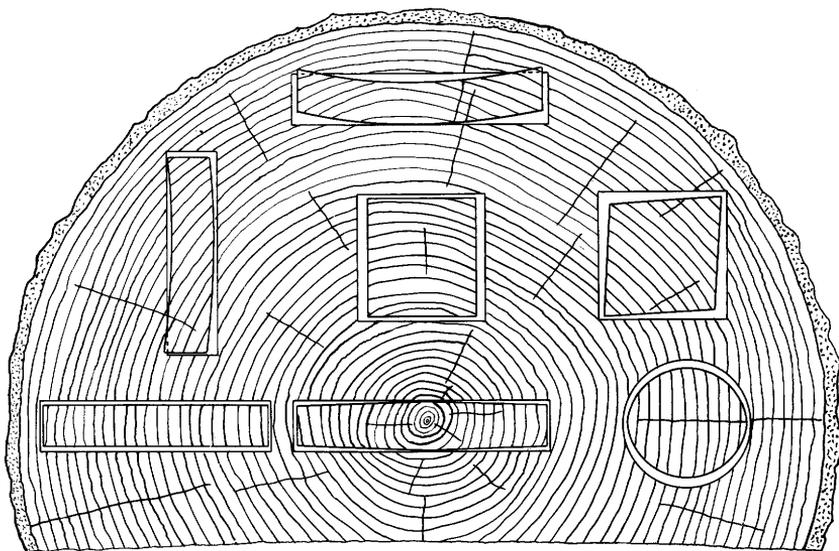


Figure 8-24.—Characteristic patterns of shrinkage and distortion for flats, squares, and rounds as affected by direction of the annual rings. (Drawing after Peck 1947.)

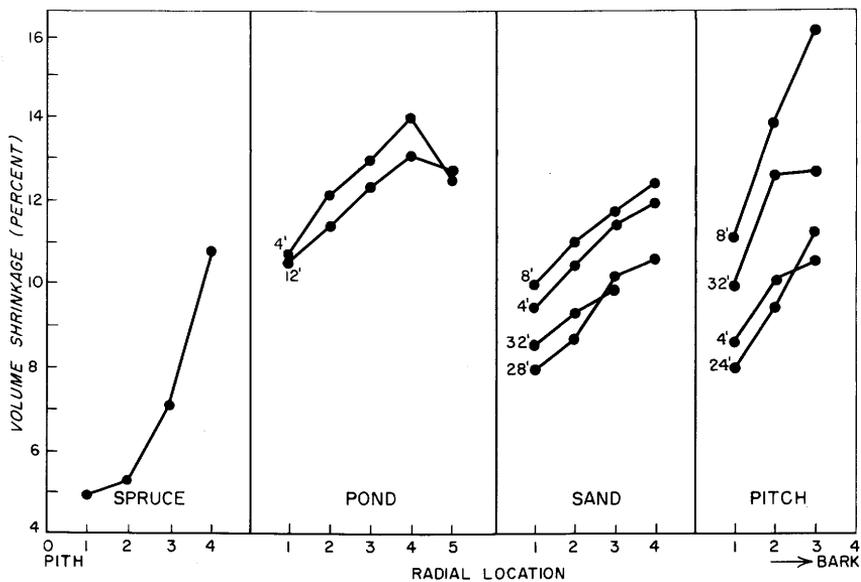


Figure 8-25.—Variation of volumetric shrinkage with radial position at various heights in stems of four minor species of southern pine. In each curve, the points to the left are for wood close to the pith and those farthest to the right are for wood adjacent to the bark. (Drawing after Choong 1969a.)

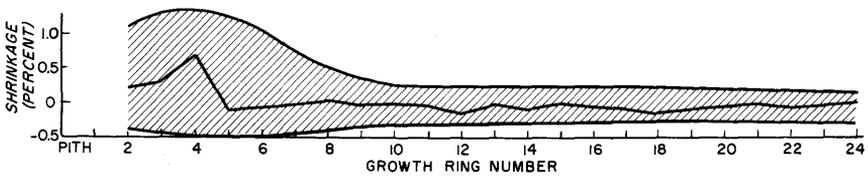


Figure 8-26.—Relationship of longitudinal shrinkage (green to oven-dry) in slash pine (var. *elliottii*) to number of rings from the pith. Specimens were taken 24 to 30 inches above ground. Curve is based on 13 trees; shaded area indicates range of values observed. (Drawing after Dadswell and Nicholls 1959.)

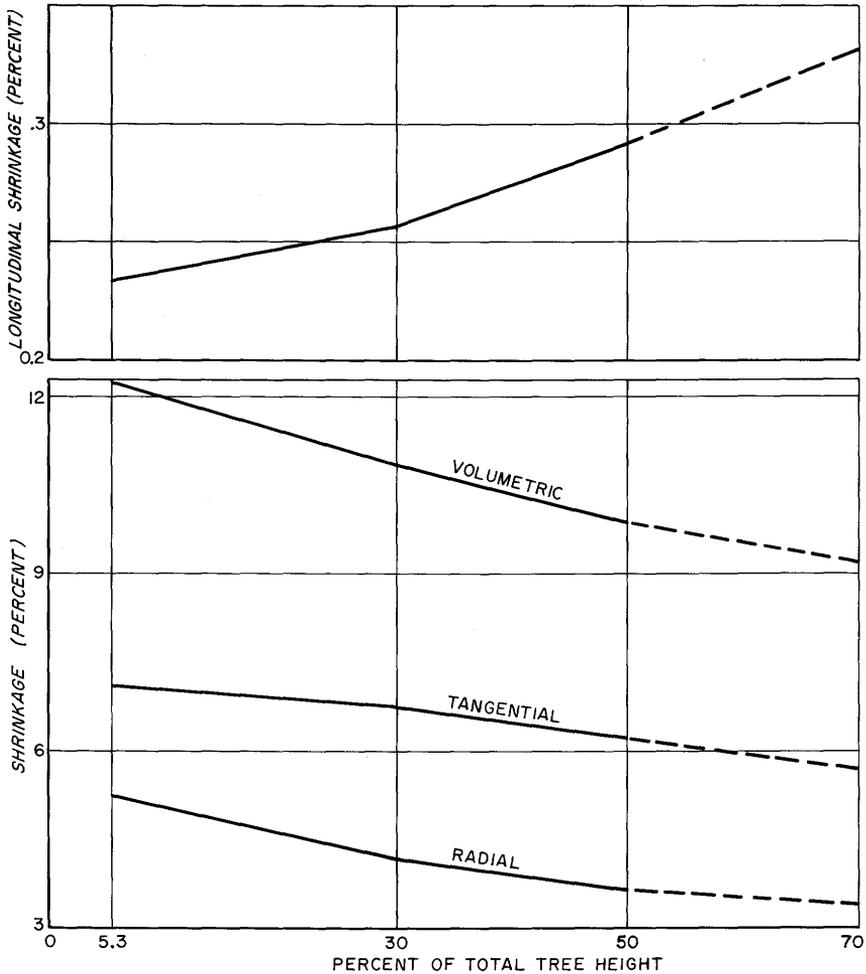


Figure 8-27.—Relationship of shrinkage (green to oven-dry) to percent of tree height in loblolly pine. Points plotted are averages from 28 trees except for values at 70 percent height, which represent only 12 trees. Twelve specimens taken from throughout a disk were measured at each height in each tree. (Drawing after Yao 1969.)

specific gravity and extractive contents are high—and fibril angles low—near the base of a tree. Conversely, average fibril angles are relatively high at the tops of stems.

Cardinal direction.—In a study of 28 loblolly pine trees from Mississippi, Yao (1969) found that wood from the south side of stems had significantly lower volumetric, tangential, and radial shrinkage, but higher longitudinal shrinkage values than wood from the other three directions. The differences were small but evidently real.

SUMMARY

From the foregoing it is concluded that volumetric, radial, and tangential shrinkage is greatest in latewood of sapwood of high density, low extractive content, and low fibril angle. Normally this type wood is found in the outer rings of the lower portion of the stem. Tangential shrinkage is normally greater than radial shrinkage; at very high wood specific gravities (about 0.72 on basis of oven-dry weight green volume) they may approach equality.

In normal wood, longitudinal shrinkage is greatest in short-fibered early-wood from fast-growing sapwood having a high fibril angle, low specific gravity, and low extractive content. This is the type of wood usually found near the top of the stem and within the first 10 rings. While longitudinal shrinkage is usually much less than tangential shrinkage, they become approximately equal when wood has a fibril angle of 45° to 50° .

In compression wood of southern pine, longitudinal shrinkage may reach 5.4 percent; more often, it is in the range from 0.3 to 1.0 percent (Pillow and Luxford 1937). The extreme shrinkage is attributable to the very high fibril angles typical of the S_2 layer (fig. 5-33F) and the abnormally thick S_1 layer in compression wood. Many of the large shrinkage values shown for wide-ringed wood in figure 8-23 were possibly observed in compression wood.

8-5 HEAT OF SORPTION

When wood adsorbs water, heat is evolved. The amount of heat given off when 1 g. of oven-dry wood is immersed in sufficient liquid water to bring the wood to fiber saturation is defined as the **total integral heat of wetting**. The total integral heat of adsorption (from water in vapor form) is the total integral heat of wetting plus the heat of vaporization.

Values of the total integral heat of wetting range from 16.6 to 20.5 calories per gram (Stamm 1964, p. 204). The range in values is attributable to the temperature of observation and fineness of the wood as well as the species. Finely divided wood gives off more heat than solid wood,

and the amount of heat evolved is negatively correlated with the temperature of the wood. Data specific to southern pine wood are limited to values given by F. Dunlap in a 1913 unpublished report on file at the U.S. Forest Products Laboratory in Madison, Wis. (Heat of absorption of water by wood, Project 169).

	<u>Total integral heat of wetting</u> <i>Calories per gram of oven-dry wood</i>
Longleaf pine sapwood -----	17.6
Longleaf pine heartwood -----	16.7

8-6 PERMEABILITY ³

The capability of wood to allow passage of fluids under pressure is called its **permeability**. The mass movement of molecules in fluids under pressure is distinct from the random motion of single molecules during diffusion to equalize concentration (or partial pressure) gradients.

Radial and tangential permeability is greater in the sapwood of southern pine than in most other species (Erickson et al. 1938). Smith and Lee (1958) observed that the longitudinal permeability of Caribbean pine (*Pinus caribaea* Morelet), a species closely related to the southern pines, was among the highest of several softwoods tested.

Because of its high radial and tangential permeability, southern pine sapwood is readily given high retentions of preservatives by pressure treatment in retorts; also it is easily kiln-dried.

The longitudinal permeability of southern pine sapwood makes possible the on-site preservative treatments reported by Scheffer and Clark (1967) and Van Allen (1956). As observed by Stasse (1964, 1966), the downward longitudinal movement of preservatives in erect southern pine poles gives them added protection near the ground line. Hudson's pressure process (1968, 1969; Hudson and Shelton 1969) for treating green poles with salt solutions capitalizes on the easy longitudinal flow of liquid through southern pine sapwood. (See ch. 22.)

VARIATION WITH DIRECTION

Because of the anisotropy of wood, it is reasonable that permeability should be different in the longitudinal, tangential, and radial directions. Some observations specific to southern pine have been published.

³ With some changes, sec. 8-6 is from Erickson (1970) by permission of H. D. Erickson and the Forest Products Research Society.

Ratio of permeability Longitudinal: radial:tangential	Medium	Southern pine species	Wood moisture content	Reference
100: 4:1	Creosote penetration	Longleaf pine heartwood	Ovendry	Teesdale (1914)
16: 5:1	Creosote penetration	Spruce pine heartwood	Ovendry	Teesdale (1914)
55: 7:1	Creosote penetration	Shortleaf pine heartwood	Ovendry	Teesdale (1914)
80: 4:1	Creosote penetration	Loblolly pine heartwood	Ovendry	Teesdale (1914)
15,000 to 1,500:150:1	Waterflow	Longleaf and slash pine sapwood	Air-dry	Erickson et al. (1937)
7,167: 38:1	Airflow	Unidentified sapwood	Air-dry	Choong and Fogg (1968)
133: —:1	Waterflow	Unidentified sapwood	Saturated	Choong and Kimble (1971)
15: —:1	Waterflow	Unidentified heartwood	Saturated	Choong and Kimble (1971)

WOOD ANATOMY AND PERMEABILITY

As with other woods, the important channels of flow through southern pine wood are openings in the cell walls. Their number, size, and degree of obstruction determine the degree of permeability. Readers interested in theoretical models that partially explain the variations in directional permeability of softwoods will find the analyses of Comstock (1970) useful.

Although checks frequently occur in tracheid walls during drying, the primary walls usually remain unruptured. The primary channels of flow are openings in the pit membranes between pit pairs.

Pit pairs are classified and described in section 5-5.

<u>Pit pairs</u>	<u>Figure number</u>
Tracheid to tracheid—bordered	5-7a, 5-9, 5-25, 5-26
Tracheid to ray tracheid—bordered	5-27
Ray tracheid to ray tracheid—bordered	5-28
Tracheid to ray parenchyma—half-bordered pinoid	5-29, 5-30, 5-31
Ray tracheid to ray parenchyma—half-bordered	5-32AB
Ray parenchyma to ray parenchyma—simple	5-32C

Although there is evidence of plasmodesmatal openings in the tori of southern pine pit membranes (Côté 1967; Thomas 1969), openings in the margins afford the primary channels for fluid movement between cells.

Networks of microfibrils in the margins of tracheid-to-tracheid bordered pit membranes are fairly loose (figs. 5-25B, 5-26DF); those in pit pairs between longitudinal and ray tracheids (fig. 5-27A) and between ray tracheids (fig. 5-28AB) are somewhat denser.

Thomas (1969), in a study of three species of southern pine, found that the number of margo microfibrils (and thus margo density) was consistently higher in latewood than in earlywood.

Thomas (1969) also observed that earlywood pit membranes in sapwood were rarely encrusted, whereas latewood membranes in both sapwood and heartwood were heavily encrusted (figs. 5-26B, 5-28B). Membranes shared by ray parenchyma appear to have no openings except the perforations accommodating plasmodesmata (fig. 5-32C).

It is believed that radial flow of water under pressure is mainly through ray tracheids into longitudinal tracheids and vice-versa; radial flow may also occur through resin canals and intercellular spaces in wood rays (Erickson 1938; Erickson et al. 1938; Buro and Buro 1959; Erickson and Balatinecz 1964). Longitudinally and tangentially, the flow is primarily through tracheid-to-tracheid pits (Bailey and Preston 1969).

Electron micrographs of a limited number of specimens showed maximum spaces in pitmembrane margins of approximately 0.5 μm . for solvent-seasoned loblolly pine (Côté 1967), 0.4 μm . in longleaf pine (Thomas 1967), and 0.2 μm . in pond pine (Hart and Thomas 1967). Probably variation within species is greater than between-species variation.

Stamm et al. (1968) found that the measurement (surface tension technique) of maximum effective size of opening in 100 pits in series was reproducible and gave a good index of preservative treatability, i.e., permeability. While the maximum openings for single pits in three samples of green loblolly pine sapwood ranged from 6.4 to 10.0 μm . in diameter, for 100 pits in series the effective opening diameters were much less (range 0.16 to 1.8 μm .).

Openings in the margo may increase in size with time since the wood was formed (fig. 5-26F). Nicholas and Thomas (1968b) found a high pectin content in tori and pit membranes of loblolly pine. Pectinase weakened the membrane and created holes in the torus. The enzymes hemicellulase and cellulase also caused some degradation of torus and membrane. Thomas (1969) concluded that the microfibril structure in earlywood margins is very dense when the wood is first formed; within 1 year the margins become less dense but exhibit substantial variation. The change to a low-density margo microfibril network is a much slower process.

PIT ASPIRATION

The valve-like action of the torus (see fig. 5-9) was noted by Bailey (1913, II). Subsequent studies by many workers have shown that pit aspiration decreases permeability in all conifers.

Comstock and Côté (1968) presented the concept that three factors are involved in aspiration.

- Surface tension forces tending to pull the torus into contact with the pit border (Griffin 1919; Phillips 1933; Hart and Thomas 1967).
- Rigidity or stiffness of the pit membrane, which results in a force opposing the surface tension forces exerted by the evaporating liquid, e.g., latewood pits tend to aspirate less than earlywood pits, evidently because latewood pits are smaller in diameter and have a thicker, more rigid membrane.
- Adhesion of torus to pit border when brought into contact. Adhesion appears to be great in the presence of water but less in the presence of organic solvents.

Smith and Lee (1958) concluded that openings available between torus and pit border may be smaller when the pit is aspirated than when it is unaspirated. Meyer (1971), who observed that longitudinal gas permeability of Douglas-fir sapwood is negatively correlated with its proportion of aspirated pits, also suggested that permeability is positively correlated with tracheid length, total number of pits per tracheid, and number of tracheids per square millimeter of transverse section.

WITHIN-TREE VARIABILITY

Permeability of southern pine wood varies according to its position in the stem.

Heartwood versus sapwood.—Heartwood is much less permeable than

Ratio of permeability, sapwood:heartwood	Medium	Wood moisture content	Southern pine species	Reference
Longitudinal				
4000:1	Water	Green	Slash	Stamm (1931)
380:1	Water	Green	Longleaf	Erickson et al. (1937)
15 to 90:1	Air	Dry	Four	Fogg (1969)
55:1	Air	Dry	Unidentified	Choong and Fogg (1968)
19:1	Water	Saturated	Unidentified	Choong and Kimbler (1971)
Tangential				
Some:0	Water	Dry	Longleaf	Erickson et al. (1937)
2:1	Water	Saturated	Unidentified	Choong and Kimbler (1971)
Radial				
240:1	Water	Dry	Longleaf	Erickson et al. (1937)
21:1	Water	Dry	Loblolly	Erickson et al. (1937)
5:1	Air	Dry	Unidentified	Choong and Fogg (1968)
Lateral (combined radial and tangential)				
5:1	Air	Dry	Shortleaf	Tesoro et al. (1966)

sapwood because most pits in heartwood are aspirated. Thomas (1967, 1969) found complete and tight aspiration in unseasoned southern pine heartwood; sapwood had fewer aspirated pit membranes. Presence of extractives in heartwood further hinders flow.

Radial position in sapwood.—In solvent-dried southern pine wood Thomas (1967, 1969) found fewest pits aspirated in outer sapwood. In heartwood all pits were tightly aspirated except for a five- to 10-ring outer zone, where some were not aspirated.

Benvenuti (1963) determined that dry outer sapwood of loblolly pine was more permeable to nitrogen gas than the inner sapwood. In contrast, Fogg (1969) found no important correlation between longitudinal permeability to air and distance from the pith in air-dried sapwood of four species of southern pine.

Earlywood versus latewood.—The data are conflicting, as indicated by the following observations of sapwood permeability. Tests by unidirectional flow do not necessarily give the same results as impregnation in a pressure chamber. In the uniform pressure of a treating chamber the liquid will enter most speedily in the direction of least resistance and build up internal back pressure unless the wood has been first highly evacuated.

<u>Medium and comment</u>	<u>Species</u>	<u>Reference</u>
Airflow		
In longitudinal direction, flow greater through seasoned earlywood than through latewood.	Loblolly pine	Tiemann (1910, pp. 359-375)
	Pitch pine	Bailey (1913)
Liquid flow in earlywood and latewood		
In both seasoned and unseasoned earlywood, longitudinal flow exceeded that in latewood by a factor of:		
30 for-----	Slash pine	Erickson et al. (1937)
8 for-----	Loblolly pine	Erickson et al. (1937)
Earlywood over 100 times more permeable (longitudinal) to water than latewood.	European larch	Huber and Merz (1958, II)
In three out of four southern pines tested, radial flow was up to twice as great in seasoned earlywood as in latewood.	Southern pine	Erickson et al. (1938)
Creosote in pressure retort		
Penetration greatest in latewood----	Longleaf pine	Weiss (1912) and MacLean
Penetration greatest in latewood----	Longleaf pine	Teesdale and MacLean (1918)
Penetration greatest in latewood----	Shortleaf pine	Blew (1955)
Penetration greatest in latewood----	Shortleaf pine	Tesoro et al. (1966)
Evidence not conclusive-----	Southern pine	Buckman (1936)

From these data it is concluded that green earlywood of pine sapwood is probably more permeable than the latewood; dry latewood is sometimes more permeable than dry earlywood. In green sapwood the greater size

and number of unencrusted and unspirated bordered pits in earlywood should permit better liquid flow. In dry sapwood, variations in ratios and numbers of aspirated pits may cause variable liquid penetration and flow. According to Comstock and Côté (1968) the more rigid membranes of latewood pits cause them to aspirate less than pit membranes in earlywood. This open condition is partially offset by the greater encrustation of latewood membranes (Thomas 1967, 1969).

Specific gravity and ring width.—Data specific to the southern pines are limited and conflicting. Fogg (1969) found no correlation between longitudinal flow of air in seasoned sapwood of four southern pines and specific gravity, ring width, or percent earlywood. Benvenuti (1963), however, reported an inverse relationship between permeability (to nitrogen gas) and specific gravity of dry loblolly pine.

In green sapwood of Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) longitudinal flow of water was found inversely related to specific gravity (Erickson and Crawford 1959).

EFFECT OF TREATMENTS

The permeability of southern pine wood is affected by its dryness, history of heat treatment, degree of extraction, and exposure to biological agents.

Drying.—The precise effects of seasoning (and the manner of seasoning) on pit aspiration and permeability are not clear. Following are summaries of observations.

Phillips (1933) noted that in conifers aspiration increased greatly as wood dried to the fiber saturation point; pits in latewood aspirated less than pits in earlywood. Drying with alcohol (exchanged for the water in green Corsican pine) generally prevented aspiration. This was attributed to the low surface tension of alcohol.

Thomas and Nicholas (1966) were able to deaspirate pit membranes in specimens of air-dry loblolly pine sapwood by resaturating in water and passing them through a solvent series.

Hudson and Shelton (1969) reported that time required to impregnate 20-foot southern pine poles with water-soluble preservatives was positively correlated with time since the pole was cut.

<u>Time since tree was felled</u>	<u>Time required to impregnate</u>
<i>Days</i>	<i>Hours</i>
1-7	1.9
31-60	2.5
100-187	5.0

Hudson's process relies on pressure-driven longitudinal flow from butt to top.

In contrast to the idea that drying green wood reduces permeability by membrane aspiration, several studies indicate that permeability is un-

changed or increases as wood is dried. Comstock's (1968) study of eastern hemlock (*Tsuga canadensis* (L.) Carr.) heartwood is an example. Fogg (1969) found that permeability to air increased as southern pine wood was dried below the fiber saturation point. Cycles of readsorption and redrying generally increased the permeability at a given moisture content; the effect was irreversible, however, if the wood was dried below 6-percent moisture content. If the cycles were maintained above 20-percent moisture content, the tendency toward increased permeability was negligible. Fogg believed the increased permeability to be caused by the development (during drying) of minute checks in the cell wall.

Thompson (1969) found no significant difference in air permeability of southern pine sapwood before and after kiln-drying or among kiln schedules. In three out of four southern pines, Erickson et al. (1937) found that longitudinal flow of water at low pressure through evacuated seasoned sapwood was greater (up to nearly two times as great) than that for unseasoned sapwood. In shortleaf the opposite was true.

Buckman et al. (1935) observed that higher pressure was required to overcome surface tension of benzene in the larger capillaries of wood as moisture content increased toward fiber saturation point. The flow rate of benzene also decreased with increasing moisture content, indicating decreased size of openings because of swelling caused by the increased moisture content.

In summary, the evidence does not clearly show that pit aspiration induced by drying closes passageways to fluids under pressure.

Steaming.—The effect of steaming on the permeability of southern pine wood is not entirely clear. Green loblolly sapwood steamed at atmospheric pressure for 4 hours was 30 times more permeable than unsteamed controls (Benvenuti 1963); Nicholas (1966) believed that the improvement was due to degradation of the pit membrane. Nicholas and Thomas (1968ab) showed that steaming green loblolly pine wood made margo fibrils more flexible and increased the effect of pectinase in making the wood more permeable. The work of Fogg (1969) showed that a 10-minute steaming produced only a small increase in permeability and additional steamings gave either no effect or a slight decrease. In Fogg's tests, however, steaming was not severe and was done on dried wood. By comparison, steaming of green Douglas-fir and western hemlock improved permeability only after the wood had been dried (Erickson and Crawford 1959); steaming increased the permeability of eastern hemlock heartwood (Comstock 1965).

Extracting.—Numerous studies indicate that permeability is greater in extracted southern pine than in unextracted pine.

Thomas (1967) found that solvent-exchange drying occasionally removed the bulk of soluble deposits from latewood pit membranes and from ray tracheid membranes.

Blocking by soluble extractives and by insoluble encrustants has been

observed by Côté (1963). Fogg (1969) found that extraction with alcohol-benzene or hot water for periods of 4 to 12 hours considerably increased air permeability of dry sapwood of four southern pines; increases in the heartwood were smaller. Earlier studies by Erickson et al. (1937) showed that the flow of benzene through both sapwood and heartwood of southern pines and other species was greater than would be expected on the basis of its viscosity compared to water. They suggested a solvent action on aspirated pits, causing the tori to be released, or on the resin ducts making them effective channels. Hartmann-Dick (1955) reported that organic solvents flowed through wood faster than water. He attributed this to dissolving out of blocking substances; the data show, however, that viscosity was the main influence.

If Monterey pine sapwood, which was resistant to penetration by aqueous solutions but penetrable by creosote, was preextracted by alcohol or ether, then sinking time in water was greatly reduced (Wardrop and Davies 1958). Fatty material on pit membranes was removed by the solvents. These findings are probably equally applicable to the southern pines. In heartwood of eastern hemlock, alcohol-benzene extraction doubled permeability to water (Comstock 1965).

Biological agents.—Southern pine sapwood infected with blue-stain fungi absorbs more water and creosote than noninfected wood (Lindgren and Scheffer 1939). The increased treatability is due to a breakdown of ray parenchyma and some direct penetration of tracheid walls by hyphae. Spraying fresh posts with fluoride solution favors growth of *Trichoderma* (sp.), which greatly increases oil absorption after the wood is dried (Lindgren 1952; Blew 1952).

Lutz et al. (1966) reported that when southern pine was stored in warm water or under a sprinkler for many months anaerobic bacteria destroyed parenchyma in rays and resin ducts, causing an increase in longitudinal and radial permeability and absorptivity. Similar results were reported by Banks (1970) in studies of Scotch pine (*Pinus sylvestris* L.).

The enzyme pectinase acting on loblolly pine sapwood improves permeability (Nicholas and Thomas 1968b) by degrading the torus and pit membrane. Ray parenchyma cells are also attacked. Heartwood, however, is not attacked (even after solvent extraction) because of protection by the encrusting materials.

Under some storage conditions green Douglas-fir wood loses much of its permeability, probably due to plugging by micro-organisms (Erickson 1960). Similar plugging may have caused some of the divergent results reported in the literature on southern pine permeability.

EFFECTS OF TEST PROCEDURES

Flow of liquids through southern pine is affected by the pressure applied, the duration of the flow, and the characteristics of the liquid.

Pressure.—According to Darcy's law, flow should be directly propor-

tional to pressure. Some data show this proportionality. In seasoned and evacuated loblolly and slash pine, Erickson et al. (1938) observed rates for water flowing longitudinally through sapwood that were proportional to pressures up to 50 cm. Hg (9.67 p.s.i.), the maximum he used. With Sitka spruce heartwood, Kelso et al. (1963) also reported proportionality of waterflow at pressures to 240 cm. Hg.

Hudson and Shelton (1969) observed longitudinal flows of water solutions through southern pine poles that were not proportional to pressure when first applied to a freshly cut pole end; however, when a second end-surface was exposed by a new cut, flow became approximately proportional to reapplied pressure (fig. 8-28).

In studies of airflow through southern pine, Fogg (1969) observed that flow was positively correlated with pressure, but flow increase was less than directly proportional to pressure increase.

The reasons for the observed lack of proportionality between flow and pressure in some experiments are not entirely clear. The possibility of pit closure by aspiration of the pit during a high rate of liquid flow was suggested by Bailey (1913 II), but he found that a pressure of 250 p.s.i. did not rupture the membranes or shut off flow through pitch pine and other species. Flow rates less than proportional to pressure have been ascribed to liquid turbulence and non-laminar flow (Sucoff et al. 1965). Kelso et al.

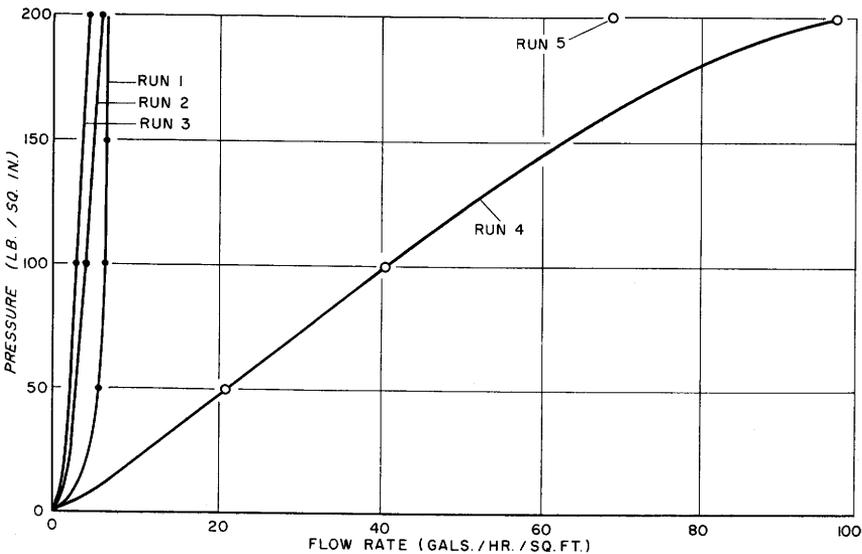


Figure 8-28.—Longitudinal flow of waterborne copper-chrome-arsenic preservative through a 20-foot southern pine pole as related to pressure applied at the freshly cut butt end. Run 1 was made with a freshly cut butt end; runs 2 and 3 were made on the same pole and cut end but on the 2 succeeding days. After cutting off a disk to expose a fresh end, reapplication of pressure resulted in run 4. Run 5 was made a week later. (Drawing after Hudson and Shelton 1969.)

(1963) demonstrated that flow is retarded by the presence of air bubbles in the liquid.

Time.—A negative correlation between rate and duration of flow of liquids has been reported for southern pines and other species by Erickson et al. (1937, 1938), Huber and Merz (1958 I, II), Hartmann-Dick (1955), Bauch (1964), and Hudson and Shelton (1969)—see fig. 8-28.

The diminishing flows have been attributed to several causes. In woods with small openings in pit membranes, dissolved air in water under substantial pressure may form bubbles and block the openings (Kelso et al. 1963). Small particles or micro-organisms in water are also believed to block pit openings (Erickson 1970). Huber and Merz (1958 I, II) concluded that the observed decreasing flow of liquid with time was due to gradual closing of the pits as the membranes stretched and tori aspirated. Bauch and Liese (1966) stated that solvents with high surface tensions give diminishing flow with extended time.

Erickson and Crawford (1959) and Erickson (1960) were able to obtain constant waterflow at low pressure by using fresh sapwood and particle- and gas-free water to eliminate blocking of the pit membrane pores. More recently Kelso et al. (1963) obtained constant flow at higher pressures through Sitka spruce heartwood using water with no dissolved gases as have also Sucoff et al. (1965) through green sapwood of northern white cedar (*Thuja occidentalis* L.). Bauch and Liese (1966) achieved constant flow through European silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) Karst) using a number of organic liquids having low surface tension.

Viscosity, molecular weight, and solution concentration.—Most studies on the permeability of wood have employed liquid flow achieved by pressure. The data have been expressed as rate of flow for given conditions or as a permeability coefficient based on Darcy's Law. Some of the recent studies have used air or other gases. Gases, being compressible, require a correction for pressure gradients and, depending upon the pore sizes and gas pressure used, a correction for molecular flow (slip flow or Knudsen's flow) along the capillary walls. The most intensive study of gas flow in southern pine was made with air by Fogg (1969).

Although the use of gas is convenient, all gases may not give the values necessary to predict liquid permeability; and the permeability of green wood to a specific liquid can only be obtained with certainty by using that liquid.

Bauch and Liese (1966) concluded that the rate of flow of an organic solvent at a given pressure is essentially dependent on its viscosity; but methanol and acetone were exceptions. They found no correlation between molecular weight and rate of flow.

Data on the effect of solution concentration are conflicting. A slightly greater flow rate was noted with a 3-percent zinc chloride solution (Erickson et al. 1937) than with a weaker one. Hudson and Shelton (1969)

report better flow of preservative salt solutions than of water through southern pine poles. The work of Hartmann-Dick (1955) on three European woods showed that most mineral salts, mercuric chloride excepted, and some bases diminish permeability, though some heavy metals show the opposite effect; increasing salt concentration generally caused a decrease in permeability. More recent work by Chen (1968) indicates no specific effect of several monovalent and divalent cations on specimen permeability.

The precise effects of various kinds of solutions on permeability are imperfectly understood. Some differences in results are related to preparation of the wood. Care is required to prevent blockage by particles in suspension, air in the wood, or formation of gas-liquid interfaces.

8-7 MECHANISM OF DRYING ⁴

The drying of wood requires the removal of moisture from the wood surface as well as its movement from the interior of the wood to the surface. It is important to keep these obvious processes constantly in mind; the relative balance between the two determines the effect of controllable factors upon the drying process. For example, if the surface of the wood remains relatively wet, the rate of drying may be substantially increased by increasing airflow. On the other hand, when the surface has approached the equilibrium moisture content, the rate of drying is almost completely dependent upon the rate of moisture movement from the interior to the surface, and an increase in air velocity is ineffective and wasteful. In either case, while the wet-bulb temperature of the air moving across a charge remains constant, its dry-bulb temperature drops in proportion to the quantity of moisture evaporated, reaching the wet-bulb temperature if the air becomes totally saturated. Thus it is desirable to use sufficient air velocity to maintain a reasonable drying capacity on the exit-air side of the charge.

REMOVAL OF MOISTURE FROM THE WOOD SURFACE

The rate at which water may be evaporated from a very wet surface by an airstream is primarily dependent upon the velocity of the air and upon the wet-bulb depression. Available information indicates that the evaporation rate is directly proportional to wet-bulb depression, but is somewhat less than directly proportional to the air velocity. A 10° wet-bulb depression should result in nearly the same surface evaporation rate at 100° F. as it does at 160° F., providing the wood surface remains quite wet.

This relationship stems from the fact that the rate of heat transfer from the moving airstream to the wood surface is directly proportional to the

⁴ The text and figures for sec. 8-7 are taken virtually verbatim except for slight revisions, from Hart (1965), by permission of C. Arthur Hart and North Carolina State University.

temperature difference between the airstream and the wood surface. Since a very wet wood surface will be cooled to wet-bulb temperature in exactly the same way that a wet bulb is cooled by evaporation, the temperature difference between the airstream and the wood surface is equal to the wet-bulb depression, and therefore the drying rate (weight loss) is directly proportional to the wet-bulb depression.

As the wood surface begins to dry out, a sufficient supply of moisture to provide for the maximum cooling effect of evaporation is no longer available, and the surface temperature of the wood rises above the wet-bulb temperature. This diminished air-to-surface temperature difference results in a diminished rate of heat flow to the surface. Until drying is completed, the rate of heat flow to the wood must be in balance with the heat consumed by the evaporation from the wood plus the heat utilized in raising the wood temperature. Thus, the temperature of the wood will approach the dry-bulb temperature as the wood approaches equilibrium moisture content, and the drying rate (and heat consumption) approaches zero.

MOVEMENT OF MOISTURE FROM THE INTERIOR OF WOOD TO THE SURFACE

Two distinct phenomena govern the movement of moisture in wood. In wood above the saturation point, **free water**, contained within cell lumens, flows like water in pipes, through continuous passageways or void structures under pressure gradients. In wood below fiber saturation, on the other hand, moisture moves either by **bound-water diffusion** across cell walls, or by **vapor diffusion** across voids; the water molecules diffuse toward regions of lower moisture content.

Free water flow.—Since freshly cut wood of most species is well below the maximum moisture content, air bubbles of substantial size might be expected to occur in most, if not in all, of the cell lumens. Because the length of a typical cell lumen is about 100 times its diameter, the bubble is roughly cylindrical in shape, although the lumen does taper toward the ends (fig. 8-29A).

The pressure exerted by a given bubble is equal to its air pressure (if any) plus the pressure of the water vapor in the bubble (100-percent relative humidity) minus the capillary pressure of the menisci at the ends. Thus, the total bubble pressure may be negative or positive, exerting a tensile force or a compressive force, depending upon which is the larger—the capillary pressure or the air plus vapor pressure. If they are equal, then the bubble is in static equilibrium.

If the bubble is in static equilibrium and the wood is then heated, the sum of the air plus water vapor pressure increases rapidly, while the capillary pressure actually decreases somewhat; the bubble will tend to expand and exert a positive pressure on the water. If the pits in the cell wall are permeable and the pressure on the other side is less, the cell

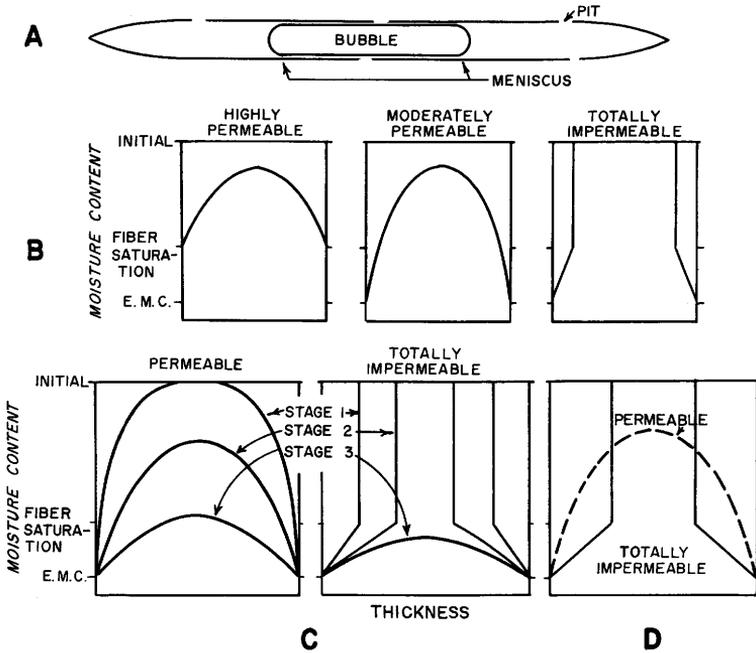


Figure 8-29.—Illustrations of wood drying processes. (A) Air bubble in lumen containing free water. (B) Moisture profiles in lumber of varying permeability. (C) Moisture profiles at three stages of drying (drying times are not equal). (D) Moisture profiles in permeable and impermeable wood, after equal amounts of moisture have been removed. (Drawings after Hart 1965.)

cavity water will be pushed through them. Among adjacent cells at equal temperature, water will thus flow from lumens of higher pressure to those where pressure is lower.

Moisture profiles.—In highly permeable woods heated almost to the boiling point, the lumen total bubble pressure can, in some cases, exceed atmospheric pressure (14.7 p.s.i. at sea level) and appreciable free water can be forced to the surface of the wood. At normal drying temperatures, however, the lumen total bubble pressure will probably be less than atmospheric pressure. In this case, little moisture is removed from the interior until surface moisture is evaporated and menisci form in the pits at the wood surface. The surface can be considered in the same manner as a bubble, that is, the total pressure is the air plus water vapor pressure, which in the case of the surface is the atmospheric pressure, 14.7 p.s.i., minus the capillary pressure of the surface pit menisci. Since the capillary pressure is directly proportional to the reciprocal of the meniscus diameter, a very strong capillary pull may be quickly developed by the surface menisci as they retreat into the pits. Thus a negative total “surface bubble” pressure, i.e., a tensile force rather than a compressive force, develops. If the lumen on the other side of the pit contains a bubble, it will expand as water evaporates from the wood surface, as will that of the next lumen,

and a pressure gradient as well as a moisture content gradient above fiber saturation can result. In very permeable woods this gradient may well extend all the way to the center of the board while the surface menisci persist, and thus substantial drying occurs while the surface remains at fiber saturation.

Sooner or later, however, the rate of mass flow of free water to the surface will fall behind the rate of surface evaporation, and the surface moisture content will fall below fiber saturation. This occurs soonest in impermeable woods with little if any of the continuous void structure which permits mass flow. The surface moisture content will immediately dry to below fiber saturation and may rapidly approach the equilibrium moisture content (e.m.c.) while the moisture content of the interior remains quite high. If the e.m.c. is too low, the tendency of the surface layers and board ends to shrink may result in excessive surface checking or splitting; thus, it is usual to start with higher e.m.c. conditions in the early stages of drying and progress to lower e.m.c. conditions as the moisture is removed.

The surface moisture content of most commercially dried woods probably falls below saturation soon after drying begins. But in such cases the mass movement of free water is still important. Consider the examples of moisture profiles shown in figure 8-29B. The first represents the condition in which the surface of a highly permeable wood has remained at fiber saturation for a substantial period of drying. The second illustrates the condition in which the surface moisture content has approached equilibrium moisture content (e.m.c.) and a bound-water moisture content profile continues almost smoothly past fiber saturation into a free water profile, thus resulting in an approximately parabolic moisture profile. The third example illustrates the situation in totally impermeable woods in which no mass flow of free water is possible. In each case bubbles are assumed to be present in all lumens, enabling the lumen water to diffuse immediately through the cell wall when the relative humidity drops below 100 percent on the far side of the cell wall.

In both the highly permeable and the moderately permeable wood, substantial mass flow of free water is occurring. The difference is that in the latter case the rate of surface evaporation has exceeded the rate of mass flow of free water to the surface, causing the surface wood to dry below fiber saturation. This permitted the surface temperature to increase, thereby reducing the difference in temperature between the surface and the air. The rate of heat flow from the air to the surface decreased correspondingly, and the rate of moisture loss from the surface decreased by the same proportion.

Just as rate of heat transfer is directly proportional to temperature gradient, the rate of moisture diffusion below fiber saturation is directly proportional to the moisture content gradient. Thus the steeper the slope of the moisture content profile at the wood surface, the faster

the drying. As the wood dries, the slope of the moisture content profile at the wood surface must decrease, so the rate of drying must decrease by the same proportion.

If three successive moisture profiles from three well spaced times during the drying period are viewed (fig. 8-29C) it is obvious that the slope of the moisture profile at the surface decreases with time, and thus the drying rate decreases in the same proportion. In figure 8-29C, all three profiles are drawn to e.m.c. at the surface in order to avoid misinterpretation, but in reality, the steeper profiles would end at somewhat higher surface moisture contents since actual surface e.m.c. cannot be achieved until drying ceases.

Consider now the case of the totally impermeable wood from figure 8-29B. Since there is no mass flow of free water without permeable pits, the free water can be brought to the surface only by diffusion below fiber saturation. Thus the **wet line**, or fiber saturation line, will recede slowly from the surface as moisture is diffused through the drying outer layers of wood. Moisture profiles at successive periods of time are illustrated in figure 8-29C. After the same amount of moisture has been lost, the slope of the moisture content profile at the wood surface will be appreciably less for highly impermeable wood than for moderately permeable wood (fig. 8-29D). Thus the moderately permeable wood (dashed line) will be drying faster. In fact, the ratio of their drying rates equals the ratio of the slopes of their moisture profiles at the wood surface. It is obvious that permeability is a very important factor in the drying of wood from the green condition.

We have classified woods as permeable and impermeable and described the shape of moisture profiles to be expected when considerable free water exists in the wood and air bubbles are present. The stipulation that air bubbles are present is important, for if air bubbles are absent (the lumens are totally filled with water), then the above described moisture profiles are reversed. In this case, the permeable wood displays impermeable type profiles while the impermeable wood may display permeable type profiles. This results because lack of either continuous passageways or bubble pressure can prevent free water flow. In permeable wood without air bubbles there would be no free flow, but the water would be evaporated as soon as the relative humidity in an adjacent lumen dropped below 100 percent. As we have already seen, this is exactly the same pattern that occurs in the impermeable wood with air bubbles and the drying rate would be similarly retarded.

The most severe difficulties in drying are encountered in the case of highly impermeable cells completely filled with water, without air bubbles. In this case, the free water does not evaporate through the cell wall as soon the humidity drops below 100 percent on the opposite side of the wall. Instead, the water is subjected to the stress of the capillary tension exerted by the menisci in the impervious pit membranes and in the cell wall on its outer face. If the pits are sufficiently im-

pervious, tensile stresses severe enough to collapse the cell may occur unless a meniscus is pulled through a pit pore or the lumen water simply ruptures under the stress, thus forming a bubble. With a wood such as oak, these water-filled lumens may still persist when the average moisture content of the wood is as low as 20 percent, or even lower. Thus, in a sense, we have free water in wood that is below fiber saturation; the moisture profiles have been found to be relatively parabolic. Free water trapped in the water-filled, bubble-free lumens does not contribute to the actual hygroscopic gradient which motivates diffusion. For example, in figure 8-28D, consider the totally impermeable profile with essentially the same bound water profile as shown but rearrange the free water so as to give the same parabolic profile as that shown by the permeable wood. The drying rate of this impermeable wood would be slower than that of a permeable wood with a similar parabolic profile (Tiemann 1951; Hart 1970; Hart and Darwin 1971). For the sake of simplicity, subsequent discussion is limited to those profiles that result when air bubbles are present; it should be remembered that absence of bubbles will result in slower drying.

Diffusion.—The term **diffusion** is restricted to the movement of moisture below fiber saturation since any movement above fiber saturation must be a mass flow phenomenon resulting from a total pressure gradient. Diffusion-controlled profiles below fiber saturation are generally almost parabolic in shape. This results from the fact that the quantity of moisture movement occurring at any point is approximately proportional to the slope of the moisture distribution curve at that point, and the quantity of moisture movement increases gradually from zero, across the center line of the board, to a maximum value across the board surfaces.

Mass flow of water vapor below fiber saturation may occur when permeable wood is heated above the boiling point of water—but in conventional drying in the range below fiber saturation there is no total pressure gradient, so the movement is one of diffusion rather than mass flow. In the cell walls this movement occurs as bound water diffusion, and the motivating force is the hygroscopic gradient that results from a difference in moisture content. In the voids, movement also occurs as water vapor diffusion, and the driving force is a vapor pressure gradient (but *not* a total pressure gradient). Vapor diffusion in the voids is believed to occur from 100 to 1,000 times more easily than bound water diffusion in the cell walls. One might conclude from this that continuous vapor diffusion through the lumen and interconnecting pits should be of considerable importance, but such is not the case. While the minute passageways through the pit membranes may transport liquid water in mass flow quite efficiently, they are much too small and scarce to provide for appreciable vapor diffusion. Bound water diffusion across the cell wall, followed by vapor diffusion across the lumen to the next cell wall, is the pathway of major importance.

Since the ease of diffusion across the lumen is very much greater than across the cell wall, the expression for overall ease with which diffusion occurs, termed the **diffusion coefficient**, is closely dependent upon the amount of cell wall material that must be penetrated. Thus the ease of diffusion varies inversely with the density of the wood. Since continuous vapor diffusion plays only a minor role, permeability is a minor factor in diffusion. Thus the impermeable heartwood of a given species will dry from fiber saturation to e.m.c. in virtually the same time as the highly permeable sapwood, providing they are of the same density.

Drying temperature also greatly affects the rate of diffusion. The diffusion coefficient, or ease of diffusion, has been found to increase with temperature in the same proportion as the vapor pressure of water increases. Water vapor pressure increases from 1 p.s.i. to 14.7 p.s.i. as the temperature is increased from 100° to 212° F., so the rate of diffusion should be 14.7 times as fast at the higher temperature. Since the density of water vapor (absolute humidity at saturation—see sec. 8-3) increases almost as rapidly with temperature as does the vapor pressure, then the absolute humidity ratio may be used to estimate the temperature effect if vapor pressure tables are not handily available. Using absolute humidity for the estimate, the rate of diffusion at 212° F. is $261.1 \div 20$, or 13.1 times as fast as at 100° F., which is sufficiently close to the 14.7 estimate obtained from the vapor pressure ratio.

APPLICATION

Moisture content is the ratio of weight of water to weight of dry wood. Thus, for a given change in moisture content, a greater weight of water must be removed from the drying surfaces of thicker boards and also from denser boards since the weight of dry wood (i.e., dry cell wall) in a board of given length and width is directly proportional to both its thickness and its density. If the rate at which moisture can be removed from the wood surface is the controlling or limiting factor, as it may be early in the drying, especially with low air velocities across wide stacks of lumber, then the time required for a given reduction in moisture content is directly proportional to board density and to board thickness. This results from the fact that the weight of water evaporated from the board surfaces in a given time is independent of both board thickness and board density, but the weight of water represented by a given change in moisture content is directly proportional to both density and thickness. Thus, a greater weight loss of water, and therefore a longer drying time, is required to obtain a given reduction in moisture content with thicker or denser boards.

If the rate of moisture diffusion from the interior to the surfaces of the board is the controlling or limiting factor, then the time required for a given reduction in moisture content is directly proportional to the square

of board density and also to the square of board thickness. This results from the fact that the ease of moisture diffusion is inversely proportional to the amount of cell wall that must be traversed, and the amount of cell wall is directly proportional to both the board density and the board thickness. But as already pointed out, the amount of water, by weight, that must be removed for a given reduction in moisture content is also directly proportional to the amount of cell wall. Thus if density or thickness increases, it is both more difficult for a given quantity or weight of water to reach the board surface and also a greater weight of water must be removed for a given reduction in moisture content.

In summary, the following are simplified "rules of thumb" believed to be relatively accurate for the stated conditions:

1. If removal of moisture from the wood surface is the limiting factor, drying time is directly proportional to board thickness, and density; it is inversely proportional to wet-bulb depression and approximately inversely proportional to air velocity over the surface.
2. If moisture diffusion is the limiting factor, drying time is directly proportional to board thickness squared and to board density squared; it is inversely proportional to the water vapor pressure at saturation.

If rule 2 (diffusion) governs, the ease of diffusion (diffusion coefficient) is highly temperature-dependent, so that much faster drying rates can be achieved with increased dry-bulb temperature (approximately in the same proportion as the increase in saturated water vapor pressure). A large wet-bulb depression causes a low e.m.c. at the wood surface and results in faster drying only to the extent that the steepness of the moisture profile at the wood surface is increased.

Permeable species, such as the southern pines, follow rule 1 early in the drying period and then rule 2 as diffusion from the interior becomes the controlling factor. Considering the influence of both drying phases, a general "rule of thumb" states that total drying time is directly proportional to board thickness to the 1.5 power and to board density to the 1.5 power.

The foregoing rules do not consider variation in initial moisture content. Where removal of moisture from the surface is the limiting factor (rule 1), initial moisture content does not affect the time required for a given amount of moisture content reduction, but simply determines the total amount to be removed. However, if moisture diffusion is the limiting factor (rule 2), a closer examination is required. For the moderately permeable wood in which a parabolic moisture profile develops, it can be seen from figure 8-30 that a greater initial moisture content results in steeper moisture profiles at the wood surface and therefore proportionately faster drying rates. Under these conditions, a board of high moisture content will dry almost as quickly as one of low moisture content.

But such is not the case with highly impermeable wood. Greater initial moisture contents do not result in steeper moisture profiles at the wood surface (fig. 8-30). Thus the board that has twice as much moisture above

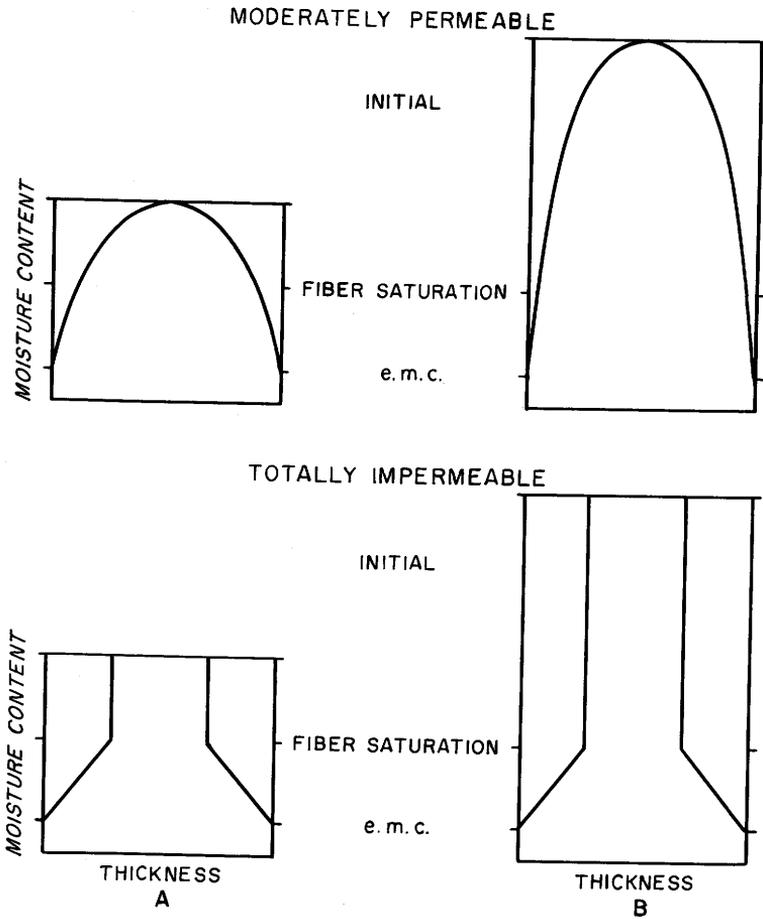


Figure 8-30.—Moisture profiles during drying. (A) Boards of low initial moisture content. (B) Boards of high initial moisture content. (Drawings after Hart 1965.)

fiber saturation will require twice as much time for this free water to be removed. But once the center reaches fiber saturation, both boards require the same additional time to dry.

The net result is that the total time required to dry lumber increases with increasing initial moisture content both for highly permeable woods, if rate of removal of moisture from the surface is the limiting factor, and also for highly impermeable woods in which diffusion controls but no mass movement of free water occurs. But for moderately permeable woods that exhibit a parabolic moisture profile throughout the drying period, the total time requirement may be independent of the initial moisture content.

While removal of moisture from the surface can theoretically be the totally controlling factor during the early stages of drying, and while diffusion from the interior to the surface may be almost completely controlling during the last stages of drying, there is generally a substantial

period in which both are of importance. The drying of wood is a dynamic balance between heat transfer from the airstream to the wood, surface evaporation from the wood, diffusion of moisture through the wood and mass flow of free water in the wood.

MECHANISM OF HIGH-TEMPERATURE DRYING

When wood is dried at a dry-bulb temperature exceeding the boiling point of water, the wet-bulb temperature will be less than the boiling-point temperature if a steam-air (i.e., vapor-air) mixture is used; it will reach its maximum value, the boiling-point temperature, if a pure steam atmosphere is employed. Whether a steam-air mixture or pure superheated steam is used, pressure is built up in the wood when the free water above fiber saturation is heated above the boiling point. The slight steam pressure thus created results in hydrodynamic flow of water vapor from the wet line to the wood surface. This, then, is the fundamental difference between low- and high-temperature drying. In low-temperature drying, the moisture movement from the wet line to the wood surface is a moisture diffusion phenomenon; in high-temperature drying it is a pressure flow or mass flow phenomenon. Pit pores, which are very ineffective for vapor diffusion, become quite adequate as passageways for pressure flow of vapor.

During the early part of drying, when the wet line remains at the surface, the rate of heat transfer to the surface alone is the controlling factor in both high- and low-temperature drying. The rules for this phase of low-temperature drying apply also to this period of high-temperature drying. When interior pressures build up, since the pit pores of permeable woods (such as southern pine) can accommodate the vapor flow (figs. 5-25, 5-26), the factor which limits the drying rate is the rate of heat transfer from the drying atmosphere to the wood surface and its diffusion into the wood to the fiber saturation or wet line. Thus, once the wet line starts to recede from the surface, heat diffusion from the surface to the wet line (to build pressure and cause mass flow) becomes more and more the controlling factor in high-temperature drying; by contrast, in low-temperature drying, moisture diffusion (at atmospheric pressure) becomes the controlling factor. In either case, of course, heat must still be transferred from the drying atmosphere to the wood surface, so this surface transfer remains a partially controlling factor.

Heat diffusion and moisture diffusion through the wood differ in one very important respect. As already pointed out, the ease of moisture diffusion is *inversely* proportional to density. But ease of heat diffusion is almost *directly* proportional to density, because heat moves much more easily across cell walls than across cell cavities. This counteracts the fact that for greater density, a greater weight of water must be removed for a given moisture content reduction; therefore, where heat diffusion into the wood is the limiting factor, the time required for a given reduction in moisture content is almost independent of wood density.

The effect of board thickness (see rule 2 from low-temperature drying when moisture diffusion is the limiting factor) remains the same in high-temperature drying since a greater distance must still be traversed as well as more water removed for a given reduction in moisture content. But the rule regarding the effect of temperature differs with high-temperature drying. In this case, the rate of heat diffusion is directly proportional to the temperature gradient between the wood surface and the wet line; this gradient is the difference between the dry-bulb temperature and the boiling-point temperature (about 212° F., because the system is vented to the atmosphere). Thus, the time required for a given moisture content reduction is proportional to the difference between the dry-bulb and the boiling-point temperatures until the free water is exhausted. The drying behavior after the free water is exhausted would be expected to deviate somewhat from this rule, depending upon the moisture content gradient associated with the particular temperature gradient in the wood, but the rule will suffice as an approximation.

In summary, the following are simplified "rules of thumb" believed to be accurate for the stated conditions in high-temperature drying:

1. The same as rule 1 for low-temperature drying, i.e., if removal of moisture from the wood surface is the limiting factor, drying time is proportional to board thickness and density; it is inversely proportional to wet-bulb depression and approximately inversely proportional to air velocity over the surface.
2. If heat diffusion from wood surface to the wet line is the limiting factor, drying time is directly proportional to board thickness squared but is independent of board density; drying time is inversely proportional to the difference between the dry-bulb and boiling-point temperatures.

These rules, particularly the last one, may be understood more fully by considering the temperature and moisture profiles that develop in high-temperature drying (fig. 8-31). In making this figure, it has been assumed that substantial free water flow under bubble pressure occurred during the early stages of drying, just as in low-temperature drying, but that the fiber saturation or wet line has now receded about halfway to the center and little mass flow of free or liquid water is now occurring. Evaporation is taking place at the wet line, which remains at the boiling-point temperature, and the water vapor is moving by mass flow, under a slight pressure gradient, from the wet line to the surface, which approaches the dry-bulb temperature and also the e.m.c. If this flow occurs quite readily and the rate of heat diffusion from the surface to the wet line is clearly the limiting factor, then the moisture content profile between the wet line and the surface is determined by the temperature profile in the wood. The e.m.c. of wood in superheated steam at atmospheric pressure is approximately as shown in figure 8-12. Thus for a given temperature profile from the surface to the wet line, the moisture content profile can be determined

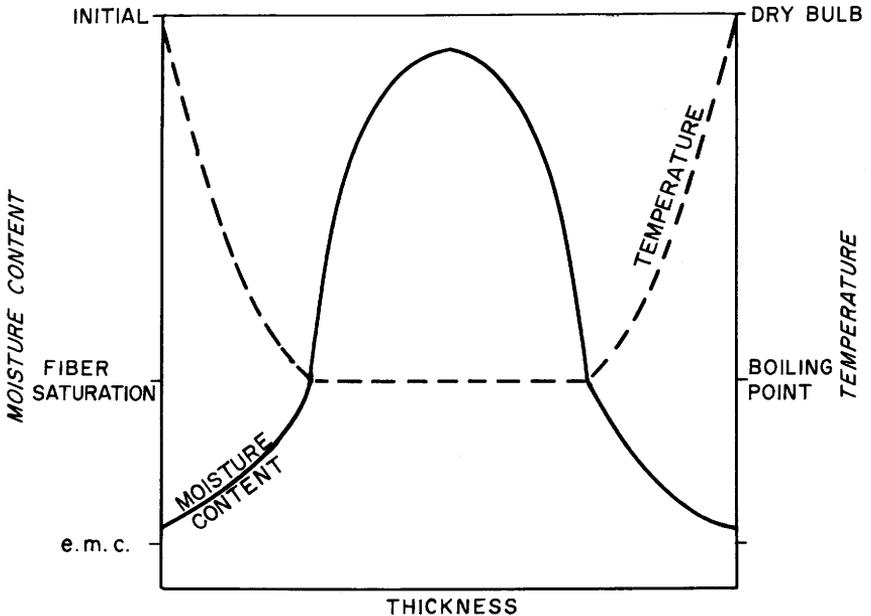


Figure 8-31.—Moisture and temperature profiles during high-temperature drying. (Drawing after Hart 1965.)

using the e.m.c. versus temperature relationship. This explains the reversed curve of the moisture profile between the surface and the wet line formed in high-temperature drying as compared to the moisture profile observed in low-temperature drying. Because of the shape of the moisture profile, the wood will be sufficiently dry for many purposes by the time the center reaches fiber saturation.

The effect of initial moisture content on the total required drying time may well be complex, just as in low-temperature drying. The transition period between period 1, when transfer of heat to the surface is controlling, and period 2, when the diffusion of heat through the wood is controlling, may occupy a substantial portion of the total drying time. Furthermore, the transition from low- to high-temperature drying behavior is not abrupt at a specific dry-bulb temperature but, rather, occurs gradually.

8-8 LITERATURE CITED

- American Society for Testing and Materials.
1968. Book of ASTM standards Part XVI. Structural sandwich construction; wood; adhesives. 930 pp. Philadelphia: Amer. Soc. for Testing and Mater.
- Anderson, A. B.
1961. The influence of extractives on tree properties. I. California redwood (*Sequoia sempervirens*). J. Inst. Wood Sci. 8: 14-34.

- Bailey, I. W.
1913. The preservative treatment of wood. I. The validity of certain theories concerning the penetration of gases and preservatives into seasoned wood. II. The structure of the pit membranes in the tracheids of conifers and their relation to the penetration of gases, liquids, and finely divided solids into green and seasoned wood. *Forest. Quart.* 11: 5-20.
- Bailey, P. J., and Preston, R. D.
1969. Some aspects of softwood permeability. I. Structural studies with Douglas fir sapwood and heartwood. *Holzforschung* 23: 113-120.
- Banks, W. B.
1970. The effect of temperature and storage conditions on the phenomenon of increased sapwood permeability brought about by wet storage. *J. Inst. Wood Sci.* 5(2): 16-19.
- Barber, N. F., and Meylan, B. A.
1964. The anisotropic shrinkage of wood. A theoretical model. *Holzforschung* 18: 146-156.
- Bauch, J.
1964. Die axiale durchlässigkeit von Kiefern-Splintholz für Wasserige Lösungen. I. Mitteilung, Anelektrolyte. *Planta* 61: 196-208.
- Bauch, J., and Liese, W.
1966. [Longitudinal permeability of green sapwood of silver fir and Norway spruce to organic solvents.] *Holzforschung* 20: 169-174.
- Benvenuti, R. R.
1963. An investigation of methods of increasing the permeability of loblolly pine. M.S. Thesis. N.C. State Coll., Raleigh. 115 pp.
- Bello, E. D.
1968. Effect of transverse compressive stress on equilibrium moisture content of wood. *Forest Prod. J.* 18(2): 69-76.
- Bersenev, A. P., Vasil'ev, B. V., and Onucin, V. J.
1963. [Determination of wood moisture content by the method of nuclear magnetic resonance.] *Les. Zh.* 6(1): 127-130.
- Beutler, A. J.
1965. An infrared backscatter moisture gage. *TAPPI* 48: 490-493.
- Blew, J. O., Jr.
1952. Treatability of southern yellow pine as influenced by fungus infection. *J. Forest Prod. Res. Soc.* 2(3): 85-86.
- Blew, J. O., Jr.
1955. Study of the preservative treatment of lumber. USDA Forest Serv. Forest Prod. Lab. Rep. 2043, 39 pp.
- Boutelje, J.
1962. The relationship of structure to transverse anisotropy in wood with reference to shrinkage and elasticity. *Holzforschung* 16: 33-46.
- Browning, B. L.
1967. *Methods of wood chemistry*. Vol. 1, 384 pp. N.Y.: Interscience Pub.
- Buckman, S. J.
1936. Creosote distribution in treated wood. Distribution of creosote in the sapwood of freshly creosoted southern yellow pine poles with special references to the bleeding of treated poles. *Ind. and Eng. Chem.* 28: 474-480.
- Buckman, S. J., Schmitz, H., and Gortner, R. A.
1935. A study of certain factors influencing the movement of liquids in wood. *J. Phys. Chem.* 39: 103-120.
- Buro, A., and Buro, E.-A.
1959. [The routes by which liquids penetrate into wood of *Pinus sylvestris*.] *Holz-forschung* 13: 71-77.
- Busker, L. H.
1968. Measurement of water content above 30% by microwave absorption methods. *TAPPI* 51: 348-353.
- Campbell, W. B.
1933. The cellulose-water relationship in papermaking. *Can. Dep. Interior Forest. Serv. Bull.* 84, 52 pp.
- Chen, P. Y. S.
1968. The effects of cations on the permeability of wood to aqueous solutions. Ph.D. Thesis. Univ. Minnesota. 60 pp.

- Choong, E. T.
1969a. Effect of extractives on shrinkage and other hygroscopic properties of ten southern pine woods. *Wood and Fiber* 1: 124-133.
- Choong, E. T.
1969b. Moisture and the wood of the southern pines. *Forest Prod. J.* 19(2): 30-36.
- Choong, E. T., and Barnes, H. M.
1968. Swelling behavior in corewood and maturewood of southern pine. *La. State Univ. LSU Wood Util. Notes* 11, 5 pp.
- Choong, E. T., and Fogg, P. J.
1968. Moisture movement in six wood species. *Forest Prod. J.* 18(5): 66-70.
- Choong, E. T., and Fogg, P. J.
1970. Variation of moisture content in standing trees of southern pine species in southeast Louisiana. *LSU Forestry Notes* 93, 4 pp.
- Choong, E. T., Box, B. H., and Fogg, P. J.
1970. Effects of intensive cultural management on growth and certain wood properties of young loblolly pine. *Wood and Fiber* 2: 105-112.
- Choong, E. T., and Kimbler, O. K.
1971. A technique of measuring water flow in woods of low permeability. *Wood Sci.* 4: 32-36.
- Cockrell, R. A.
1943. Some observations on density and shrinkage of ponderosa pine wood. *Amer. Soc. Mech. Eng. Trans.* 65: 729-739.
- Cole, D. E., Zobel, B. J., and Roberds, J. H.
1966. Slash, loblolly, and longleaf pine in a mixed natural stand; a comparison of their wood properties, pulp yields, and paper properties. *TAPPI* 49: 161-166.
- Comstock, G. L.
1965. Longitudinal permeability of green eastern hemlock. *Forest Prod. J.* 15: 441-449.
- Comstock, G. L.
1968. Relationship between permeability of green and dry eastern hemlock. *Forest Prod. J.* 18(8): 20-23.
- Comstock, G. L.
1970. Directional permeability of softwoods. *Wood & Fiber* 1: 283-289.
- Comstock, G. L., and Côté, W. A.
1968. Factors affecting permeability and pit aspiration in coniferous sapwood. *Wood Sci. and Technol.* 2: 279-291.
- Côté, W. A., Jr.
1963. Structural factors affecting permeability of wood. *J. Polymer Sci. (Part C, Polymer Symp.)* 2: 231-242.
- Côté, W. A., Jr.
1967. Wood ultrastructure—an atlas of electron micrographs. 57 pp. Seattle: Univ. Wash. Press.
- Dadswell, H. E., and Nicholls, J. W. P.
1959. Assessment of wood qualities for tree breeding. I. CSIRO Div. Forest Prod. Tech. Pap. 4, 16 pp.
- Duff, J. E.
1966. A probe for accurate determination of moisture content of wood products in use. USDA Forest Serv. Res. Note FPL-0142, 10 pp. Forest Prod. Lab., Madison, Wis.
- Erickson, H. D.
1938. The flow of liquid through radial resin canals. *J. Forest.* 36: 417-423.
- Erickson, H. D.
1960. The effects of storage conditions and time upon permeability of green sapwood. *Amer. Wood Preserv. Assoc. Proc.* 56: 156-165.
- Erickson, H. D.
1970. Permeability of southern pine wood—a review. *Wood Sci.* 2: 149-158.
- Erickson, H. D., and Balatinecz, J. J.
1964. Liquid flow paths into wood using polymerization techniques—Douglas-fir and styrene. *Forest Prod. J.* 14: 293-299.
- Erickson, H. D., and Crawford, R. J.
1959. The effects of several seasoning methods on the permeability of wood to liquids. *Amer. Wood Preserv. Assoc. Proc.* 55: 210-220.
- Erickson, H. D., Schmitz, H., and Gortner, R. A.
1937. The permeability of woods to liquids and factors affecting the rate of flow. *Minn. Agr. Exp. Sta. Tech. Bull.* 122, 42 pp.

- Erickson, H. D., Schmitz, H., and Gortner, R. A.
1938. Directional permeability of seasoned woods to water and some factors which affect it. *J. Agr. Res.* 56: 711-746.
- Feist, W. C., and Tarkow, H.
1967. Polymer exclusion in wood substance: A new procedure for measuring fiber saturation points. *Forest Prod. J.* 17(10): 65-68.
- Fogg, P. J.
1969. Longitudinal air permeability for four species of southern pine wood. *Wood Sci.* 2: 35-43.
- Gibson, E. J., and Rusten, D.
1964. Determination of the moisture content of pulp chips by an instrument method. *Norsk Skogindustri* 18: 351-356.
- Griffin, G. J.
1919. Bordered pits in Douglas fir: A study of the position of the torus in mountain and lowland specimens in relation to creosote penetration. *J. Forest.* 17: 813-822.
- Hann, R. A., Oviatt, A. E., Markstrom, D. M., and Duff, J. E.
1970. Moisture content of laminated timbers. USDA Forest Serv. Res. Pap. FPL 149, 6 pp. Forest Prod. Lab., Madison, Wis.
- Harris, J. M., and Meylan, B. A.
1965. The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. *Holzfor-schung* 19: 144-153.
- Hart, C. A.
1965. The drying of wood. N.C. State Univ. Sch. Forest. Tech. Rep. 27, 24 pp.
- Hart, C. A.
1970. Water-filled lumens in steady-state flow in oak and poplar. *Wood & Fiber* 1: 308-318.
- Hart, C. A., and Darwin, W. M., Jr.
1971. The slow drying rate of white oak. *Wood Sci.* 4: 46-54.
- Hart, C. A., and Thomas, R. J.
1967. Mechanism of bordered pit aspiration as caused by capillarity. *Forest Prod. J.* 17(11): 61-68.
- Hartmann-Dick, U.
1955. Untersuchungen über die Durchlässigkeit des Holzes bei Druckfiltration. II. Durchlässigkeit für Lösungen verschiedener Art. *Forstwissenschaftliches Cent.* 74(5/6): 163-183.
- Hedlin, C. P.
1967. Sorption isotherms of twelve woods at subfreezing temperatures. *Forest Prod. J.* 17(12): 43-48.
- Heebink, B. G.
1966. Some thoughts on the term "EMC." *Soc. Wood Sci. and Technol. Log.* November, pp. 1-3.
- Higgins, N. C.
1957. The equilibrium moisture content—relative humidity relationship of selected native and foreign woods. *Forest Prod. J.* 7: 371-377.
- Hill, J. L., and Munkittrick, R. H.
1970. Performance of remote moisture sensing devices. *Forest Prod. J.* 20(8): 39-46.
- Hiller, C. H.
1954. Variation in fibril angles in slash pine. USDA Forest Serv. Forest Prod. Lab. Rep. 2003, 6 pp.
- Hopkins, W. C.
1960. Moisture content of building structural members. *Forest Prod. J.* 10: 506-508.
- Huber, B., and Merz, W.
1958. Über die Bedeutung des Hoftüpfelverschlusses für die axiale Wasserleitfähigkeit von Nadelhölzern. I. Mitteilung. Grunderscheinungen. II. Mitteilung. Vergleichende Untersuchungen und praktische Anwendungen. *Planta* 51: 645-659; 660-672.
- Hudson, M. S.
1968. New process for longitudinal treatment of wood. *Forest Prod. J.* 18(3): 31-35.
- Hudson, M. S.
1969. Chemical drying of southern pine wood . . . a review. *Forest Prod. J.* 19(3): 21-24.
- Hudson, M. S., and Shelton, S. V.
1969. Longitudinal flow of liquids in southern pine poles. *Forest Prod. J.* 19(5): 25-32.

- James, W. L.
1963. Electric moisture meters for wood. USDA Forest Serv. Res. Note FPL-08, 24 pp. Forest Prod. Lab., Madison, Wis.
- James, W. L.
1965. Effects of wood preservatives on electrical moisture-meter readings. USDA Forest Serv. Res. Note FPL-0106, 12 pp. Forst Prod. Lab., Madison, Wis.
- James, W. L.
1968. Effect of temperature on readings of electric moisture meters. Forest Prod. J. 18(10): 23-31.
- Kajanne, P., and Hollming, A.
1958. On moisutre determination in wood chips using gamma ray scattering. Paperi ja Puu 40(4a): 153-157.
- Kauman, W. G.
1956. Equilibrium moisture content relations and drying control in superheated steam drying. Forest Prod. J. 6: 328-332.
- Kellogg, R. M., and Wangaard, F. F.
1969. Variation in the cell-wall density of wood. Wood and Fiber 1: 180-204.
- Kelsey, K. E.
1963. A critical review of the relationship between the shrinkage and structure of wood. CSIRO Div. Forest Prod. Technol. Pap. 28, 35 pp. Melbourne.
- Kelso, W. C., Jr., Gertjeansen, R. O., and Hossfeld, R. L.
1963. The effect of air blockage upon the permeability of wood to liquids. Minn. Agr. Exp. Sta. Tech. Bull. 242, 40 pp.
- Koehler, A.
1931. Longitudinal shrinkage of wood. Amer. Soc. Mech. Eng. Trans. 53(5): 17-20.
- Koehler, A.
1938. Rapid growth hazards usefulness of southern pine. J. Forest. 36: 153-159.
- Kollmann, F. F. P., and Côté, W. A., Jr.
1968. Principles of wood science and technology. I. Solid wood. 592 pp. N.Y.: Springer-Verlag New York, Inc.
- Ladell, J. L.
1957. High-temperature kiln-drying of eastern Canadian softwoods, drying guide and tentative schedules. Forest Prod. Lab. of Can. FPL Tech. Note 2, 18 pp. Ottawa.
- Libby, T. B., and Haygreen, J. G.
1967. Moisture content change induced by tensile stress in whole wood. J. Inst. Wood Sci. 3(18): 54-60.
- Lindgren, R. M.
1949. Density and moisture relations in slash pine wood. USDA Forest Serv. South. Forest. Exp. Sta. South. Forest. Notes 63.
- Lindgren, R. M.
1952. Permeability of southern pine as affected by mold and other fungus infection. Amer. Wood Preserv. Assoc. Proc. 48: 158-168.
- Lindgren, R. M., and Scheffer, T. C.
1939. Effect of blue stain on the penetration of liquids into air-dry southern pine wood. Amer. Wood Preserv. Assoc. Proc. 35: 325-336.
- Loos, W. E.
1961. The relationship between gamma ray absorption and wood moisture content and density. Forest Prod. J. 11: 145-149.
- Loos, W. E.
1965. A review of methods for determining moisture content and density of wood by nuclear radiation techniques. Forest Prod. J. 15: 102-106.
- Loos, W. E., and Robinson, G. L.
1968. Techniques for determining moisture in wood-plastic combinations. Forest Prod. J. 18(11): 36-41.
- Lowery, D. P., and Kotok, E. S.
1967. Evaluation of a microwave wood moisture meter. Forest Prod. J. 17(10): 47-51.
- Lundstrom, J. W.
1970. On-line chip moisture measurements. TAPPI 53: 857-861.
- Lutz, J. F., Duncan, C. G., and Scheffer, T. C.
1966. Some effects of bacterial action on rotary-cut southern pine veneer. Forest Prod. J. 16(8): 23-28.

- McMillin, C. W.
1969. Performance evaluation of stained, rough-sawn southern pine siding. *Forest Prod. J.* 19(2): 51-52.
- Metz, L. J., and Wells, C. G.
1965. Weight and nutrient content of the aboveground parts of some loblolly pines. USDA Forest Serv. Res. Pap. SE-17, 20 pp. Southeast, Forest Exp. Sta., Asheville, N.C.
- Meyer, R. W.
1971. Influence of pit aspiration on earlywood permeability of Douglas-fir. *Wood & Fiber* 2: 328-339.
- Meylan, B. A.
1968. Cause of high longitudinal shrinkage in wood. *Forest Prod. J.* 18(4): 75-78.
- Miller, S. R., Jr.
1959. Variation in inherent wood characteristics in slash pine. Fifth South. Conf. on Forest Tree Impr. Proc. 1959: 97-106.
- Nearn, W. T.
1955. Effect of water soluble extractives on the volumetric shrinkage and equilibrium moisture content of eleven tropical and domestic woods. Penn. Agr. Exp. Sta. Bull. 598, 38 pp.
- Nicholas, D. D.
1966. Structure and chemical composition of the pit membrane in relation to the permeability of loblolly pine (*Pinus taeda* L.). PhD. Thesis. N.C. State Univ., Raleigh. 115 pp.
- Nicholas, D. D., and Thomas, R. J.
1968a. Influence of steaming on ultrastructure of bordered pit membrane in loblolly pine. *Forest Prod. J.* 18(1): 57-59.
- Nicholas, D. D., and Thomas, R. J.
1968b. The influence of enzymes on the structure and permeability of loblolly pine. *Amer. Wood Preserv. Assoc. Proc.* 64: 70-76.
- Pearson, R. G., and Gilmore, R. C.
1971. Characterization of the strength of juvenile wood of loblolly pine (*Pinus taeda* L.). *Forest Prod. J.* 21(1): 23-31.
- Panshin, A. J., DeZeeuw, C., and Brown, H. P.
1964. Textbook of wood technology. 643 pp. N.Y.: McGraw Hill Book Co., Inc.
- Peck, E. C.
1928. Shrinkage of boards of Douglas fir, western yellow pine and southern pines. *Amer. Lumberman* 2774: 52-54.
- Peck, E. C.
1947. Shrinkage of wood. USDA Forest Serv. Forest Prod. Lab. Rep. R1650, 6 pp.
- Peck, E. C.
1953. The sap or moisture in wood. USDA Forest Serv. Forest Prod. Lab. Rep. D768 rev., 10 pp.
- Peck, E. C.
1960. Method of calculating shrinkage or swelling of wood with change in moisture content. USDA Forest Serv. Forest Prod. Lab. Rep. 1769-27, 9 pp.
- Phillips, E. W. J.
1933. Movement of the pit membrane in coniferous woods, with special reference to preservative treatment. *Forestry* 7: 109-120.
- Pillow, M. Y., and Luxford, R. F.
1937. Structure, occurrence, properties of compression wood. USDA Tech. Bull. 546, 32 pp.
- Pillow, M. Y., Terrell, B. Z., and Hiller, C. H.
1953. Patterns of variation in fibril angles in loblolly pine. USDA Forest Serv. Forest Prod. Lab. Rep. D1935, 31 pp.
- Quijada, M. R.
1967. Variation and relationships of wood characteristics of longleaf pine in North Carolina. M.S. Thesis. N.C. State Univ., Raleigh. 91 pp.
- Scheffer, T. C., and Clark, J. W.
1967. On-site preservative treatments for exterior wood of buildings. *Forest Prod. J.* 17(12): 21-29.
- Schmidt, R. N.
1967. Some wood-moisture relations at -20° C. M.F. Thesis. Univ. Washington, Seattle. 81 pp.
- Schroeder, J. G., and Phillips, D. R.
1972. Seasonal moisture content of loblolly and slash pine. *Forest Prod. J.* 22(4): 54-56.

- Seborg, C. O.
1937. Hysteresis in water sorption by papermaking materials. *Ind. Eng. Chem.* 29: 169-172.
- Seborg, C. O., Simmonds, F. A., and Baird, P. K.
1938. Sorption of water vapor by papermaking materials. Irreversible loss of hygroscopicity due to drying. *Pap. Trade J.* 107(19): 45-50.
- Simpson, W. T., and Skaar, C.
1968a. Effect of restrained swelling on wood moisture content. USDA Forest Serv. Res. Note FPL-0196, 4 pp. Forest Prod. Lab., Madison, Wis.
- Simpson, W. T., and Skaar, C.
1968b. Effect of transverse compressive stress on loss of wood moisture. USDA Forest Serv. Res. Note FPL-0197, 3 pp. Forest Prod. Lab., Madison, Wis.
- Smith, D., and Lee, E.
1958. The longitudinal permeability of some hardwoods and softwoods. *Dep. Sci. and Ind. Res. Forest Prod. Res. Spec. Rep.* 13, 13 pp. London.
- Spalt, H. A.
1958. The fundamentals of water vapor sorption by wood. *Forest Prod. J.* 8: 288-295.
- Stamm, A. J.
1931. Three methods of studying capillary structure as applied to wood. *J. Appl. Phys.* 1: 116-128.
- Stamm, A. J.
1935. Shrinkage and swelling of wood. *Ind. Eng. Chem.* 27: 401-406.
- Stamm, A. J.
1956. Thermal degradation of wood and cellulose. *Ind. Eng. Chem.* 48: 413-417.
- Stamm, A. J.
1964. Wood and cellulose science. 549 pp. N.Y.: Ronald Press Co.
- Stamm, A. J., Burr, H. K., and Kline, A. A.
1946. Staybwood—heat-stabilized wood. *Ind. Eng. Chem.* 38: 630-634.
- Stamm, A. J., Clary, S. W., and Elliott, W. J.
1968. Effective radii of lumen and pit pores in softwood. *Wood Sci.* 1: 93-101.
- Stamm, A. J.
1971. Review of nine methods for determining the fiber saturation points of wood and wood products. *Wood Sci.* 4: 114-128.
- Stasse, H. L.
1964. A study of creosote treatment of seasoned and green southern pine poles. IX. Effect of variables on vapor loss and movement of oil. *Amer. Wood Preserv. Assoc. Proc.* 60: 109-128.
- Stasse, H. L.
1966. A study of creosote treatment of seasoned and green southern pine poles. X. Composition and retention of creosote residual at the groundline after exposure for ten years. *Amer. Wood Preserv. Assoc. Proc.* 62: 265-285.
- Sucoff, E. I., Chen, P. Y. S., and Hossfeld, R. L.
1965. Permeability of unseasoned xylem of northern cedar. *Forest Prod. J.* 15: 321-324.
- Swanson, T., Stejskal, E. O., and Tarkow, H.
1962. Nuclear magnetic resonance studies on several cellulose-water systems. *TAPPI* 45: 929-932.
- Taras, M. A.
1967. Moisture content variation in finished and partially finished wood in homes in the Southeast. *Forest Prod. J.* 17(8): 60-63.
- Teesdale, C. H.
1914. Relative resistance of various conifers to injection with creosote. *USDA Bull.* 101, 43 pp.
- Teesdale, L. V.
1930. The kiln drying of southern yellow pine lumber. *USDA Tech. Bull.* 165, 66 pp.
- Teesdale, C. H., and MacLean, J. D.
1918. Tests of the absorption and penetration of coal tar and creosote in longleaf pine. *USDA Bull.* 607, 43 pp.
- Tesoro, F. O., Choong, E. T., and Skaar, C.
1966. Transverse air permeability of wood as an indicator of treatability with creosote. *Forest Prod. J.* 16(3): 57-59.

- Thomas, R. J.
1967. The structure of the pit membranes in longleaf pine: an electron microscope study. *Amer. Wood Preserv. Assoc. Proc.* 63: 20-28.
- Thomas, R. J.
1969. The ultrastructure of southern pine bordered pit membranes as revealed by specialized drying techniques. *Wood and Fiber* 1: 110-123.
- Thomas, R. J., and Nicholas, D. D.
1966. Pit membrane structure in loblolly pine as influenced by solvent exchange drying. *Forest Prod. J.* 16(3): 53-56.
- Thompson, W. S.
1969. Effect of steaming and kiln drying on the properties of southern pine poles. I. Mechanical properties. *Forest Prod. J.* 19(1): 21-28.
- Tiemann, H. D.
1906. Effect of moisture upon the strength and stiffness of wood. *USDA Forest Serv. Bull.* 70, 144 pp.
- Tiemann, H. D.
1910. The physical structure of wood in relation to its penetrability by preservative fluids. *Amer. Railway Eng. and Maintenance of Way Assoc. Bull.* 120, 391 pp.
- Tiemann, H. D.
1951. *Wood technology*. Ed. 3, 396 pp. N.Y.: Pitman Publ. Corp.
- Urquhart, A. R., and Eckersall, N.
1932. The absorption of water by rayon. *Textile Insti.* 23: T163-T170.
- USDA Forest Products Laboratory.
1955. *Wood handbook*. USDA Agr. Handbook 72, 528 pp.
- USDA Forest Products Laboratory.
1957. Special methods of seasoning wood. High temperature drying: Its application to the drying of lumber. *USDA Forest Serv. Forest Prod. Lab. Rep.* 1665-1, 6 pp.
- USDA Forest Products Laboratory.
1967. FPL '67 annual report of research at the Forest Products Laboratory. USDA Forest Serv., 38 pp. Madison, Wis.
- Van Allen, R. G.
1956. A new method of applying pentachlorophenol to wood in place. *Forest Prod. J.* 6: 374-381.
- Wall, R. F.
1958. Process analysis by thermal conductivity. *Ind. Eng. Chem.* 50(12): 69A-70A.
- Wangaard, F. F.
1957. A new approach to the determination of fiber saturation point from mechanical tests. *Forest Prod. J.* 7: 410-416.
- Wangaard, F. F., and Granados, L. A.
1967. The effect of extractives on water-vapor sorption by wood. *Wood Sci. and Technol.* 1: 253-277.
- Wardrop, A. B., and Davies, G. W.
1958. Some anatomical factors relating to the penetration of water into xylem of gymnosperms. *Australian J. Bot.* 6(2): 96-102.
- Weiss, H. F.
1912. Structure of commercial woods in relation to the injection of preservatives. *Amer. Wood Preserv. Assoc. Proc.* 8: 159-187.
- Welch, M. B.
1932. The longitudinal variation of timber during seasoning. *J. and Proc. Roy. Soc. New S. Wales* 66: 492-497.
- Wooten, T. E., Barefoot, A. C., and Nicholas, D. D.
1967. The longitudinal shrinkage of compression wood. *Holzforschung* 21: 168-171.
- Yao, J.
1969. Shrinkage properties of second-growth southern yellow pine. *Wood Sci. and Technol.* 3: 25-39.
- Zobel, B., Matthias, M. Roberds, J. H., and Kellison, R. C.
1968. Moisture content of southern pine trees. *N.C. Sch. Forest. Tech. Rep.* 37, 44 pp.



9

Physical Properties

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9

Physical Properties

9-1 COLOR CHARACTERIZATION ¹

The sapwood of the southern pines is nearly white to yellowish or orange-white; heartwood is yellow to orange or reddish brown or light brown. Readers interested in identifying the source of color in wood will find the work by Pew and Connors (1971) useful; they found that phenylbenzoquinones and coniferaldehyde groupings are the major contributors to the color of natural lignin in coniferous wood. Because young southern pines have a relatively small core of heartwood, the color of sapwood predominates.

In sapwood the most striking visual feature is the contrast between the color of earlywood and latewood. The growth rings are conspicuous in rotary-cut veneer or plain-sawn lumber, and distinct in quarter-cut wood.

While visual judgement plays an important part in characterizing color, two methods that quantitatively describe color have been applied to evaluate a limited sample of rotary-cut loblolly pine sapwood.

In the first method, known as the Commission Internationale de l'Eclairage system (CIE), color is described with a set of three parameters, denoted by x , y , and z , and referred to as **chromaticity coordinates**. The first two, namely x and y , will locate the **hue** on a special color chart (fig. 9-1) well known in the field of colorimetry. The third coordinate, z , is not commonly used. The determination of these chromaticity coordinates is based on average psychophysical responses of man (Judd and Wyszecki 1963, p. 43).

To use this system, color data are expressed as **tristimulus values** that represent the amounts of the primary colors—blue, red, and green—required in combination to match the color being analyzed. The method of computation has been described by Moslemi (1967).

Tristimulus values are designated as X , Y , and Z and are related to the chromaticity coordinates defining color hue.

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad (9-1)$$

¹ Taken with some editorial change from Moslemi (1969) by permission of Ali A. Moslemi and the Forest Products Research Society.

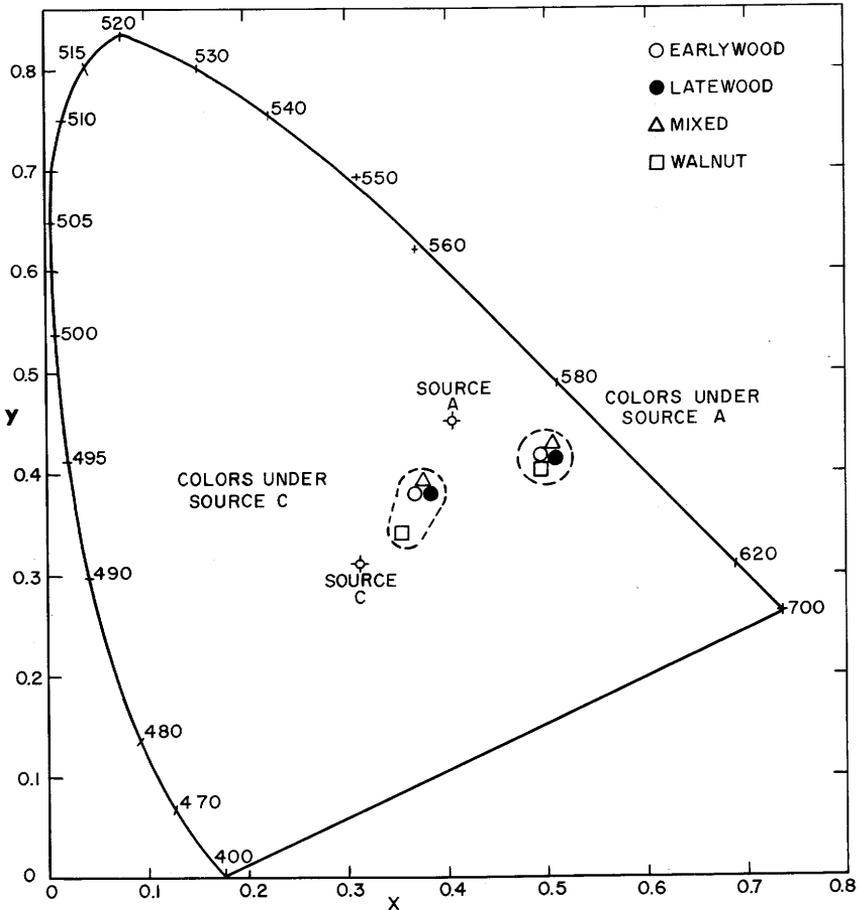


Figure 9-1.—CIE chart of the color hue of loblolly pine veneers. Numbers from 400 to 700 refer to wavelengths (in millimicrons); lines connecting them outline the approximate limits of visible light. For comparison, the color of black walnut veneer is also shown. (Drawing after Moslemi 1969.)

In the second color system, color is described in terms of R , a , and b , defined as follows (Judd and Wyszecki 1963):

$$R = Y \quad \text{indicator of luminance} \quad (9-2)$$

$$a = 1.75f_v(1.02X - Y) \quad (9-3)$$

$$b = 0.70f_v(Y - 0.847Z) \quad (9-4)$$

in which X , Y , and Z are tristimulus values in the CIE color system and f_v is given by:

$$f_v = \frac{0.51(21 + 0.2Y)}{(1 + 0.2Y)} \quad (9-5)$$

Figure 9-2 illustrates the arrangement of color in the R, a, b system. This figure shows that parameter a measures redness when positive and greenness when negative; b measures yellowness when positive and blueness when negative. R (vertical axis) indicates the luminance of the specimen surface. The luminance factor equals $\frac{Y}{100}$.

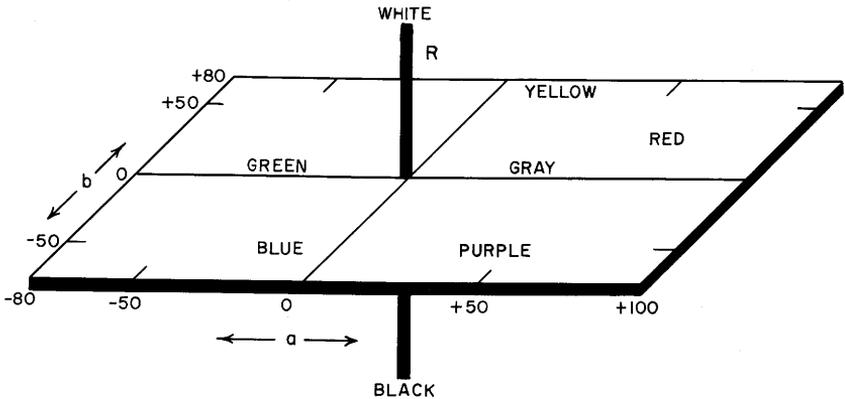


Figure 9-2.—The R, a, b color system to characterize color.

Reflectance is a measure of the degree a material reflects light. It is expressed as a percentage and, for colors other than white and black, varies with the wavelength of the impinging light. Pure white reflects 100 percent of all visible wavelengths, while black reflects 0 percent.

In Moslemi's (1969) study, dry, rotary-cut, loblolly pine veneer, which had previously been protected from extended exposure to light, was evaluated by the CIE system on a spectrophotometer (Model 14, Carey Instruments, Chicago, Ill.). The percentage reflectance of visible light, wavelengths 400–700 $m\mu$ (a millimicron is 10^{-6} mm.), was greater for earlywood than latewood. Specimens of mixed earlywood and latewood were intermediate (fig. 9-3). Direction of measurement—along or across the grain—had no effect on percentage of light reflected.

Loblolly pine wood, due to its generally light color, reflects light of all wavelengths in the visible range much better than darker woods such as black walnut (*Juglans nigra* L.). Data for walnut (Moslemi 1967)—plotted in Figure 9-3—show that with increasing wavelengths over 600 $m\mu$, reflectance of walnut increases faster than does the reflectance of loblolly pine.

The tristimulus values for loblolly pine using the standard illuminants A (artificial light simulating a well-lit living room at night) and C (daylight) show that grain direction has virtually no effect on results (table 9-1).

Chromaticity coordinates (CIE) show the difference in color hue between earlywood and latewood and confirm that grain direction has no

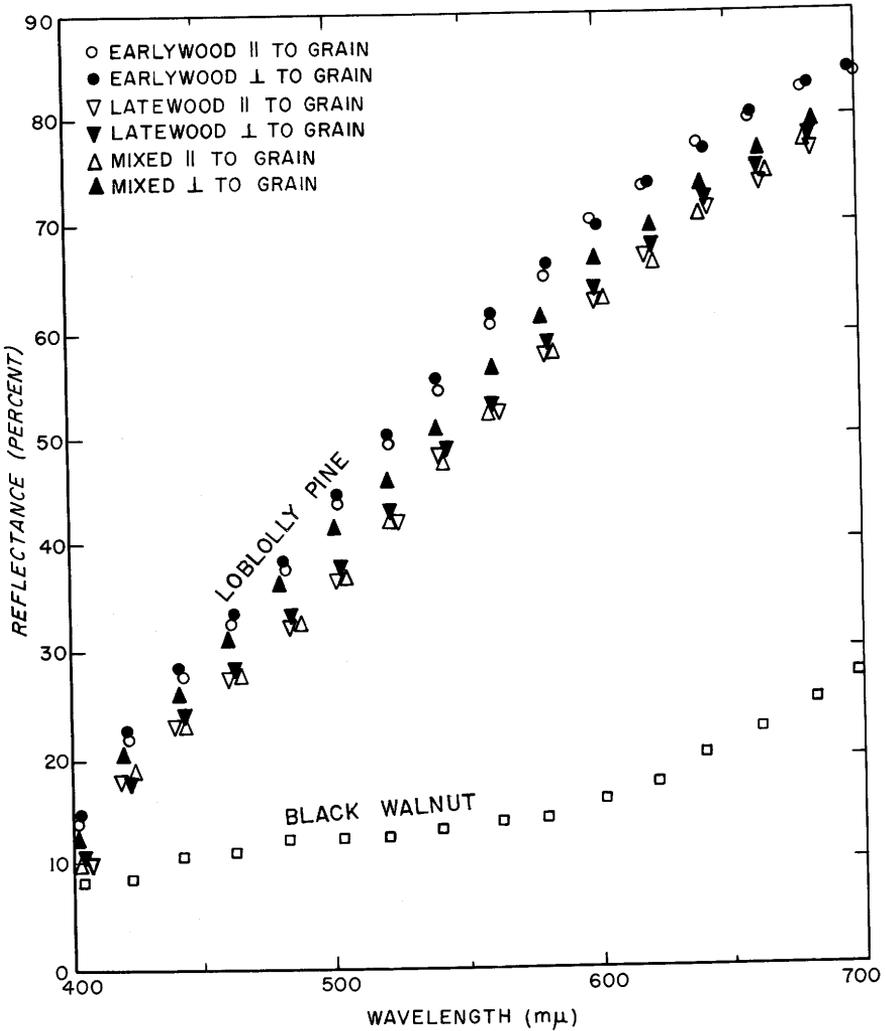


Figure 9-3.—Percentage of visible light of various wavelengths reflected by loblolly pine earlywood, latewood, and mixed wood as measured along and across the grain. The values for black wa'nut are presented for comparison. (Drawing after Moslemi 1969.)

significant effect (table 9-2). Figure 9-1 locates the color hue of loblolly pine sapwood on the CIE chromaticity coordinates. The color is different under A and C illumination sources because the lights themselves differ in color. The average color of black walnut (Moslemi 1967) is also plotted for comparison. Because figure 9-1 embraces all colors in nature, the scale in the area of interest is necessarily small.

Figure 9-4 defines the color hue of the same loblolly pine earlywood, latewood, and mixed wood veneers in the R, a, b system (parameters measured with a color and color difference meter, Gardner Instruments,

TABLE 9-1.—*Tristimulus values for sapwood veneer from loblolly pine*¹

Cell type	Grain	Source A ²			Source C ³		
		X	Y	Z	X	Y	Z
Earlywood.....	Along	74.22	62.54	11.93	59.02	58.97	37.41
	Across	75.02	63.24	12.08	59.68	59.64	37.86
Latewood.....	Along	67.73	56.03	10.13	53.26	52.34	31.68
	Across	67.21	55.70	10.29	52.40	52.10	32.29
Mixed.....	Along	67.94	56.37	10.30	53.52	52.74	32.24
	Across	70.12	58.67	11.13	55.68	55.19	35.52

¹ Rotary-cut veneer not previously exposed to light for an extended period.

² Approximates artificial light.

³ Approximates daylight.

TABLE 9-2.—*CIE chromaticity coordinates for sapwood veneer from loblolly pine*¹

Cell type	Grain	Source A ²			Source C ³		
		x	y	z	x	y	z
Earlywood.....	Along	0.499	0.421	0.077	0.380	0.380	0.240
	Across	.499	.421	.080	.380	.380	.240
Latewood.....	Along	.506	.418	.075	.388	.382	.230
	Across	.505	.418	.077	.386	.379	.235
Mixed.....	Along	.504	.419	.078	.385	.380	.235
	Across	.501	.419	.081	.381	.377	.242

¹ Rotary-cut veneer not previously exposed to light for an extended period.

² Approximates artificial light.

³ Approximates average daylight.

Bethesda, Md.). The veneer was yellow to yellow-orange prior to extended exposure to sunlight and grey-red after exposure to 100 days of summer sunlight in Illinois. Exposed specimens were protected from precipitation. The data indicated that measurements along and across the grain were not significantly different.

In colorimetric work, **color difference** between a standard and the material of interest may be expressed in terms of a single number designated ΔE . While this quantity is defined differently by different authors (Judd and Wyszecki 1963, pp. 293-296), it is here defined according to Moslemi (1967):

$$\Delta E = [(L - L_s)^2 + (a - a_s)^2 + (b - b_s)^2]^{1/2} \quad (9-6)$$

where $L = (10)Y^{1/2}$ and subscript s denotes values obtained from a

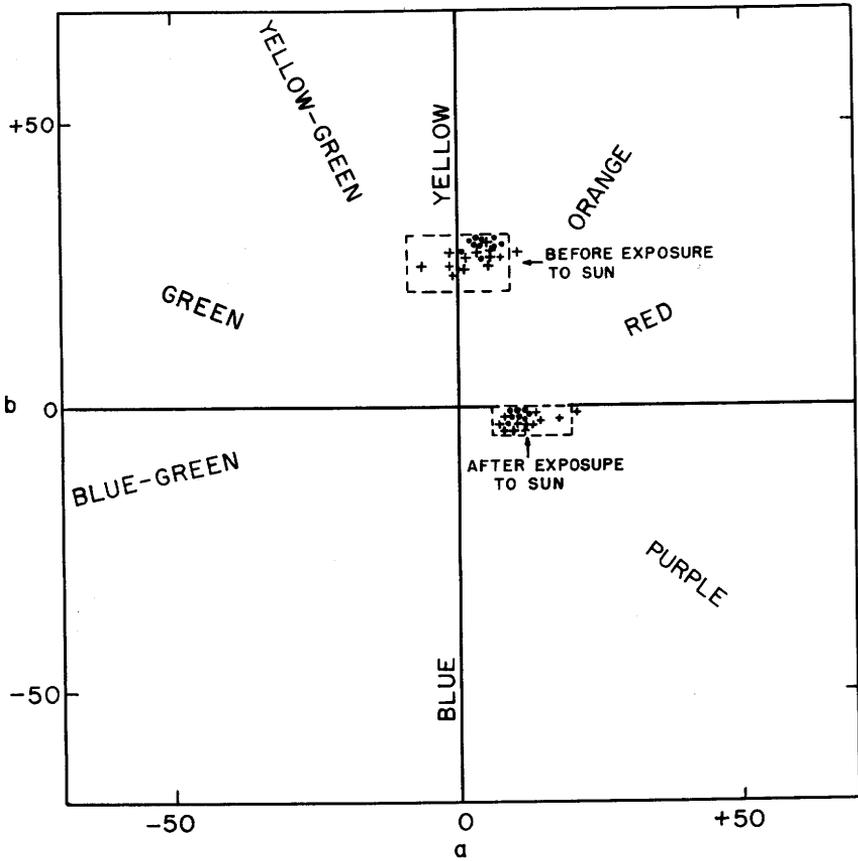


Figure 9-4.—Color hue of loblolly pine veneers of mixed earlywood and latewood before and after 100-day exposure to sunlight. Determinations were made either along (+) or across (*) the grain. (Drawing after Moslemi 1969.)

standard specimen (in this case Gardner CG6622). Figure 9-5 shows that significant darkening took place when light-colored earlywood and mixed wood veneers were exposed to the sun. Color change in the initially dark latewood was slight. Measurements along and across the grain were not significantly different.

The luminance factor (equal to $Y/100$) often varies significantly among species with similar hues (Gray 1963; Moslemi 1967). When evaluated with light source C (daylight), the luminance of unexposed loblolly specimens dropped about 0.2 units (i.e., 20 percent) after exposure to the sun for 101 days. Prior to exposure, earlywood luminance factor was 0.52, and latewood was 0.43. By comparison, the luminance of black walnut is less than 0.2.

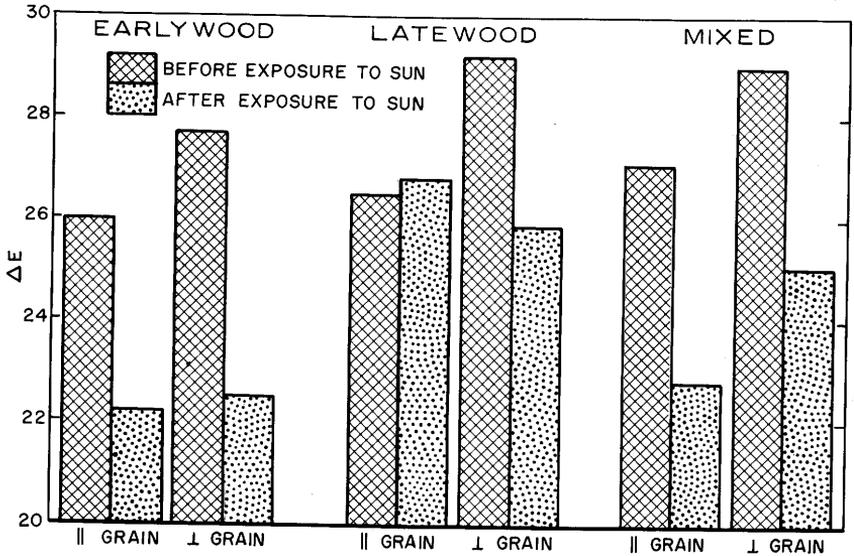


Figure 9-5.—Effect of 100-day outdoor exposure to sunlight on color difference values (see equation 9-6) for earlywood, latewood, and mixed wood of loblolly pine. (Drawing after Moslemi 1969.)

9-2 ACOUSTICAL PROPERTIES

The building industry is the major market for wood products—especially those from southern pines; therefore, the most significant acoustical properties of wood are those related to architectural acoustics. To a limited degree, the vibrational properties of wood are also used in nondestructive testing to classify individual pieces of lumber according to strength.

NONDESTRUCTIVE TESTING

It has been demonstrated that velocity of stress (or sound) waves travelling longitudinally in wood is proportional to dynamic modulus of elasticity, and that dynamic modulus of elasticity is closely correlated with static modulus of elasticity; both moduli are in turn correlated—but to a lesser degree—with modulus of rupture (Galligan and Courteau 1965; Marra et al. 1966; Koch and Woodson 1968).

The basic equation for determining modulus of elasticity by this means is:

$$E_d = c^2 \rho \quad (9-7)$$

where:

E_d = dynamic modulus of elasticity, p.s.i.

c = velocity of stress wave propagation, inches per second

$$\rho = \text{density} = \frac{\text{mass}}{\text{volume}} = \frac{\text{weight in pounds}}{\text{(386) (volume in cubic inches)}}$$

In an evaluation of 10,350 dry (7.6-percent moisture content) southern pine veneers 8 feet in length, velocity of longitudinal stress waves (excited by a solenoid-operated hammer striking the veneer end) was observed to range from 9,020 to 21,540 inches per second with average of 15,270 inches per second; dynamic moduli of elasticity for the two veneers that exhibited the lowest and highest velocities were 551,200 and 3,063,900 p.s.i. respectively (Koch and Woodson 1968).

The velocity of sound travelling longitudinally in southern pine ranges from less than, to more than, the velocity in air; it is only a fraction of that in aluminum.

<u>Medium</u>	<u>Temperature</u>	<u>Velocity</u>
	° C.	<i>Feet per second</i>
Vulcanized rubber---	0	177
Air-----	0	1,087
Oxygen-----	0	1,041
Loblolly pine-----	20	1,273 (range 752-1,795)
Hydrogen-----	0	4,220
Lead-----	20	4,030
Water-----	15	4,760
Copper-----	20	11,700
Aluminum-----	20	16,700
Iron-----	20	16,800

Transverse vibrations in wood have also been employed to nondestructively evaluate strength properties in wood. Two methods have been used. In the first, the plank is driven into forced transverse vibration and its resonant frequency measured (Jayne 1959; James 1964; Miller and Tardif 1967; Miller 1968). For a beam, the relationship is as follows:

$$E_d = \frac{f_n^2 WL^3}{c^2 I g} \tag{9-8}$$

where:

- E_d = dynamic modulus of elasticity, p.s.i.
- f_n = resonance frequency, cycles per second
- W = weight of beam, pounds
- L = length of beam, inches
- c = constant dependent upon mode of support (e.g., $c = 1.57$ for beams simply supported at the ends)
- I = moment of inertia, inches⁴
- g = acceleration due to gravity (386 inches per second²)

In a second method (Pellerin 1965; Marra et al. 1966), the plank to be evaluated is simply supported at the two ends and started by a single impact into free transverse vibration. With this method, the modulus of rupture is inversely proportional to the energy dissipation as measured by the rate of decay, or logarithmic decrement (δ) of the vibrating body; that is, as modulus of rupture increases, δ decreases.

$$\delta = \frac{1}{n} \ln \frac{A_1}{A_n} \quad (9-9)$$

where A_1 and A_2 are the amplitudes of two oscillations n cycles apart on a vibration decay curve. In practice, the mechanism that senses the two amplitudes A_1 and A_n is set to trigger at amplitudes such that the natural logarithm of A_1/A_n is equal to unity. Under these conditions the number of oscillations n which occur between these two amplitudes is the reciprocal of the logarithmic decrement δ . To apply the method, it is first necessary to empirically establish a regression relationship between the logarithmic decrement and the modulus of rupture of the class of planks to be evaluated.

ARCHITECTURAL ACOUSTICS ²

Architectural acoustics involves proper acoustical environment for listening in churches and auditoriums, and—more important in terms of sales volume—reasonable degrees of quiet (not silence) in offices and dwellings.

Methods for achieving these goals include control of noise at the source, orientation of dwellings with respect to streets and other sources of noise, and separation of the noisy areas of dwellings from quiet areas; most pertinent to this text, however, is the selection of wall and floor structures that absorb sound generated within rooms, and that prevent the excessive transmission of sound and vibration from one room to the next.

There are two distinct aspects of acoustical treatment, **sound absorption** and **sound transmission loss**.

Sound absorption treatment calls for the application of materials to the boundaries of the room containing the sound source to prevent "buildup" of sound and to provide a comfortably unreverberant background for the occupants of the room. Absorption of sound in a material in no way implies that the passage of sound through it will be hindered.

Sound transmission loss determines, and is inversely correlated with, the transmission of sound through the structure separating two rooms. In order to isolate one room acoustically from another, the dividing wall must be a massive, impermeable structure so as to reflect as much sound as possible; this generally implies a very poor ability to absorb sound.

There is a difference, then, in treatments which absorb sound and those which contain sound and thereby prevent its transmission. A third objective in sound control is the protection of dwellings from the noise of footfalls and other mechanical impacts originating in rooms overhead.

Sound absorption.—Sound-absorbent materials are of two types: (1) porous, relatively lightweight materials, such as acoustical blankets or tiles; and (2) resonant panels. Most of the commercial acoustical materials are of the porous type; resonant panels are usually custom-made.

² Taken, with minor editorial changes, from Schultz (1969) by permission of Theodore J. Schultz and the Forest Products Research Society.

The total amount of sound absorption in a room not only determines the **reverberation time**, but also limits the loudness of sound produced by a particular source—the more absorption, the less loud the resulting sound. Therefore sound-absorbing materials are used to control the **level** of sound while the source is on and the **persistance** of sound after the source stops.

The effectiveness of a room surface in absorbing sound is expressed in terms of the **absorption coefficient**, α , which is the fraction of the incident sound energy that is absorbed or otherwise not reflected by the surface.

The absorption coefficient of a typical acoustical tile cemented to a wall ranges from about 0.15 at low frequencies (125 cycles per second, c.p.s.) through 0.70 to 0.95 at mid-frequencies (500 to 1,000 c.p.s.), to about 0.65 at high frequencies (4,000 c.p.s.). The absorption of low frequencies is greatly increased if the tile is mounted several inches away from the wall.

The volume of a room V , together with its total sound absorption, represented by the sum of all the surfaces S_i , each multiplied by its absorption coefficient, α_i , determine the **reverberation time**, R.T., of the room, or the time it takes the sound to diminish 60 dB³ after the source stops.

$$\text{R.T.} = \frac{.049V}{\sum_i S_i \alpha_i} \quad (9-10)$$

where V is in cubic feet, S_i is in square feet, R.T. is in seconds, and α_i has no dimensions. Reverberation time usually varies with frequency and is longer at low than at high frequencies in most rooms. Although it seems paradoxical, diffraction effects at the edges of absorptive materials can sometimes channel the sound so that the coefficient, α , as determined from standard reverberation time measurement techniques, exceeds unity. The Acoustical Materials Association has, for years, by common consent, “adjusted” any such measured values greater than unity and published them as 0.99. There is an increasing tendency, however, to state data as measured, so that absorption coefficients as high as 1.3 may be published.

Porous materials absorb sound by permitting it to penetrate the numerous pores at the surface and to be dissipated, by conversion into heat, through viscous losses at the boundaries of the tiny, narrow passageways within the material. If the surface of the material is dense or impermeable, it will reflect the sound wave instead of permitting it to enter. If the fibers of the

³ The **decibel** (abbreviated dB) is a logarithmic measure of how much greater one quantity is than another. It can be used to express the intensity of a sound by stating how much greater its intensity is than a tacitly understood, arbitrary reference intensity. Thus, we speak of a sound pressure level of 84 dB, meaning that the sound pressure is 84 dB greater than the reference pressure of 0.0002 dynes per sq. cm. (The word “level” always implies decibel measure with respect to an arbitrarily understood, or stated, reference quantity.) Alternately, the decibel can be used to express how well a wall attenuates sound by stating how much the intensity of sound striking the wall exceeds the intensity of the sound transmitted by the wall and radiated away on the other side. If this difference is 50 dB, we say the wall has a transmission loss of 50 dB.

material are too far apart, on the other hand, the sound will pass through easily without substantial dissipation. Thus, optimum sound absorption requires a careful balance between density, porosity, fineness of fibers, bulk elasticity, and thickness. Only the geometry matters—the material of which the fibers are made is not important.

Porosity is essential. Panels of wood, hardboard, or plywood adhered to rigid surfaces are poor sound absorbers; they absorb only 5 to 10 percent and reflect more than 90 percent. Leaving the wood surface rough improves absorption only slightly. On the other hand, well-designed, porous acoustical tiles made of wood fiber may absorb up to 90 percent and reflect only 10 percent of impinging sound in a broad spectrum of the higher audible frequencies. Such wood fiber tiles and board are important in the acoustical materials industry.

Solid as well as porous wood products have a place in acoustical design. Decorative plywood paneling can be incorporated in **resonant panels** designed to absorb low-frequency sounds, which are poorly absorbed by acoustical tiles. Resonant panels are typically framed plywood sheets, spaced a few inches from a rigid backup surface. Air trapped behind the panel constitutes the primary stiffness component, which, together with the mass of wood, leads to a resonance whose frequency can be designed to fall within the range not adequately absorbed by other acoustical materials.

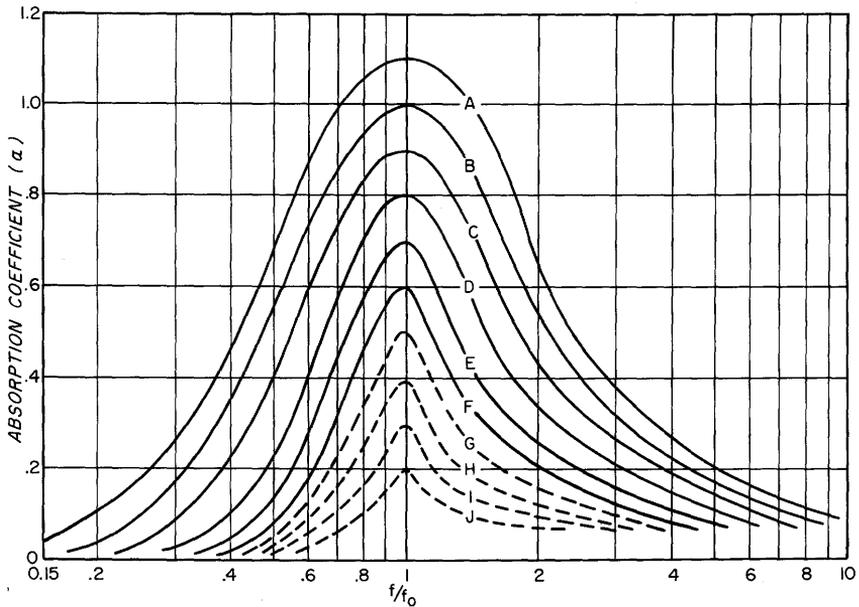
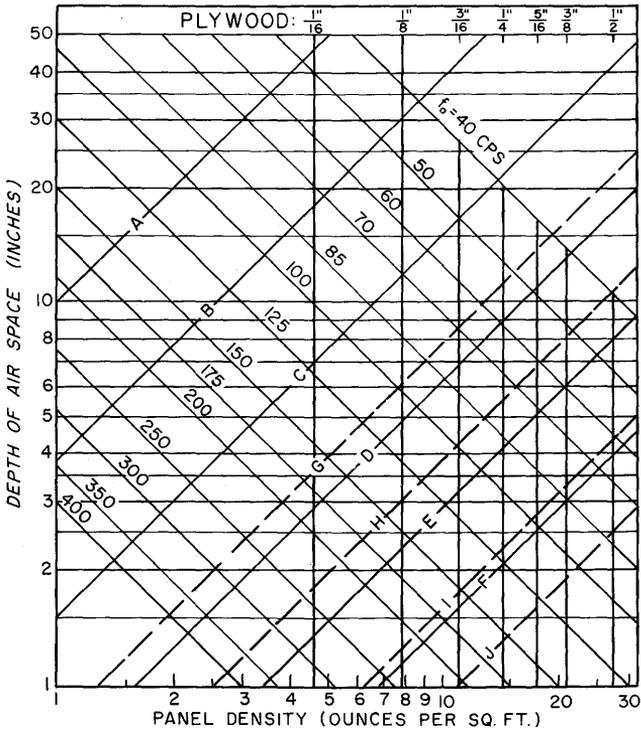
Figure 9-6 shows curves for the convenient design of resonant-panel sound absorbers. To determine the resonance frequency of a panel mounted over a closed airspace, enter the chart of figure 9-6 (top) with the weight of the panel (in ounces per square foot) on the horizontal axis and the average depth of airspace (in inches) on the vertical axis. The point at the intersection of these two coordinates determines both the resonance frequency (interpolated between the lines running from lower right to upper left) and the appropriate curve of absorption to be used for figure 9-6 (bottom) as identified by letters on the lines running from upper right to lower left.

The solid lines (A to F) in figure 9-6 (bottom) apply to configurations in which absorptive material (e.g., fiber batting or acoustical blanket) is added to the airspace behind the panel; the dashed lines (G to J) are for configurations with empty airspace. The curves indicate the absorption coefficient (α) for various sound frequencies expressed as a ratio (f/f_0),

Figure 9-6.—Design curves for resonant panels. (Top) Bands of resonance frequencies (f_0), upper left to lower right; absorption curve identifications for use with bottom chart (lines A through J), upper right to lower left; as related to panel density and depth of airspace. Plywood weights adjusted to approximate southern pine at 10-percent moisture content. (Bottom) Absorption curves, relating absorption coefficients to sound frequency, expressed as a fraction of resonant frequency. The curves apply to panels with density and airspace falling along identically lettered lines on top chart. Curves A through F apply where absorptive material is added to airspace; G through J apply where airspace is empty. (Drawings after Schultz 1969.)

where (f) is the frequency of interest and (f_0) is the resonance frequency of the panel-absorber.

For example, suppose a 1/4-inch-thick plywood panel is mounted against



a solid masonry wall by nailing to 2 by 4's so that the airspace measures about $3\frac{1}{2}$ inches, and that an absorptive material (like thermal insulation) is placed in the airspace. Entering figure 9-6 (top) at the vertical line for $\frac{1}{4}$ -inch plywood and the horizontal line for $3\frac{1}{2}$ -inch airspace, it is seen that this structure will resonate at about 110 c.p.s. and that its absorptive characteristics—as a function of frequency—are approximated by curve (E) in figure 9-6 (bottom). At a frequency, (f), of 110 c.p.s. ($f/f_0 = 1$), the structure absorbs about 70 percent of the energy that strikes it. For a frequency of 220 c.p.s. ($f/f_0 = 2$), about 27 percent of the incident energy is absorbed. At very high or very low frequencies—that is, well away from resonance—the panel is no more absorptive than a rigidly mounted wood surface.

It is clear that configurations with thin panels and deep airspace containing absorptive material have the highest absorption coefficients.

Sound absorption by wood paneling attached to a wood frame structure may cause unexpected results in churches and auditoriums. Figure 9-7 (dotted line) shows a desirable relationship between reverberation time and sound frequency; music has warmth and is pleasant to the ear if played in rooms where reverberation time is high at low frequencies and lower at high frequencies. If extensively paneled or decked with wood over frames, church walls or roofs may function as resonant panels absorbing sound at frequencies between 100 and 300 c.p.s. (fig. 9-7, solid line), causing the music of choir and organ to sound shrill and unpleasant. In churches and auditoriums, any extensive areas of wood paneling must be firmly adhered to a rigid backup surface, or their resonance frequencies must be designed to avoid undesirable sound absorption. Because exposed decorative southern pine decking attached to laminated beams is extensively used in churches and auditoriums, the foregoing discussion is pertinent to many contemporary designs.

Sound transmission loss.—The ability of a partition or floor structure to prevent the transmission of sound across its thickness is measured by its sound transmission loss expressed in decibels (dB) ³. For effective acoustical isolation between dwellings or offices, the transmission loss of the walls and floors should exceed 45 dB at mid-frequencies.

For thin homogeneous partitions whose sides move with identical motion, the transmission loss at most frequencies of interest depends almost entirely on the mass of the partition. At more extreme frequencies, however, effects of partition stiffness reduce losses below those predicted from the mass alone (fig. 9-8).

At frequencies below the lowest resonance frequency, f_0 , the transmission loss increases with increasing partition stiffness (fig. 9-8). In most structures these frequencies are below the usual range of interest. At and near the lowest partition resonances, the transmission loss is small because of sound radiation due to vigorous panel motion.

At mid-frequencies (Region II, fig. 9-8), lies the mass law region where

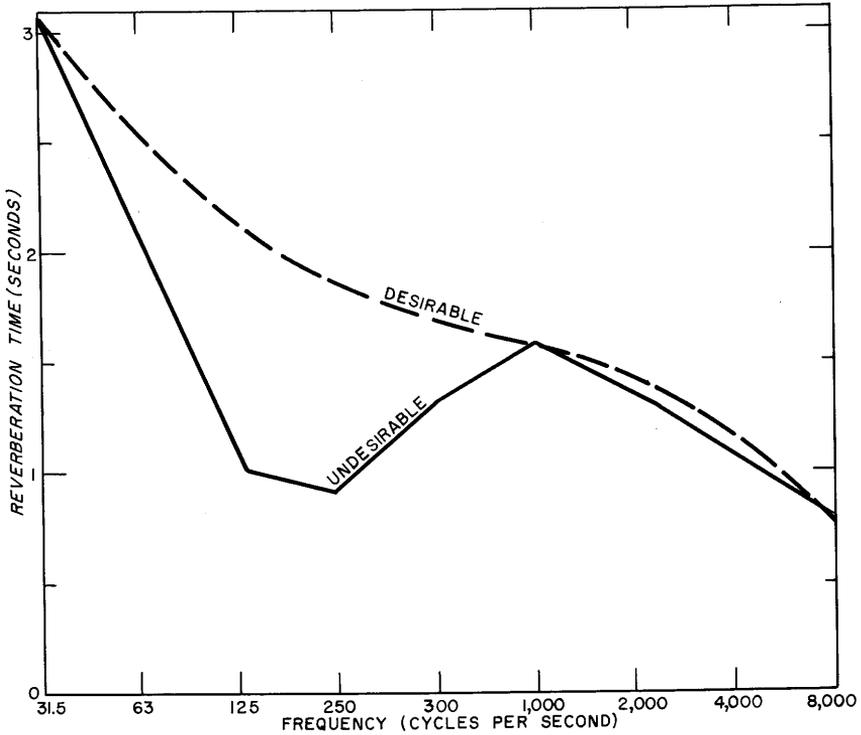


Figure 9-7.—Reverberation time in churches (unoccupied and with no pew cushions). The solid line illustrates unintentional degradation of acoustics by extensive wood paneling, whose resonance absorbs sound in the frequency range from 100 to 300 cycles per second. (Drawing after Schultz 1969.)

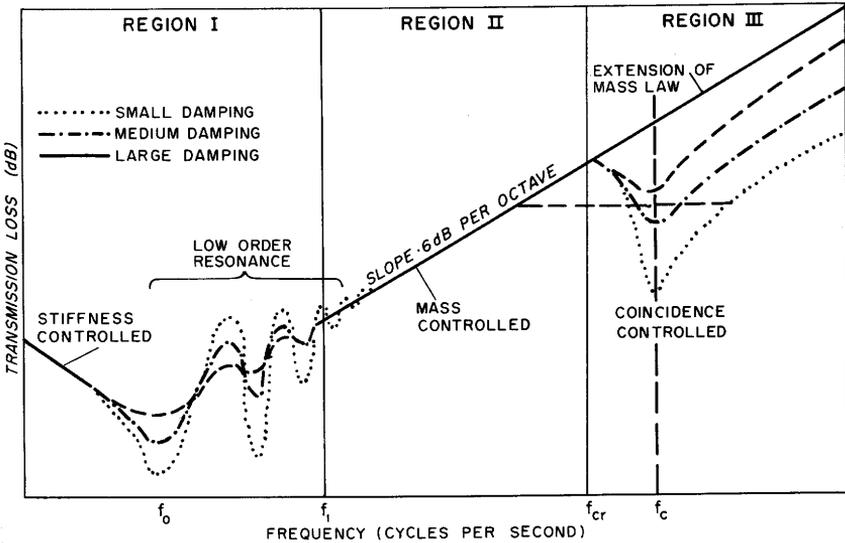


Figure 9-8.—Typical transmission-loss curve for thin homogeneous partitions. (Drawing after Schultz 1969.)

the transmission loss is related entirely to the mass per unit area of the partition. In many constructions this region accounts for most of the frequency range of interest. Here transmission loss (T.L., decibels) improves as the weight (w , pounds per square foot) or the frequency (f , c.p.s.) is increased, but decreases as the incidence angle of the sound on the wall (ϕ) increases from perpendicular toward grazing, according to the following equation:

$$\text{T.L.} = 10 \ln \left[1 + \left(\frac{wf \cos \phi}{25} \right)^2 \right] \quad (9-11)$$

If the sound strikes the wall from all directions, due to multiple reflections in the source room, the so-called **field incidence** transmission loss is given by:

$$\text{T.L.} = 10 \ln \left[1 + \left(\frac{wf}{45} \right)^2 \right] \quad (9-12)$$

In a still higher range above a critical frequency f_{cr} of the panel, the acoustic wavelength in the air can match the flexural wavelength on the panel. Since the acoustic wavelength in air is inversely proportional to frequency, whereas the flexural wavelength in the panel varies inversely as the square root of frequency, there is always some frequency at which these wavelengths match. The critical frequency for 1-inch plywood is 850 c.p.s., for 1/2-inch 1,800 c.p.s., and for 1/4-inch 3,300 c.p.s. At the **coincidence frequency**, f_c , where such wavelength matching occurs, coupling between the sound waves in the surrounding air and the flexural wave in the partition is almost perfect; sound is transmitted readily through the partition, and there is a sharp decrease in transmission loss.

Since the ratio of the acoustic to the flexural wavelength decreases with increasing frequency, this matching of acoustic and flexural wavelength occurs for each frequency only at a specific angle of incidence of the sound upon the partition. Conversely, for every frequency within Region III, there will be some angle of incidence at which there is nearly perfect transmission of sound through the partition. Consequently, in Region III there is a substantial drop in transmission loss below the extension of the mass law curve. The dashed line extending from Region II to Region III represents a fair engineering approximation of the performance of the panel in this range.

Panel stiffness affects the width of both Regions I and III of figure 9-8; the stiffer the panel the higher the resonance frequency, f_o , in Region I and the lower the critical frequency, f_{cr} , in Region III. In a very stiff, lightweight panel, the mass-controlled Region II is so narrowed that transmission loss may be very low and almost independent of frequency over a very wide middle-frequency range. Addition of damping to partitions

improves performance somewhat in Regions I and III but seldom increases transmission loss to equal mass law behavior.

The very qualities that make wood suitable for musical instruments—i.e., its high resonance and low ratio of mass to stiffness—necessitate special care in using wood to reduce sound transmission. Some examples illustrate the point.

Most wooden construction, unlike the theoretical thin homogeneous partition, is built up of panels attached to a framework of 8-foot 2 by 4's. The two sides of the wall do not necessarily vibrate with identical motion. Over the studs both sides of the wall (and the stud) tend to move together; between studs, the effect is more nearly that of a double wall. As a result, the transmission loss of a partition with studs often lies somewhere between that of a simple, homogeneous wall and that of a completely isolated double wall. The degree to which the studs couple the two sides of the wall together becomes very important in determining the transmission loss performance of a wall.

In a standard wood-gypsum board partition there is a substantial area of firm contact between the gypsum board and the stud on both sides of the wall. When an incident sound wave sets up a flexural vibration in the gypsum on one side, resultant torsion in the studs excites a flexural wave in the gypsum board on the other side (fig. 9-9A). This motion is radiated away as sound on the far side of the wall, the transmission loss is low (about 34 to 36 dB at mid-frequencies according to Grantham 1970), and the partition readily transmits noise.

With softboard under the gypsum board of the previous construction, contact with the studs is somewhat spongy. Even though the softboard is "short-circuited" by the attachment nails (or screws), less torsion is induced in the studs and less flexure is transmitted to the gypsum board on the far side of the wall (fig. 9-9B). Moreover, the softboard adds some absorption within the airspace which minimizes standing waves there. Consequently, transmission loss is higher. If both gypsum board and softboard are nailed (8 inches between nails) to the studs, the T.L. is about 36 at mid-frequencies; if only the softboard is nailed to the studs and the gypsum board is glued to the softboard, then the T.L. increases to about 49 (Grantham 1970).

Figure 9-9C represents the case of a flexible steel stud which bends freely to minimize transmission of flexural motion from one side of the wall to the other. In a partition with gypsum board on both sides of steel studs, this behavior results in a T.L. of about 42 at mid-frequencies (Grantham 1970).

In partitions having gypsum board fastened on both sides (fig. 9-10) T.L. varies with sound frequency as observed in figure 9-8, with fundamental resonance, f_0 , at about 125 c.p.s. and the coincidence dip, f_c , at about 3,000 c.p.s. With 6-inch screw spacing the T.L. may be 10 dB less than with 48-inch spacing. In partitions built around flexible-flange (e.g., steel) studs, T.L. varies only slightly with screw spacing.

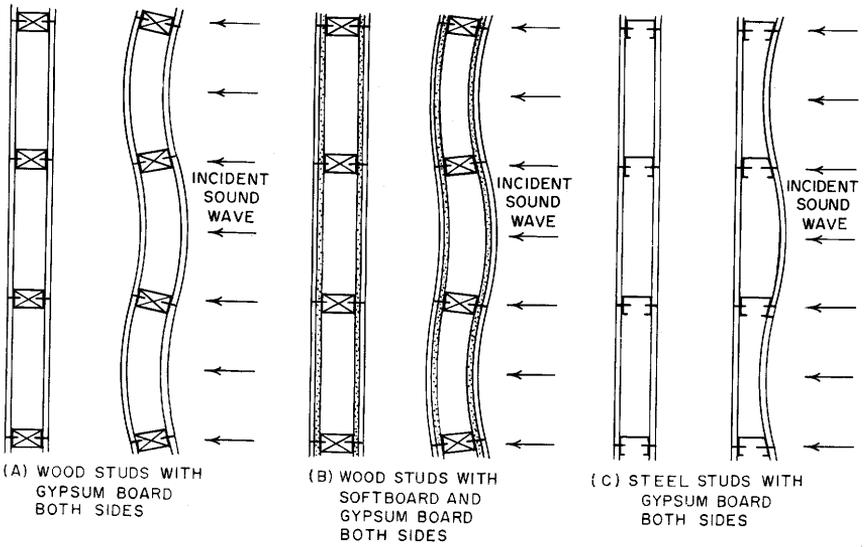


Figure 9-9.—Sound-induced deformations that affect transmission of midfrequency sound through partitions of three constructions. (Drawing after Schultz 1969.)

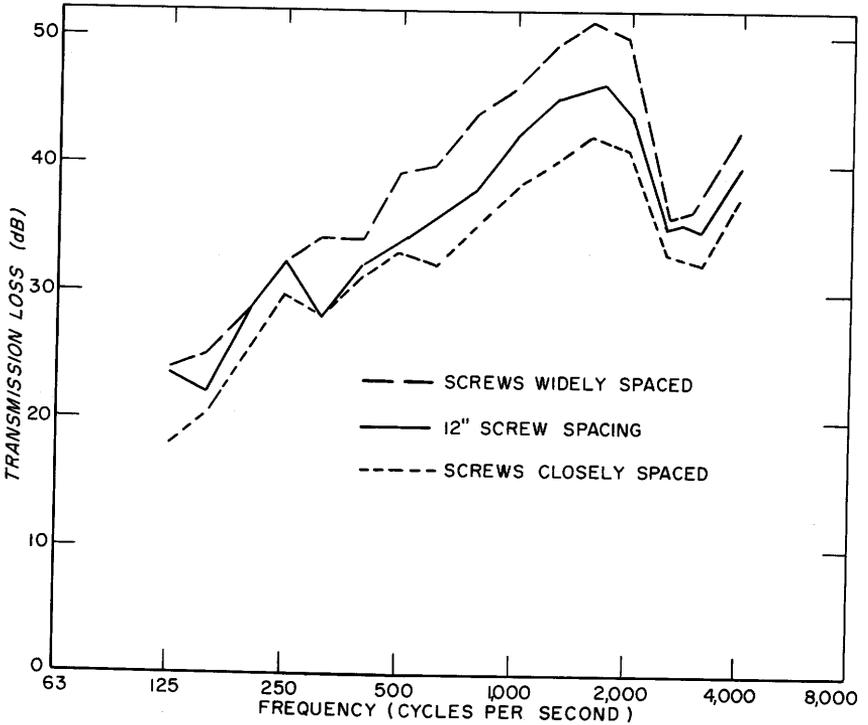


Figure 9-10.—Relationship of sound frequency and screw spacing to sound loss through a partition of 1/2-inch plasterboard screwed to each side of wood studs placed 24 inches apart. (Drawing after Schultz 1969.)

In all three cases illustrated by figure 9-9, an absorptive blanket in the airspace between the two sides of the wall can considerably increase transmission loss by damping flexural vibration in the cladding and acoustic standing waves in the airspace (Owens-Corning Fiberglas Corporation 1969).

To achieve a T.L. at mid-frequencies in excess of 45, builders can use several wall constructions incorporating wood studs, but all are more expensive than that shown in figure 9-9A (Grantham 1970).

<u>Construction</u>	<u>Transmission loss</u>
	<i>dB</i>
Wood studs with one of the two gypsum-board faces secured to a metal resilient channel nailed in turn to the stud, and the other nailed direct to the stud.	46 to 47
Two rows of 2 by 4 wood studs, each row on 16-inch centers but staggered on a single plate so that there are only 8 inches between stud centers and each gypsum-board facing is nailed to only one row.	45 to 48
Figure 9-9B (with gypsum board glued to softboard).	49
Wood studs equipped with metal resilient channels on both edges to which both gypsum-board facings are attached, and with 3 inches of thermal blanket between studs.	47 to 52
Two rows of 2 by 4 wood studs on separate plates spaced 1 inch apart; studs on 16-inch centers; gypsum board nailed to outer face of each row.	49 to 50

Additional effective wood wall constructions have been illustrated by Prestemon (1970).

Impact isolation.—The degree to which a floor-ceiling construction prevents transmission of the sound of footfalls or other impacts to the floor below is termed **impact isolation**. It is evaluated by a test⁴ in which a specially designed machine administers a series of standard impacts to the floor surface while the resulting sound pressure level is measured in the room below. The lower that level, the better the floor is taken to be, i.e., the more isolation it provides; thus, a high number means poor performance in this test, as contrasted with transmission loss.

Impact noise ratings (INR) are assigned according to a special FHA curve-fitting procedure (see Federal Housing Administration 1963), such that an INR value of zero represents a reasonably good floor; increasing positive INR values represent better isolation and increasing negative values poorer performance.

Generally, impact isolation is best if the floor is heavy and does not

⁴ This controversial test procedure originated in Europe and has been in use there for many years, but with increasing dissatisfaction; it is also mistrusted in this country because it fails to rank constructions in the same order as footfalls rank them (see Mariner and Hehmann 1967). It is, however, serving until an alternative method is adopted.

resonate. In both respects wood is at a disadvantage, since on a per-pound basis wood is not cheap and wood joist constructions tend to be resonant. Moreover, in addition to transmitting the noise of the impact, some wood floors generate noise of their own in the form of cracks.

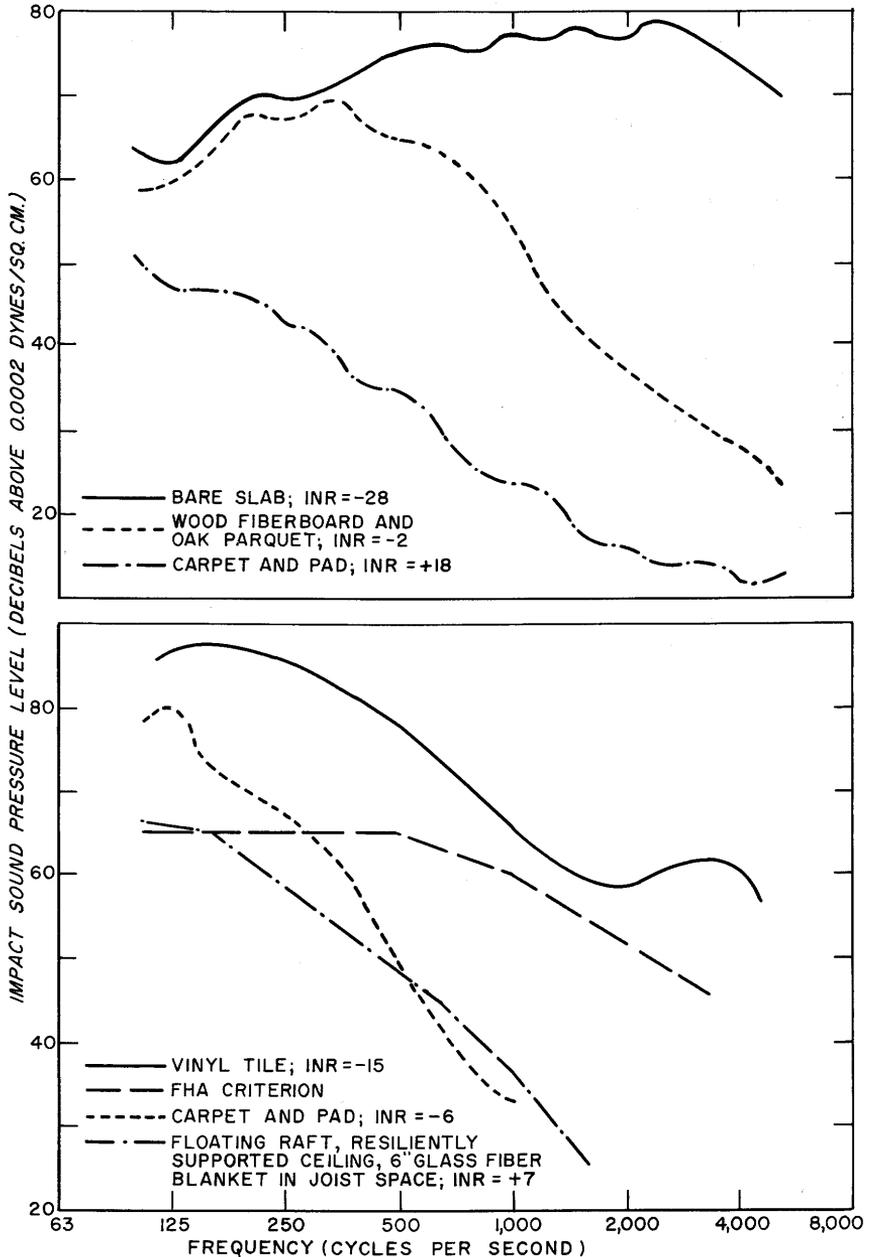


Figure 9-11.—Impact sound pressure levels for floor structures. (Top) Six-inch concrete slab with various floor coverings. (Bottom) Standard wood joist floors with various treatments. Impact noise ratings based on FHA criteria. (Drawings after Schultz 1969.)

Although a bare concrete slab floor, in spite of its weight, is one of the worst constructions (INR = -28), with a carpet and a pad it becomes one of the best (INR = $+18$). A concrete slab with parquet flooring is intermediate with an INR of -2 (fig. 9-11 top).

Unfortunately, the addition of a carpet and pad to a wood joist floor still provides inadequate impact isolation (INR = -6 , see fig. 9-11 bottom).

It requires a fairly complex floor-ceiling configuration—such as a floating “raft” floor resting on glass fiber on the subfloor plus a resiliently suspended plaster ceiling with a heavy glass-fiber blanket in the joist space—to provide impact isolation in a wood floor that would be satisfactory in multifamily dwellings. Such constructions are difficult to apply in kitchens and bathrooms.

References.—For further information on architectural acoustics, the reader may consult Ingemansson and Kihlman (1959), Parkin et al. (1960), Reiher et al. (1960), Federal Housing Administration (1963), Berendt et al. (1968), Mariner and Hehmann (1967), National Association of Home Builders Research Foundation (1967), and Owens-Corning Fiberglas Corporation (1969) for accounts that are not overly technical. More advanced treatments are provided by London (1949, 1950), Zwicker and Kosten (1949), Schoch and Feher (1952), Cremer (1953), Kosten (1953), and Lyon and Maidanik (1964). Berenek (1960) gives both technical and descriptive matter—chapter 12 on properties of acoustical materials, chapter 13 on the transmission and radiation of acoustic waves by solid structures, chapter 14 on sound transmission through structures containing porous materials, and chapter 15 on acoustical materials for architectural uses. Godshall and Davis (1969) have tabulated sound absorption coefficients for plywood, particleboard, perforated hardboard and wood fiber acoustical panels.

9-3 FRICTIONAL PROPERTIES

The coefficient of friction of wood against steel affects the holding power of mechanical fasteners, the configuration of chips and surfaces produced by machining operations, and the feed power required to slide or feed wood through processing equipment.

Classically, the tangential force of kinetic friction between two surfaces sliding past each other is regarded as proportional to the normal force. The proportionality constant or friction coefficient depends on the materials and roughness of the surface, but over a wide range it is independent of the contact area and the relative velocities of the sliding surfaces.

Published data specific to southern pine wood are limited to those obtained on spruce pine by Lemoine et al. (1970) and McMillin et al. (1970ab).

In their experiments the horizontal force (F_h) required to slide a 1-square-inch surface subjected to a known vertical force component (F_v) was measured and the coefficient of kinetic friction (μ) calculated by the relationship $\mu = F_h/F_v$. (9-13)

An Instron testing machine was used to maintain a constant sliding velocity of 2 inches per minute as well as to measure the horizontal force (fig. 9-12). A thin copper wire was attached to the specimen and to a 1-pound load cell mounted on the movable crossarm of the testing machine. Movement of the crossarm thus provided a constant sliding velocity, while the load cell simultaneously detected the horizontal force component. A 1-pound weight was placed on the upper surface of the cube and it, plus the weight of the sample, was considered the total vertical force component.

An oil-hardened, tool steel plate was used as the stationary surface. Its surface roughness was 9 microinches root mean square (RMS), and the specimens were pulled parallel to the grinding marks. Wood surfaces were sanded with 220-grit sandpaper.

EFFECT OF WOOD VARIABLES ⁵

Lemoine et al. (1970) have shown the effects of some wood variables on the coefficient of friction between steel and spruce pine wood. Tests were conducted at 24°C. with variables as follows:

- Unextracted specific gravity (ovendry weight and green volume basis): less than 0.45, more than 0.45.
- Extractive content (percent of ovendry unextracted weight): extractive-free, unextracted with average of 1.4 percent.

⁵ Condensed from Lemoine et al. (1970) by permission of the authors and the Forest Products Research Society.

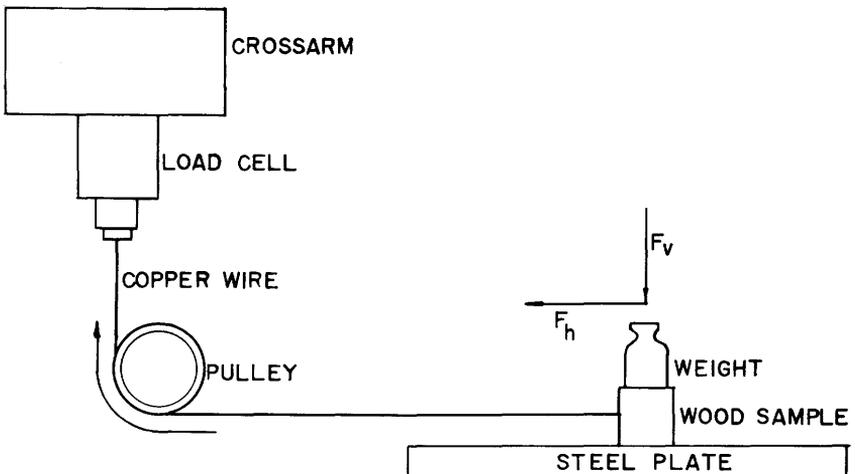


Figure 9-12.—Experimental setup for determining coefficient of friction. (Drawing after Lemoine et al. 1970.)

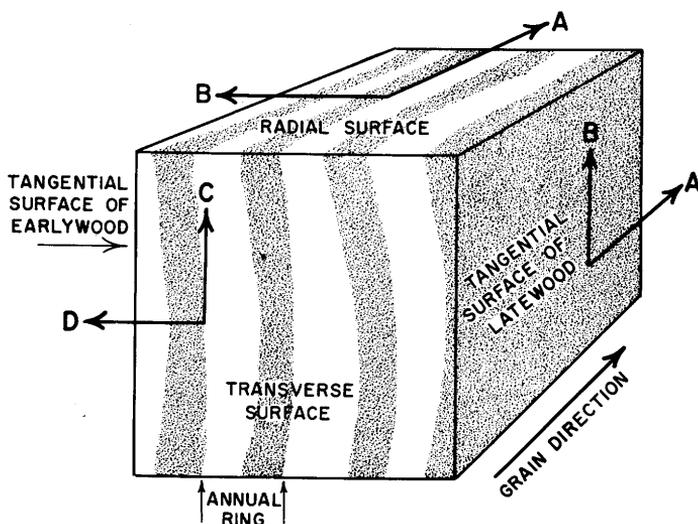


Figure 9-13.—Friction specimens. The letters A, B, C, and D refer to direction of slide in relation to grain orientation. Direction A is parallel to the wood grain, while direction B is perpendicular. Direction C is parallel to the annual rings, while direction D is perpendicular. (Drawing after Lemoine et al. 1970.)

- Moisture content (percent of green weight): 0, 11.2, and 18.4 percent.

On the radial and tangential surfaces, specimens were pulled first parallel and then perpendicular to the grain (directions A and B in fig. 9-13). On the transverse surface they were pulled both parallel and perpendicular to the annual rings (directions C and D in fig. 9-13).

Mean values for the friction coefficient by moisture content, specific gravity, and extractive content are listed in table 9-3 for each combination of direction of slide and wood surface.

For samples pulled in the parallel direction and averaged over all moisture contents, specific gravities, and extractive contents, the friction coefficient was significantly greater for the transverse surface of whole wood (avg. 0.218) than for the tangential surface of latewood (avg. 0.189). No differences were detected between coefficients for the remaining surfaces.

For samples pulled in the perpendicular direction, the friction coefficient was significantly greater (avg. 0.215) for the transverse surface of whole wood than for the tangential surface of latewood (avg. 0.183) or the tangential surface of earlywood (avg. 0.192). No differences were detected between friction coefficients among the remaining surfaces.

Tangential surface of latewood.—When averaged over all moisture contents and specific gravities (table 9-3) the friction coefficient for tangential latewood was higher in extractive-free wood than in unextracted wood, both when pulled parallel to the grain (0.199 versus 0.179) and when pulled perpendicular to the grain (0.192 versus 0.174). Differences associated with moisture contents or specific gravities were not significant.

TABLE 9-3.—*Effect of wood variables on the coefficient of friction between spruce pine wood and steel (data from Lemoine et al. 1970)*

Factor	Parallel slide ¹				Perpendicular slide ¹			
	Tangential (latewood)	Tangential (earlywood)	Transverse	Radial	Tangential (latewood)	Tangential (earlywood)	Transverse	Radial
Moisture content				*				
Low (0 percent).....	0.187	0.204	0.221	0.194	0.178	0.199	0.210	0.203
Intermediate (avg. 11.2 percent).....	.186	.199	.218	.190	.182	.190	.224	.193
High (avg. 18.4 percent)....	.193	.196	.216	.216	.190	.187	.210	.202
Specific gravity		*	*					*
Less than 0.45 (avg. 0.39)....	.190	.208	.229	.205	.186	.198	.223	.206
More than 0.45 (avg. 0.51)....	.189	.192	.207	.194	.180	.186	.206	.193
Extractive content	*		*		*		*	
Extractive free (0 percent)....	.199	.205	.197	.203	.192	.190	.196	.201
Unextracted (avg. 1.4 percent).....	.179	.195	.239	.197	.174	.194	.234	.198
Grand mean.....	.189	.200	.218	.200	.183	.192	.215	.199

¹ For all factors significance was tested at the 0.05 level; values in columns immediately below asterisks are significantly different.

When averaged over all study variables, friction coefficient showed no significant difference between directions of slide; averages were 0.189 parallel to the grain and 0.183 perpendicular.

Tangential surface of earlywood.—When tangential earlywood was pulled parallel to the grain, the friction coefficient, averaged over all moisture and extractive contents, was greater (avg. 0.208) in wood of low than in wood of high specific gravity (avg. 0.192). No other factor affected the coefficient significantly.

The interaction of specific gravity and moisture content was significant. As the following tabulation indicates, the friction coefficient decreased with increasing specific gravity when the moisture content was intermediate. At high or low moisture contents, the coefficient remained unchanged with increasing specific gravity. Thus, when a tangential surface of earlywood is pulled parallel to the grain, low coefficients of friction (avg. 0.180) are associated with dense wood of intermediate moisture content.

<u>Specific gravity</u>	<u>Wood moisture contents</u>		
	<u>Low</u>	<u>Intermediate</u>	<u>High</u>
Less than 0.45.....	0.208	0.218	0.198
More than 0.45.....	.201	.180	.194

None of the primary variables proved significant for the tangential surface of earlywood pulled perpendicular to the grain, but the interaction of specific gravity and moisture content was again significant. The coefficient was least for dense wood of intermediate moisture content (avg. 0.171), and no differences were detected between specific gravities when the moisture content was high or low:

<u>Specific gravity</u>	<u>Wood moisture contents</u>		
	<u>Low</u>	<u>Intermediate</u>	<u>High</u>
Less than 0.45.....	0.196	0.210	0.188
More than 0.45.....	.203	.171	.185

Further, moisture content interacted with extractive content. The friction coefficient decreased with increasing extractive content when the moisture content was intermediate, increased with increasing extractive content when the moisture content was high, and was unaffected by changes in the level of extractives at low moisture contents. The coefficient was lowest for unextracted wood of intermediate moisture content (avg. 0.179) and extractive-free wood of high moisture content (avg. 0.175).

<u>Extractive content</u>	<u>Moisture contents</u>		
	<u>Low</u>	<u>Intermediate</u>	<u>High</u>
Extractive-free.....	0.193	0.202	0.175
Unextracted.....	.205	.179	.198

When averaged over all moisture contents, specific gravities, and extractive contents, the coefficient for tangential earlywood did not differ between directions of slide.

Transverse surface.—When averaged over all moisture and extractive contents, and when pulled parallel to the annual rings, wood of low specific gravity had a higher friction coefficient (avg. 0.229) than wood of high specific gravity (avg. 0.207). Extractive-free wood had a lower friction coefficient (avg. 0.197) than unextracted wood (avg. 0.239). No differences were detected between moisture contents, although the interaction of extractive content and moisture content was significant. The coefficient of friction increased with increasing extractive content at high and low moisture contents but remained relatively constant with increasing extractive content at intermediate moisture. The coefficient was least (avg. 0.170) when the moisture content was high and the wood was extractive free; it was greatest (avg. 0.263) when the moisture content was high and the wood was unextracted.

Extractive content	Moisture contents		
	Low	Intermediate	High
	μ		
Extractive-free.....	0.200	0.222	0.170
Unextracted.....	.242	.214	.263

When the transverse surface was pulled perpendicular to the annual rings, extractive-free wood had a lower friction coefficient (avg. 0.196) than unextracted wood (avg. 0.234). The interaction of extractive content and moisture content was also significant; the trends were similar to those observed when the specimen was pulled parallel to the rings. Thus, the coefficient was least (avg. 0.165) when the moisture content was high and the wood extractive-free; it was greatest (avg. 0.255) when the moisture content was high and the wood was unextracted.

Extractive content	Moisture contents		
	Low	Intermediate	High
	μ		
Extractive-free.....	0.195	0.229	0.165
Unextracted.....	.226	.220	.255

When averaged over all variables, the mean coefficient for the transverse surface was 0.215 for samples pulled perpendicular to the annual rings and 0.218 for samples pulled parallel. The means were not significantly different.

Radial surface.—In radial surfaces pulled parallel to the grain, the coefficient of friction was least when the moisture content was low or intermediate (avg. 0.194 and 0.190, respectively), and greatest when the moisture content was high (avg. 0.216). The interaction of moisture content and extractive content was also significant. When the wood was

unextracted, the coefficient was least when the moisture content was intermediate (avg. 0.174). There was no difference in coefficients between high and low moisture contents. In extractive-free wood the coefficient was least when the moisture content was low (avg. 0.180) and greatest when the moisture content was high (avg. 0.224).

Extractive content	Moisture contents		
	Low	Intermediate	High
	μ		
Extractive-free.....	0.180	0.206	0.224
Unextracted.....	.208	.174	.208

When a radial surface was pulled perpendicular to the grain, the coefficient decreased with increasing specific gravity. Wood of low gravity averaged 0.206, while wood of high gravity averaged 0.193. The interaction of specific gravity and extractive content was significant. Thus, friction decreased with increasing specific gravity in unextracted wood but remained unchanged in extractive-free wood. The coefficient was least (avg. 0.185) in dense, unextracted wood.

Extractive content	Specific gravities	
	Less than 0.45	More than 0.45
	μ	
Extractive-free.....	0.201	0.201
Unextracted.....	.211	.185

The interaction of moisture content and extractive content was also significant. With increasing moisture content friction increased in extractive-free wood but decreased in unextracted wood.

Extractive content	Moisture contents		
	Low	Intermediate	High
	μ		
Extractive-free.....	0.188	0.200	0.215
Unextracted.....	.218	.186	.190

When averaged over all moisture contents, specific gravities, and extractive contents, the friction coefficient of the radial surface was 0.199 for samples pulled perpendicular to the grain and 0.200 for samples pulled parallel; the means were not significantly different.

Summary.—The friction coefficient was at maximum for the unextracted transverse surface of high moisture content pulled parallel to the rings (avg. 0.263). It was at minimum for the extractive-free transverse surface of high moisture content pulled perpendicular to the rings (avg. 0.165).

EFFECT OF TEMPERATURE

McMillin et al. (1970a) used the apparatus and specimen configuration shown in figures 9-12 and 9-13 to determine the effect of temperature on the coefficient of friction between oven-dry spruce pine wood and steel with surface roughness of 9 microns RMS. The specimens were pulled parallel to the grinding marks on the steel plate at 2 inches per minute; temperature of the plate was controlled by varying the voltage to electrical strip heaters attached to its lower surface.

Their results are summarized in figure 9-14. The coefficient of friction ranged from 0.10 to 0.25 and was negatively correlated with temperature for tangential earlywood, tangential latewood, and radial surfaces pulled parallel and perpendicular to the grain and for transverse surfaces pulled parallel and perpendicular to the annual rings. For transverse surfaces pulled parallel to the annual rings, tangential latewood surfaces pulled

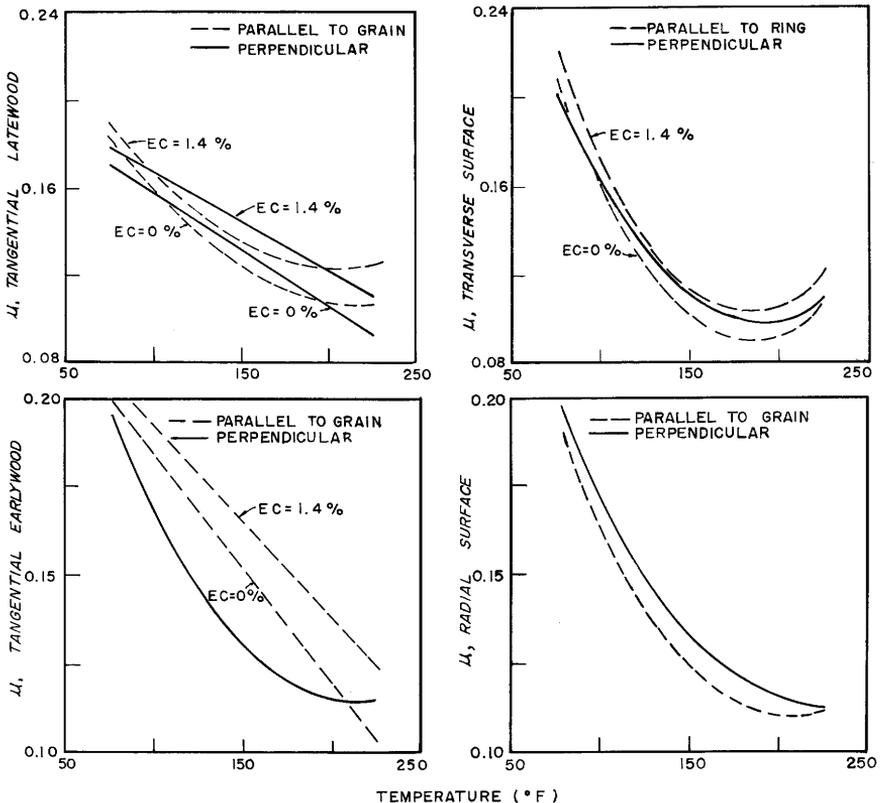


Figure 9-14.—Friction coefficient (μ) for oven-dry spruce pine wood sliding on a heated steel plate as related to temperature and percentage of extractive content (EC). Where value of EC is not indicated, coefficients for extracted and unextracted samples were not significantly different. (A) Tangential surface of latewood. (B) Transverse surface. (C) Tangential surface of earlywood. (D) Radial surface. (Drawing after McMillin et al. 1970a.)

parallel or perpendicular to the grain, and tangential earlywood surfaces pulled parallel to the grain, the coefficient also increased with increasing extractive content for a given temperature. No significant relationships were detected between the coefficient and wood specific gravity after the effects of temperature and extractive content had been accounted for.

EFFECT OF LUBRICANTS ⁶

McMillin et al. (1970b) using the apparatus and specimen configuration shown in figures 9-12 and 9-13, studied the effect of several lubricants on the friction coefficient between steel having a surface roughness of 9 micro-inches RMS and spruce pine cubes extracted in alcohol-benzene. In their experiment, several milliliters of liquids thought to have lubricating properties were dropped ahead of the moving specimen (fig. 9-12) and the change in horizontal force noted. Table 9-4 summarizes the information on coefficients of friction before and after application of water, ethanol, and octanoic acid. Other intended lubricants (xylene, polyethelene glycol 1000, and didecyl phthalate) did not appreciably affect the friction coefficient.

⁶ Condensed from McMillin et al. (1970 b) by permission of the authors and the Forest Products Research Society.

TABLE 9-4.—*Effect of lubricants on friction coefficients at 76° F. between extracted, sanded spruce pine wood and steel with surface roughness of 9 microinches RMS (data from McMillin et al. 1970b)¹*

Lubricant	Radial surface		Transverse surface	
	Unlubricated	Lubricated	Unlubricated	Lubricated
----- μ -----				
OVENDRY SAMPLES				
Water.....	0.21	0.42	0.22	0.46
Ethanol.....	.23	.40	.26	.38
Octanoic acid.....	.21	.18	.23	.18
SATURATED SAMPLES				
Water.....	.60	.47	.72	.61
Ethanol.....	.64	.56	.78	.61
Octanoic acid.....	.61	.28	.71	.28

¹ Each numerical value is the average of three observations.

The general effect of the treatments may be compared from the ratios of μ after treatment to μ before treatment. In the following tabulation ratios greater than 1 indicate that the coefficient was increased by treatment, while ratios less than 1 indicate it was decreased; values are averaged over both surfaces:

	<u>Ratios</u>	
	<u>Ovendry</u>	<u>Saturated</u>
Water -----	2.05	0.82
Ethanol -----	1.59	.82
Octanoic acid ----	.82	.42

The introduction of water and ethanol increased the coefficient for dry samples but decreased the coefficient when the samples were wet. Octanoic acid decreased the coefficient for both dry and wet samples.

Differences between the means in table 9-4 were tested by variance analysis at the 0.05 level of significance. For unlubricated surfaces only two significant differences were observed. The coefficient was greater when the samples were saturated (avg. 0.68) than when dry (avg. 0.23). For saturated unlubricated wood, the coefficient was greater for the transverse surface (avg. 0.74) than for the radial surface (avg. 0.63).

There was a significant interaction with initial moisture content when the samples were lubricated with water. Water increased the coefficient of dry samples from 0.22 to 0.44 but reduced the coefficient of saturated samples from 0.66 to 0.54. With saturated samples, a thin film of free water probably forms at the interface and acts as a lubricant.

For water-lubricated owendry samples, the coefficient did not differ between surfaces (avg. 0.44). When saturated samples were lubricated with water, the coefficient was lower for a radial surface (avg. 0.47) than for a transverse surface (avg. 0.61).

Ethanol is slightly less polar than water. It also is a dehydrating agent and a solvent for surface extractives. As with water, when ethanol was applied to dry samples, the coefficient was significantly greater (avg. 0.39) than for unlubricated surfaces (avg. 0.25). For saturated samples, the coefficient was less for lubricated (avg. 0.59) than for unlubricated surfaces (avg. 0.66). The coefficient did not differ between surfaces for lubricated owendry samples (avg. 0.39). For saturated samples lubricated with ethanol, the coefficient was lower for radial surfaces (avg. 0.56) than for transverse surfaces (avg. 0.61).

Octanoic acid is a liquid whose molecule is nonpolar on the hydrocarbon end and very polar, with good hydrogen bonding capability, on the opposite end. The interaction of initial moisture content and presence of this lubricant was significant. With dry samples, differences in coefficients between lubricated and unlubricated surfaces (avg. 0.20) were not significant. With saturated samples, the coefficient was significantly greater for unlubricated (avg. 0.66) than for lubricated surfaces (avg. 0.28). The coefficient for wood lubricated with octanoic acid did not differ between radial and transverse surfaces in either owendry or saturated samples.

Octanoic acid is adsorbed readily on owendry wood but is immiscible with water. Thus, in water-saturated samples, it was possible to maintain a boundary layer of lubricant at the interface.

9-4 THERMAL PROPERTIES

The thermal characteristics of wood affect both the processes by which it is converted and the performance of finished wood products.

SPECIFIC HEAT

The specific heat of wood is the heat capacity of a given mass of wood compared to the heat capacity of the same mass of water at 15° C. Heat capacity of a material may be expressed as the number of calories required to raise 1 g. 1° C. in temperature. Because heat capacity of water at 15° C. is 1 calorie per gram per degree C., heat capacity and specific heat are numerically equal.

Specific heat of chemical constituents.—The specific heat of wood is determined by the specific heat of its constituents and of the air contained within the lumens. McMillin (1970) found that the specific heats of alpha-cellulose, holocellulose, lignin, and extractives were positive linear functions of temperature in the range 333° to 413° K. (table 9-5). Table 9-6 summarizes the values for each constituent at three temperatures. The value for holocellulose (avg. 0.3529) was nearly identical to that for alpha-cellulose (avg. 0.3526). The specific heat of lignin was somewhat less (avg. 0.3477), and that for extractives was substantially greater (avg. 0.4770).

Specific heat of wood.—For oven-dry whole wood representative of spruce pine trees throughout their major commercial range, Koch (1969) determined the specific heat in the interval 60° to 140° C.

$$\text{Specific heat} = 0.2651 + 0.001004 (\text{temperature in degrees C.}) \quad (9-14)$$

This equation accounted for 95.4 percent of the observed variation with a standard error of the estimate of 0.0072. Dunlap (1912) and Volbehr⁷ have shown that, for wood species in general, the relationship between

⁷ Volbehr, B. 1896. Swelling of wood fibers. Unpublished doctoral thesis. Kiel.

TABLE 9-5.—Regression equations of specific heat on temperature for chemical constituents of loblolly pine wood^{1,2} (data from McMillin 1970).

Constituent	Equation	Standard error of estimate	r ²
Holocellulose.....	$c_p = -0.01724 + 0.00099 (K)$	0.0124	0.880
Alpha-cellulose.....	$c_p = -0.01708 + 0.00099 (K)$	.0136	.858
Lignin.....	$c_p = 0.06133 + 0.00077 (K)$	.0134	.791
Extractives.....	$c_p = 0.06945 + 0.00109 (K)$	.0149	.890

¹ c_p = specific heat; K = temperature of observation in degrees Kelvin.

² Applicable within range of input data, i.e., 333° to 413°K.

TABLE 9-6.—*Specific heat of chemical constituents of loblolly pine wood*¹ (data from McMillin 1970)

Temperature of observation	Holocellulose	Alpha-cellulose	Lignin	Extractives
°K.	----- c_p -----			
333	0.3110	0.3107	0.3165	0.4292
373	.3573	.3572	.3486	.4853
413	.3904	.3900	.3780	.5166
Mean	.3529	.3526	.3477	.4770

¹ Each numerical value is the average of 10 within-sample observations.

specific heat and temperature is also linear in the range 0° to 100° C. (fig. 9-15).

From Koch's (1969) data on 1,296 specimens of earlywood and latewood of spruce pine, it also appeared that sapwood had a lower specific heat than heartwood.

Specimen location	Specific heat at		
	60°C.	100°C.	140°C.
Heartwood (avg. of 58)	0.3284	0.3703	0.4080
Sapwood (avg. of 1,238)	.3247	.3650	.4008

Latewood had higher specific heat than earlywood, but the difference was minute.

McMillin (1969) determined the specific heat of oven-dry loblolly pine wood in the range 333° to 413° K.

(9-15)

Specific heat = $0.0115321 + 0.0009497$ (temperature, degrees K.)

This equation accounted for 89 percent of the total variation in specific heat; the standard error was 0.0110 (fig. 9-15).

Moist wood has a higher heat capacity than the relative proportions of wood and water would suggest. Hearmon and Burcham (1955) found that the true heat capacity of moist wood less the calculated heat capacity on the basis of a simple mixture was equal to 0.054 calorie per gram of moist wood per degree C. when measured at 50° C. on beech sawdust at 25 percent moisture content.

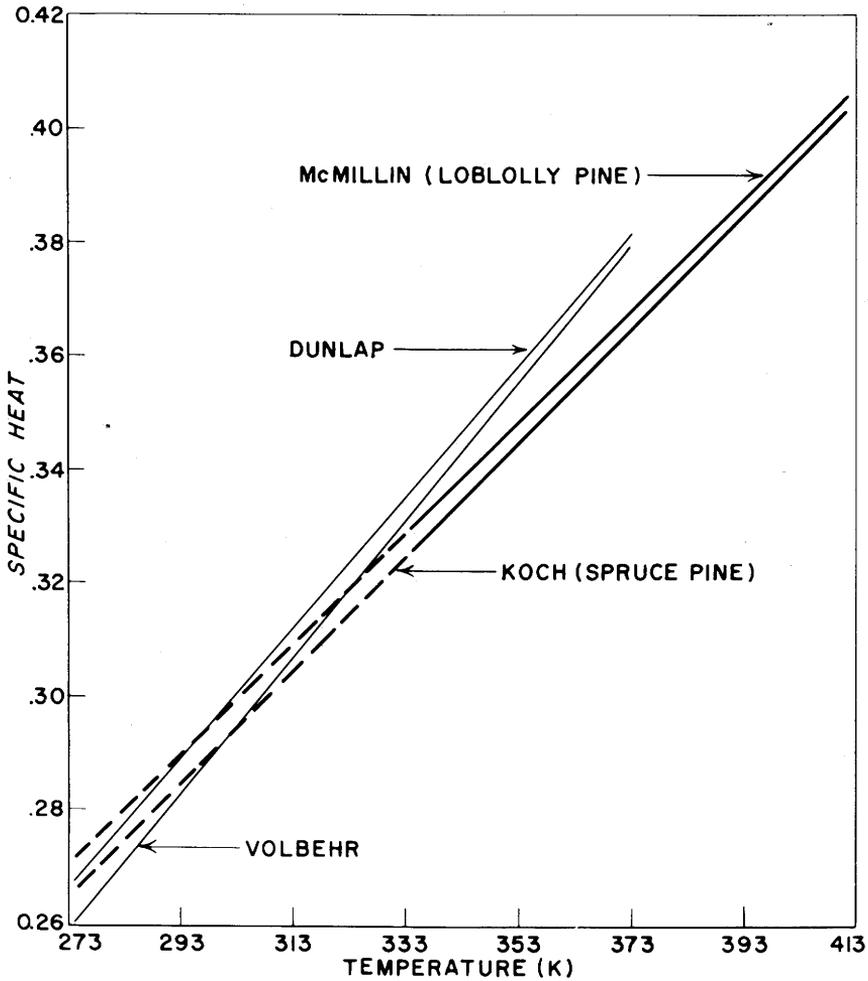


Figure 9-15.—Relationship of temperature (degrees Kelvin) to specific heat of overdry wood as reported by Dunlap, Volbehr, Koch, and McMillin. (Drawing after McMillin 1969.)

HEAT TRANSMISSIVITY⁸

Heat flow in wood is governed by the laws of diffusion. Two conditions of diffusion are of interest. The first, termed **steady state**, requires constant but different temperatures on each side of the wood product. In the second, called **unsteady state**, wood is either warming or cooling in response to changing temperatures.

⁸ Taken, with minor editorial changes, from Wangaard (1969) by permission of Frederick F. Wangaard and the Forest Products Research Society.

For steady-state heat flow, Fick's first law of diffusion can be written:

$$Q = kAt \left[\frac{T_1 - T_2}{x} \right] \quad (9-16)$$

where

Q = B.t.u.

k = thermal conductivity

A = area, sq. ft.

t = hr.

$T_1 - T_2$ = temperature difference °F.

x = thickness, in.

When x , A , t , and $T_1 - T_2$ are all unity, $k = Q = \text{B.t.u./in.}/\text{sq. ft./hr.}/^\circ\text{F.}$ or, in currently preferred form, $k = \text{B.t.u. inch per hr., sq. ft., }^\circ\text{F.}$ The dimensions of k are therefore $\text{B.t.u.} \times \text{in.} \times \text{hr.}^{-1} \times \text{ft.}^{-2} \times \text{ }^\circ\text{F.}^{-1}$. Thermal conductivity k may also be expressed in c.g.s. units as $\text{cal. per cm., sec., }^\circ\text{C.}$, having the dimensions $\text{cal.} \times \text{cm.}^{-1} \times \text{sec.}^{-1} \times \text{ }^\circ\text{C.}^{-1}$. Current preference under Standards Internationale employs watt-seconds instead of calories whereby thermal conductivity is expressed in watts per meter, $^\circ\text{C.}$ For the conversion of British to c.g.s. values of k , 1 B.t.u. inch per hr., sq. ft., $^\circ\text{F.} = 0.000345 \text{ cal. per cm. sec., }^\circ\text{C.}$, or 0.1444 watts per meter, $^\circ\text{C.}$ in units preferred by the International Standards Organization.

Under steady-state conditions the temperature gradient across a slab is essentially linear.

For the determination of temperature gradients in the unsteady-state—when wood is either warming or cooling—thermal diffusivity must be known.

The basic equation involves Fick's second law of diffusion:

$$du/dt = h^2 d^2u/dx^2 \quad (9-17)$$

where

du/dt = change in temperature with time

$\frac{du}{dx}$ = change in temperature with distance from surface.

In this equation h^2 is termed thermal diffusivity having the dimensions $\text{in.}^2 \times \text{sec.}^{-1}$. Thermal diffusivity h^2 can be calculated from k through the relation:

$$h^2 = k/cd \quad (9-18)$$

where, to illustrate appropriate units:

k = thermal conductivity, B.t.u. per second, inch, $^\circ\text{F.}$

d = density, pounds per cu. in.

c = heat capacity, B.t.u. per pound per $^\circ\text{F.}$

Knowing h^2 , the integration of $du/dt = h^2 d^2u/dx^2$ permits the calculation of temperature gradients for any specified condition of heating

by a rather complicated Fourier analysis. Graphical solutions are available for certain standardized conditions, however, that make for easy use of the relationship (MacLean 1942, 1943).

Following work by Gröber (1910), the guarded hot-plate method was developed by Poensgen (1912), adopted by the U. S. Bureau of Standards (Van Dusen 1920), and approved by the American Society for Testing Materials (ASTM Standard C177) as the standard procedure for determination of thermal conductivity (k) under steady-state conditions. Most of the available data on the thermal conductivity of wood have been obtained with this plate method.

A variable-state method involving a heat source and heat sink of known thermal capacity, which permits the simultaneous determinations of thermal conductivity (k) and specific heat (c), has been introduced (Clarke and Kingston 1950). As yet this method has been little used with wood.

Thermal conductivity.—Studies by Rowley (1933), Kollmann (1934), Wangaard (1940), and MacLean (1941) have supplied data on thermal conductivity of many tree species, and have established relationships between the transverse thermal conductivity of wood and its density and moisture content.

Thermal conductivity of wood increases with specific gravity (fig. 9-16), but is little affected by other species characteristics. Variations among individual shortleaf and longleaf pines (fig. 9-17) were similar to those among the species averages of figure 9-16.

MacLean (1941) and Kollmann (1934, 1951) expressed their results in the form of equations. MacLean's equation for thermal conductivity

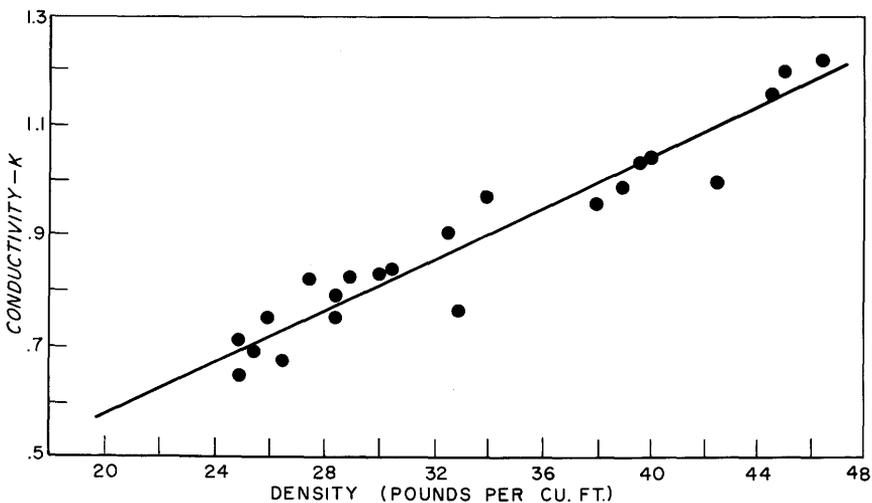


Figure 9-16.—Relation between conductivity and density at 12-percent moisture content, showing limited scatter of 22 individual species average values about the regression line. The units of k are B.t.u. inch per sq. ft., hr., °F. (Drawing after Rowley 1933.)

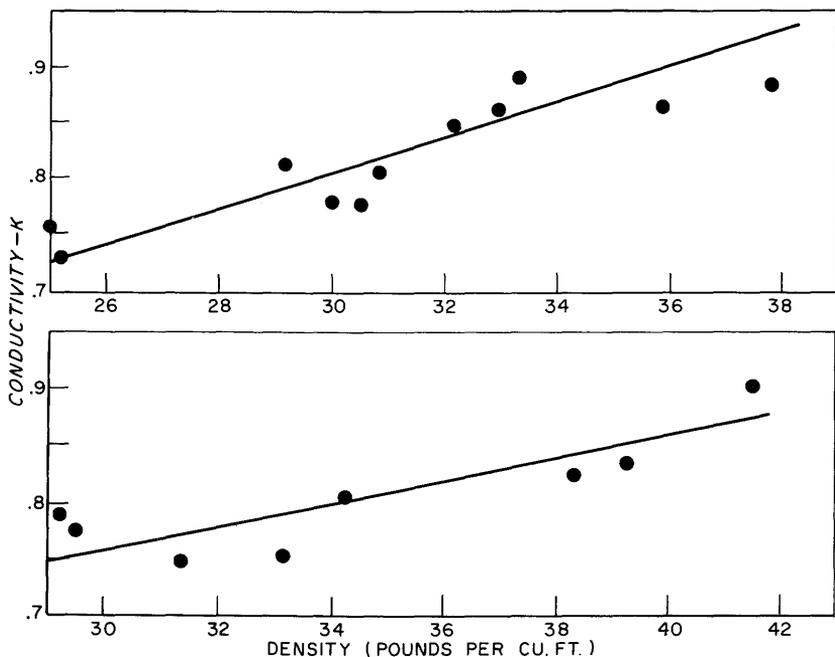


Figure 9-17.—Density-thermal conductivity relation for two species of southern pine at 0-percent moisture content. (Top) Shortleaf pine. (Bottom) Longleaf pine. k is expressed as B.t.u. inch per sq. ft., hr., °F. (Drawing after Rowley 1933.)

at moisture contents below the fiber saturation point, based on tests of 32 species, is:

$$k = S(1.39 + 0.028M) + 0.165 \quad (9-19)$$

where:

k = B.t.u. inch per sq. ft., hr., °F.

S = specific gravity based on oven-dry weight and volume at test

M = moisture content, percent

Kollmann (1951) expressed his results in an equation applicable at 12-percent moisture content as thermal conductivity in kilocalories/m., hr., °C.

$$\lambda = 0.168d_u + 0.022 \quad (9-20)$$

where:

d_u = density in g. per cc. including the weight of water

For purposes of conversion k in B.t.u. inch per hr. sq. ft., °F. = 8.05λ . The additive constant in each equation is approximately equal to the conductivity of still air. Wood derives its low thermal conductivity from the effective resistance to heat flow of air trapped in cell cavities and intercellular spaces.

Wangaard (1940) expressed his results, based on 236 tests on 40 species, combined with Rowley's (1933) 313 tests on 22 species, in an alignment chart relating thermal conductivity k to density (pounds of dry wood per cubic foot at time of test) and percent moisture content. The data were

subsequently reproduced (Wangaard 1943) employing parameters identical to those of MacLean (1941).

Figure 9-18A permits comparison of the result determined by these investigators at 12 percent as well as extrapolations of the MacLean and Wangaard curves to 0-percent moisture content at average temperatures

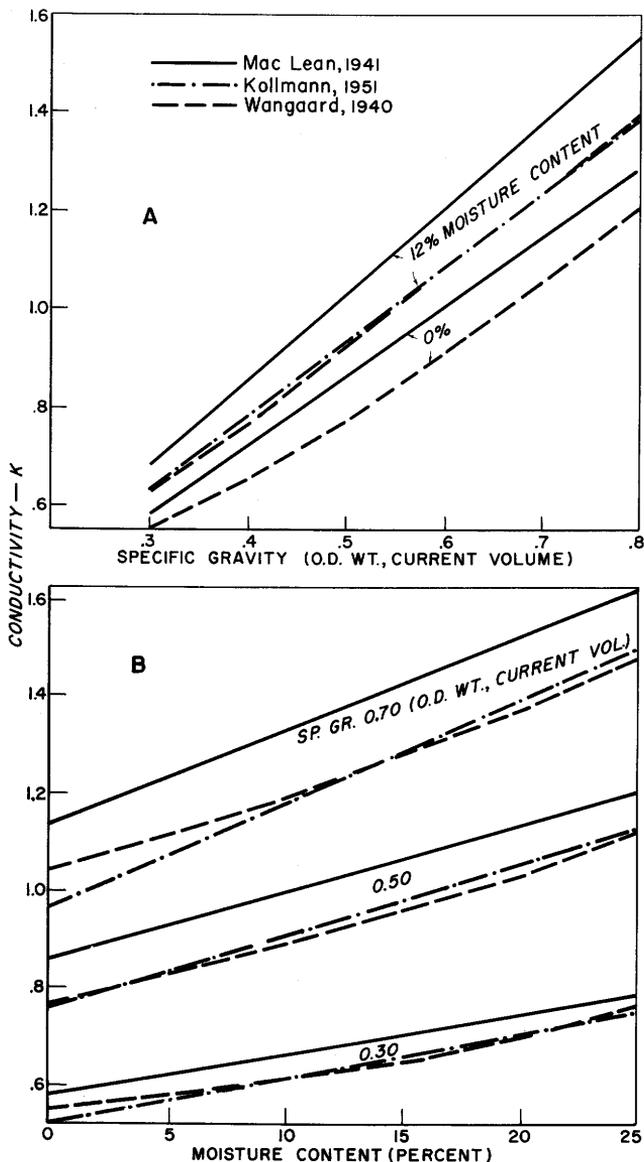


Figure 9-18.—Thermal conductivity k (B.t.u. inch per sq. ft., hr., °F.) of wood. (A) In relation to specific gravity at two levels of moisture content. (B) In relation to moisture content at three levels of specific gravity. (Drawings after Wangaard 1969.)

in the range of 75° to 85° F. The relationship between conductivity and specific gravity is quite well defined.

Thermal conductivity, k , is positively correlated with moisture content (fig. 9-18B). The curves of MacLean and Wangaard were drawn directly from their results as published. The curves attributed to Kollmann have been adapted from his equation for wood at 12-percent moisture content by a method suggested in Kollmann and Côté (1968). The similar slopes of the straight lines fitted by the least squares method to the MacLean and Kollmann data indicate essentially the same effect of moisture content. Wangaard's curvilinear regression line has a similar average slope, but shows a slight increase in slope with increasing moisture content. The steeper slopes shown at higher specific gravities result from greater absolute amounts of moisture change involved.

MacLean (1941) also found that above the fiber saturation point, the effect of moisture content change on heat conductivity was greater than at moisture contents below fiber saturation. He suggested that for moisture levels exceeding 40 percent, the following equation better represented his results (k in B.t.u. inch per hr., sq. ft., °F.):

$$k = s (1.39 + 0.038M) + 0.165 \quad (9-21)$$

The validity of estimating thermal conductivity k from specific gravity and moisture content regardless of other species characteristics is supported by MacLean's data in which 75 percent of the individual test specimens representing 32 species differed from his equation-derived values by less than 10 percent. The Wangaard-Rowley data showed a standard deviation of residuals about alignment chart values of 7.5 percent, hence in a normal distribution, 68 percent of the individual test values would be expected to lie within this limit. In these data the average deviation from alignment chart predictions for loblolly pine was +3.2 percent, for shortleaf +6.2 percent and for longleaf pine -0.4 percent. MacLean reported an average deviation for southern pine of only +0.9 percent from his equation-predicted values. The Rowley-Wangaard data showed no significant difference between radial and tangential conductivity in softwood species.

MacLean (1941) attributed species deviations from the thermal conductivity-specific gravity-moisture content relationship to differences in chemical composition, particularly in extractive content. He noted, however, that the resin content of the southern pines showed no effect on thermal conductivity. Wangaard (1943) reported that in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), significantly lower than normal thermal conductivity values were associated with small fibril angles in the S_2 layers of tracheid walls and values higher than normal by as much as 15 percent were associated with large fibril angles. The ratio of longitudinal to transverse thermal conductivity of Douglas-fir wood was also related to fibril angle, the ratio decreasing as fibril angle increased.

Thermal conductivity parallel to the grain is commonly considered to

range from $2\frac{1}{4}$ to $2\frac{3}{4}$ of that perpendicular to the grain (MacLean 1941; Kollmann and Côté 1968) and possibly somewhat higher (Wangaard 1943). An indication of the influence of fibril angle on the ratio of longitudinal to transverse thermal conductivity in latewood of slash pine is shown in figure 9-19.

Since determination of conductivity from such small specimens as excised latewood layers is difficult, values shown in figure 9-19 should be considered as relative rather than absolute. It is evident, however, that variations in thermal conductivity in southern pine are related to fibril angle.

The thermal conductivity of wood increases with increasing temperature. Kollmann (1951) gives an equation that may be expressed as

$$k_2 = k_1[1 + (1.1 - 0.98g)] \text{ per } 100^\circ\text{C. increase in temperature} \quad (9-22)$$

where:

g = specific gravity, oven-dry volume.

In the Fahrenheit temperature scale, wood having specific gravity of 0.50 has a temperature coefficient of thermal conductivity of $0.0034/^\circ\text{F.}$; in other words $k_2 = (1.0034)k_1$ for a 1°F. increase in temperature, or $k_2 = (1.34)k_1$ for a 100°F. increase in temperature. For a wood having specific gravity of 0.30 the corresponding temperature coefficient is $0.0045/^\circ\text{F.}$

Thermal conductivity through the thickness of plywood is essentially that of the same wood in the direction perpendicular to the grain (MacLean 1941).

Until recently the most extensive data available on the thermal conductivity of particleboard were those of Kollmann and Malmquist (1956),

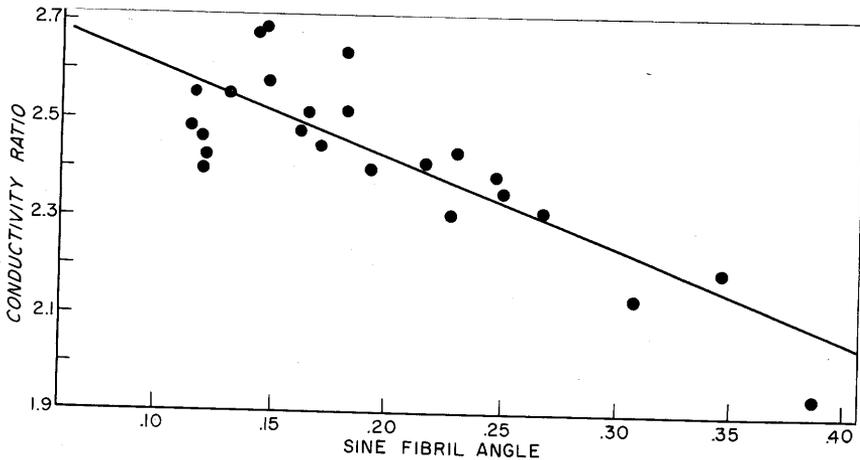


Figure 9-19.—Ratio of thermal conductivity parallel to grain to conductivity perpendicular to grain of latewood of slash pine as related to sine of fibril angle of S_2 layer. (Drawing after Wangaard et al. 1966.)

later reproduced by Kollman and Côté (1968). Conductivity values for particleboard, as for wood, are strongly dependent upon density, with little evidence of species influence. Values for particleboard, however, lie substantially below predicted values for wood of the same specific gravity.

Lewis (1967) reported thermal conductivity of platen-pressed fiberboards and particleboards ranging widely in density. All boards were tested in a standard hot-plate apparatus at 0-percent moisture content. The results shown in table 9-7 represent "design" values, a few percent higher than those actually found with the special laboratory-processed boards but in good agreement with results obtained on a number of American commercial boards. The plotted curves of Lewis (1967) are in good agreement with the ones published by Kollmann and Malmquist (1956) and Kollmann and Côté (1968). The latter authors explained the lower conductivity of particleboard as compared with wood on the basis of reduced internal thermal contact or "heat bridges." It is of interest to note that in a series of tests involving one extruded-type board along with several platen-pressed boards Ward and Skaar (1963) found that the extruded-type board showed a thermal conductivity through its thickness about 60 percent higher than that of the other boards.

It is evident that at comparable density, the thermal conductivity of fiberboard is less than that of particleboard (table 9-7). This is attributed to the greater number of smaller airspaces in the fiberboard contributing greater resistance. This difference in conductivity between fiberboard and particleboard was also found by Kollmann and Malmquist (1956) and is clearly shown in curves reproduced by Kollmann and Côté (1968). Lewis (1967) reported average increases in thermal conductivity k with temperature of 0.00053/°F. and 0.00093/°F. for fiberboard and particleboard, respectively.

A summary of thermal conductivity data on wood and wood-base materials and their application in building insulation has been published by the USDA Forest Products Laboratory (Lewis 1968).

Thermal Diffusivity.—Thermal diffusivity h^2 determines the rate of

TABLE 9-7.—*Thermal conductivity of fiberboard and particleboard, oven-dry, at 75° F. (data from Lewis 1967)*

Specific gravity	Thermal conductivity, k	
	Fiber-board	Particle-board
0.20	0.35	0.36
.40	.46	.52
.60	.57	.72
.80	.73	.94
1.00	.97	1.18

temperature change in wood or any other material when subjected to a change in ambient temperature. Transverse thermal diffusivity of wood is negatively correlated with both moisture content and specific gravity (fig. 9-20). Values for h^2 in this figure have been calculated from equation 9-18: $h^2 = k/cd$.

For overdry southern pine wood with a specific gravity of 0.51 for example, k at 85° F. from MacLean's equation = $1.39 (0.51) + 0.165 = 0.875$ B.t.u. inch per hr., sq. ft., °F., which, converted to B.t.u. per inch,

$$\text{sec., } ^\circ\text{F.} = \frac{0.875}{144 \times 3600} = 0.00000168.$$

$$d = 0.51 \text{ g./cc. which, converted to lb./cu.in.}$$

$$= \frac{0.51 \times 62.4}{1728} = 0.0184.$$

c at 85°F., calculated from the data of Koch (1969) for spruce pine = 0.294 B.t.u./lb./°F.

$$h^2 = \frac{0.00000168}{0.294 \times 0.0184} = 0.000310 \text{ in.}^2/\text{sec.}$$

At 12-percent moisture content the calculation is similar except that c is calculated by simple weighting of the specific heats of water and dry wood as recommended by Kollmann and Côté (1968) :

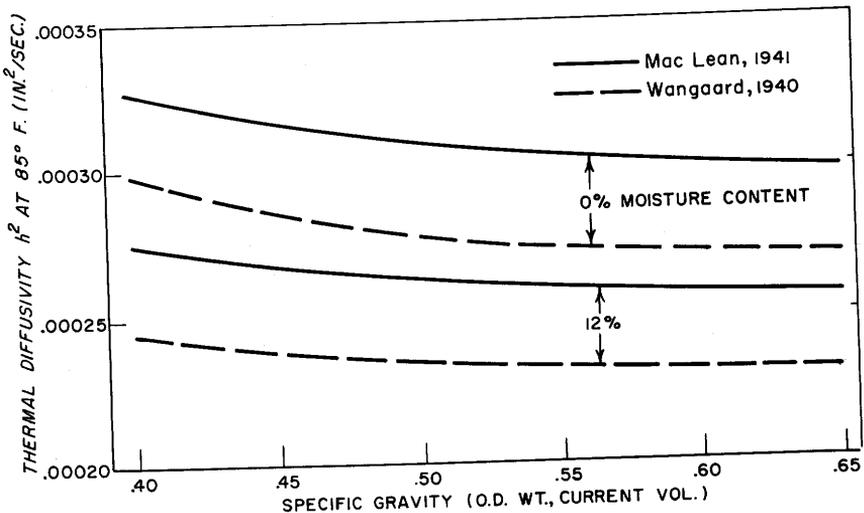


Figure 9-20.—Thermal diffusivity h^2 of wood in relation to specific gravity and moisture content. (Drawing after Wangaard 1969.)

$$c = \frac{0.12 + 0.294}{1.12} = 0.369 \text{ B.t.u./lb./}^\circ\text{F.}$$

$$\text{and } h^2 = \frac{0.00000202}{0.369 \times 0.0205} = 0.000265 \text{ in.}^2/\text{sec.}$$

Since this disregards the increase in specific heat of moist wood beyond that derived by simple weighting (Hearmon and Burcham 1955; Kelsey and Clarke 1955), the calculated value of h^2 may be slightly too high.

The values of thermal diffusivity (h^2) shown for wood in figure 9-20 were calculated from the conductivity data of MacLean (1941) and Wangaard (1940) for the specific gravity range common to the southern pines. Thermal diffusivity (h^2) decreases slightly with increasing specific gravity. At 12-percent moisture content and 0.55 specific gravity, MacLean's and Wangaard's data yield h^2 values of 0.000260 and 0.000235 in.²/sec. respectively. By comparison, an h^2 value of 0.000210 in.²/sec. was derived independently from unsteady-state measurements of southern pine heated under conditions controlled to maintain 12-percent moisture content (MacLean 1942, 1943).

By similar calculation the thermal diffusivity of fiberboard can be determined. At specific gravity 0.20, fiberboard has a k value at 85° F. of 0.35 B.t.u. inch per sq. ft., hr., °F. and a diffusivity (h^2) value of 0.000322 in.²/sec., whereas hardboard at a specific gravity of 1.00 has a k value of 0.975 B.t.u. inch per sq. ft., hr., °F. and $h^2 = 0.000177$ in.²/sec. Under similar conditions the thermal diffusivity of particleboard having a specific gravity of 0.60 is calculated to be 0.000221 in.²/sec.

HEAT OF COMBUSTION⁹

Heat of combustion is defined as the quantity of heat evolved by the complete combustion of a unit mass of substance in an enclosure of constant volume. As used in this text, it is the total amount of heat obtainable from oven-dry material, allowing no deductions for heat losses. The available heat obtained by burning in open systems is considerably less, as heat is permitted to escape in the form of steam and other gases.

In oxygen-bomb calorimetry, a weighed sample is burned in an oxygen-filled metal "bomb" submerged in a measured quantity of water, all held within an insulated chamber. By observing the rise in water temperature resulting from the explosive combustion of the sample, the number of heat units liberated may be calculated. Corrections must be made to compensate for the heat of formation of nitric acid from atmospheric nitrogen

⁹ Data under this heading are taken from Howard, E. T. Heat of combustion of loblolly pine wood, southern pine earlywood, spruce pine bark, resinous knots and mixed southern pine bark, needles, and rootwood. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.35 dated May 15, 1971.

present and heat of combustion of the fuse wire. The values obtained provide a basis for comparison of fuels.

Heat of combustion of woody material varies considerably with chemical content. Resin, tannins, lignin, terpenes, and waxes have high heat content; carbohydrates are relatively low in heat. Brown et al. (1952) state that hardwoods contain 8,300 to 8,700 B.t.u. per oven-dry pound, whereas heat of combustion of softwoods ranges from 9,000 to 9,700 B.t.u. per pound of dry wood. The higher values for conifers is attributed to their greater resin and lignin content.

The calorific value of wood is negatively correlated with moisture content. Kollmann and Côté (1968, p. 150) give the heat value of oven-dry wood as about 8,100 B.t.u. per pound, of air-dry wood as about 6,840 B.t.u. per pound, and of wood at 30-percent moisture content as about 5,940 B.t.u. per pound. Parr and Davidson (1922) reported a value of 8,836 B.t.u. (dry wood basis) for pine; at 8.88-percent moisture content, heat value was 8,050 B.t.u. per pound.

Howard⁹ has provided data specific to southern pine; her data are summarized in table 9-8.

Resin, charcoal, resin-impregnated wood, and needles.—Of the materials tested, liquid resin collected from injured trees had the highest heat of combustion (14,625 to 16,250 B.t.u. per pound). Charcoal briquets sampled averaged 12,335 B.t.u. per oven-dry pound, a value somewhat

TABLE 9-8.—*Heat of combustion of various oven-dry materials from southern pine trees (data from Howard⁹)*

Material	Average	Range
	— B.t.u. per oven-dry pound —	
Resin		14,625 to 16,250
Charcoal	12,335	11,225 to 12,740
Resinous stumpwood		10,250 to 10,840
Decay-resistant knots		10,140 to 11,490
Needles	9,030	8,935 to 9,105
Mixed bark		
One foot above ground	8,985	8,870 to 9,140
Mid-height	8,825	8,650 to 8,910
4-inch top	8,700	8,550 to 8,835
Loblolly pine stemwood	8,600	8,310 to 9,352
Earlywood	8,610	8,470 to 8,760
Latewood	8,585	8,385 to 8,755
Rootwood	8,605	8,560 to 8,680
Spruce pine bark		
One foot above ground	8,705	8,310 to 9,105
Mid-height	8,595	8,040 to 8,975
4-inch top	8,550	8,170 to 8,920
Tops (bark and wood at 1-inch top)	8,395	8,015 to 8,745
Old cones	8,130	8,085 to 8,190
Kraft black liquor	5,965	5,820 to 6,130

lower than that for pure carbon, 14,100 B.t.u. Probably the ash content of the briquets, and the low heat value of the binder starch used in their manufacture accounts for this difference.

Heat of combustion of stumpwood from old longleaf pines was positively correlated with stumpwood extractive content as follows:

Specific gravity class (basis of unextracted ovendry weight and volume)	Heat of combustion	Extractive content
	<i>B.t.u. per ovendry pound</i>	<i>Percent</i>
0.86-0.99	10,460	26.9
1.00-1.06	10,610	31.3
1.07-1.16	10,785	35.4

Resinous decay-resistant knots collected from the forest floor beneath a longleaf stand had heats of combustion positively correlated with extractive content as follows (unextracted specific gravity of the knots evaluated was about 1.0, basis of ovendry volume and weight):

Heat of combustion	Extractive content
<i>B.t.u. per ovendry pound</i>	<i>Percent</i>
10,230	28.7
10,320	29.4
10,400	32.8
11,225	39.9

Composite samples of needles assembled from single trees of each of the four major species had higher heat value (9,030 B.t.u. per ovendry pound) than either wood or bark. Alcohol-benzene extractive content of the needles was 28.8 percent.

In an evaluation of Virginia pine needles, Madgwick found an almost identical value (9,035 B.t.u. per ovendry pound). Hough (1969) measured the heat of combustion of needles from three other pine species with results as follows: loblolly, 8,900 B.t.u.; sand, 9,615 B.t.u.; and slash, 9,370 B.t.u. per ovendry pound.

Bark.—To evaluate the heat of combustion of bark, Howard sampled one mature tree of each of the southern pine species, varieties, and races (exclusive of spruce pine); an equal weight of bark from each tree was mixed into composite 11-tree samples (taken from three heights) with results as shown in table 9-8; bark heat of combustion was negatively correlated with height above ground. Sufficient data to determine a statistically valid average value are not available, but bark from the major southern pines probably averages close to 8,900 B.t.u. per ovendry pound.

This estimated average value is somewhat lower than that reported by Chang and Mitchell (1955) for slash pine bark at 6.4-percent moisture content (9,002 B.t.u. per pound); it is higher, however, than that reported by Madgwick (1970) who determined that stem bark of Virginia pine had a heat of combustion of 8,425 B.t.u. per ovendry pound.

Howard⁹ found that spruce pine bark had a lower heat of combustion than a composite bark sample from the other southern pine species. Spruce pine trees 15, 30, and 45 years old, both fast grown and slow grown, were sampled throughout the major range of the species. In all 72 trees cut, bark samples were evaluated 1 foot above ground level, at a 4-inch top, and halfway between. Heat of combustion of spruce pine bark was negatively correlated with height in the tree (fig. 9-21).

Stemwood and rootwood.—To evaluate the heat of combustion of stemwood of loblolly pine, 50 mature trees were felled in central Louisiana and portions of the stemwood were factorially divided into classes of high and low specific gravity, fast and slow growth, and three radial positions. Average heat of combustion for the loblolly pine evaluated was 8,600 B.t.u. per oven-dry pound. Heat value was not strongly related to growth rate or specific gravity but was negatively correlated with number of rings from the pith as follows:

<u>Rings from pith</u>	<u>Heat of combustion</u> <i>B.t.u. per oven-dry pound</i>
0-10	8,795
11-20	8,565
21-30	8,445

Extractive content in loblolly pine stemwood proved to have a strong positive correlation with heat of combustion (fig. 9-22); the proportions of other chemical constituents, however, had only minor effects on heat value.

To compare the heat of combustion of earlywood and latewood, com-

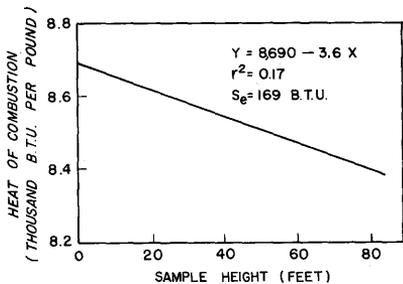


Figure 9-21.—Heat of combustion of oven-dry spruce pine bark related to height in tree. (Drawing after Howard.⁹)

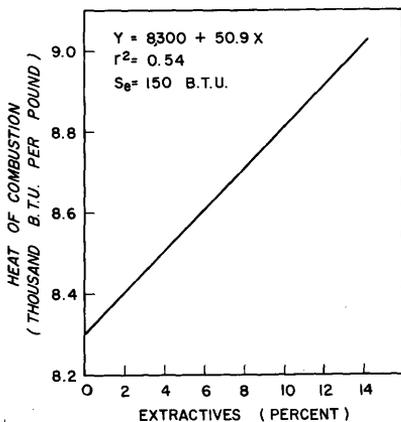


Figure 9-22.—Correlation between heat of combustion of oven-dry loblolly pine stemwood and alcohol-benzene extractive content. (Drawing after Howard.⁹)

posite samples comprised of stemwood from twelve mature southern pines (one tree of each species, variety, or race) were assembled. For each tree, a 15-degree wedge, one-inch-thick, was taken from each of three heights—one foot above ground, one-third of tree height, and two-thirds of tree height. Wedges from the three heights were chipped and combined into one sample per tree. Seventy-two chips from each tree were randomly selected and dissected into earlywood and latewood. Two samples were mixed—one composed of two grams of earlywood per tree and the other consisting of two grams of latewood per tree. Eighteen replications were made of earlywood and eighteen of latewood. The heat of combustion of the two types of tissue proved not significantly different; both averaged about 8,600 B.t.u. per oven-dry pound. Similarly, rootwood from the same 12 trees averaged about 8,600 B.t.u. per oven-dry pound.

Madgwick's (1970) data for Virginia pine compare closely with these values; he determined that stemwood of trees 18 to 59 years of age had a heat of combustion of 8,532 B.t.u. per oven-dry pound.

Tops and cones.—A composite sample of mixed wood and bark from 1-inch tops was prepared by Howard⁹ from a single tree of each of the 12 species, varieties, and races; heat of combustion of this material was lower than that of stemwood or bark; it averaged 8,395 B.t.u. per oven-dry pound. This value is not much different than that obtained by Madgwick (1970) for branches from the live crown (not including needles) of 17-year-old Virginia pine (8,875 B.t.u. per oven-dry pound).

Howard's⁹ composite sample comprised of an equal weight of dry, open cones from each of the 4 major southern pine species averaged 8,130 B.t.u. per oven-dry pound.

Madgwick (1970) found that the male flowers of Virginia pine at time of pollen shed had a heat of combustion of 9,018 B.t.u. per oven-dry pound.

Kraft black liquor.—Evaporated black liquor from a Louisiana kraft pulp mill (southern pine) proved to have a heat value of only 5,965 B.t.u. per oven-dry pound; this low value was reasonable since the resins and fatty acids had been removed prior to sampling.

THERMAL EXPANSION AND CONTRACTION

Dry southern pine, like most woods and other solids, expands when heated and contracts when cooled. The **coefficient of linear expansion**—defined as the increase in length per unit length for a temperature rise of 1°C. differs in the three different structural directions of wood.

Weatherwax and Stamm (1947) evaluated the thermal linear expansion coefficients of nine species of hardwoods and softwoods; their study did not, however, include any of the southern pines. Stamm (1964, p. 289) noted that coefficients of thermal linear expansion in the fiber direction were found to be virtually independent of species and specific gravity; all values were within the range from 3×10^{-6} to 5×10^{-6} per °C. All

the softwoods they tested gave radial and tangential coefficients of linear expansion that varied with specific gravity as follows:

$$C_r = (56G)(10^{-6}) \quad (9-23)$$

$$C_t = (81G)(10^{-6}) \quad (9-24)$$

where:

C_r is radial coefficient of linear expansion per °C.

C_t is tangential coefficient of linear expansion per °C.

G is specific gravity (basis of oven-dry volume and weight)

To compute the probable increase (or decrease) in dimension with a given increase (or decrease) in temperature, the dimension of the piece is multiplied by the appropriate coefficient and again by the change in temperature (°C.).

Although the coefficient of linear expansion varies slightly with temperature, for all ordinary uses it may be considered constant (Weatherwax and Stamm 1947).

The coefficient of linear thermal expansion in the longitudinal direction of wood is one-tenth to one-third that of the common metals, concrete, and glass. The values for wood in the transverse directions, although larger than those in the longitudinal direction, are usually less than those of other structural materials.

Data and computations from Weatherwax and Stamm (1947) indicate that southern pine plywood probably has coefficients of linear expansion not much greater than those for longitudinal expansion of solid wood.

The USDA Forest Products Laboratory (1955, p. 48) notes that the coefficient of thermal expansion of wood can be neglected in most structural designs, because the thermal expansion is much smaller than the swelling and shrinking of the wood that occurs under normal exposure conditions. Thermal expansion is of importance only in the case of special structures that are kept dry and are subjected to considerable temperature change.

Green wood behaves differently from dry wood when heated; it expands tangentially and shrinks radially. A discussion of this behavior and of the rate of temperature change in wood when heated is beyond the scope of this text, but information may be found in MacLean (1946, 1951, 1952).

9-5 ELECTRICAL PROPERTIES ¹⁰

There are few data published on the electrical properties of southern pine wood. Readers desiring additional information on electrical proper-

¹⁰ The text under this heading is taken from USDA Forest Products Laboratory (1955, pp. 48-52).

ties of wood species in general will find discussions by Stamm (1964, pp. 359-385), Kollmann and Côté (1968, pp. 199, 257-274) and Lin¹¹ useful.

The most important electrical properties of wood are its resistance to the passage of an electric current and its dielectric properties. The electrical resistance of wood, which is the reciprocal of the conductance, is utilized in electric meters for determining the moisture content of wood (Dunlap and Bell 1951). It is of importance in connection with the use of wood poles and crossarms to carry high-voltage electrical powerlines and wood handles on linemen's tools. The dielectric properties—dielectric constant and power factor—assume importance when wood is heated in an oscillating high-frequency electric field, as in the curing of glues, and in connection with some moisture meters.

ELECTRICAL RESISTANCE

The direct-current electrical resistance of wood (Hiruma 1913; Hasselblatt 1926; Stamm 1927, 1930) varies greatly with moisture content, especially below the fiber saturation point of 30 percent, decreasing as the moisture content increases. It also varies with species, is greater across the grain than along it, and approximately doubles for each drop in temperature of 22.5°F. The electrical resistance varies inversely with the density of the wood. Fortunately, the electrical resistance is affected so much more by variations in moisture content that the effect of density of the wood on moisture content determinations by the resistivity method is not highly significant. The variation among species is probably caused by minerals or electrolytic materials in the wood or dissolved in water present in the wood.

Table 9-9 lists the electrical resistance along the grain of shortleaf and longleaf pine and Douglas-fir at different uniform values of moisture content, between needle electrodes driven each time to the same depth. The specific resistance, which is the resistance of a centimeter cube of wood, varies from 3×10^{17} to 3×10^{18} ohm-centimeters for oven-dry wood to 10^8 ohm-centimeters for wood at 16-percent moisture content (Weatherwax and Stamm 1945).

Since the electrical resistance of wood may increase as much as 10^5 times with a moisture content change from 25 to 7 percent, the moisture content of wood used as an insulator, as in powerline poles or tool handles, is highly important. The leakage of current from powerlines increases with increase in the moisture content of the crossarms and poles. Salts should not be used as a preservative treatment for powerline poles, since the salt dissolved in the water of the wood causes an additional lowering of the electrical resistance.

¹¹ Lin, R. T. Electrical properties of southern pine wood—a review. Presentation at a symposium, "Utilization of the southern pines," Alexandria, La. November 6-8, 1968.

DIELECTRIC PROPERTIES

At a low moisture content, wood is normally classified as an electrical insulator, or dielectric, rather than as a conductor (Skaar 1948). A dielectric can be heated by using it as the medium between electrodes carrying charges of oscillating high-frequency electricity or placing it in an

TABLE 9-9.—Average electrical resistance along the grain of wood in two southern pine species and Douglas-fir at various moisture contents, measured at 80°F. between two pairs of needle electrodes 1- $\frac{1}{4}$ inches apart and driven to a depth of $\frac{5}{16}$ inch (USDA Forest Products Laboratory 1955)

Moisture content	Longleaf pine	Shortleaf pine	Douglas-fir
Percent	----- Megohm -----		
7	25,000	43,600	22,400
8	8,700	11,750	4,780
9	3,160	3,720	1,660
10	1,320	1,350	630
11	575	560	265
12	270	255	120
13	135	130	60
14	74	69	33
15	41.7	38.9	18.6
16	24.0	22.4	11.2
17	14.4	13.8	7.1
18	8.9	8.7	4.6
19	5.76	5.76	3.09
20	3.72	3.80	2.14
21	2.46	2.63	1.51
22	1.66	1.82	1.10
23	1.15	1.29	.79
24	.79	.93	.60
25	.60	.66	.46

electrical field of like nature. This property is utilized in the curing of glue lines in wood by high-frequency electric current. The rate at which the wood is heated and electrical power is absorbed depends on the dielectric constant and the power factor. The resistivity of a dielectric can be determined by formula (Skaar 1948) from the relationship between the dielectric constant and the power factor, and when wood and glue lines are heated, the relative power absorbed in the wood and in the glue lines can be calculated from the resistivity values and dimensions of the wood and glue lines.

The dielectric constant of wood is the ratio of the capacitance of a condenser in which the wood is used as the dielectric to the capacitance of a similar condenser in which a vacuum dielectric is employed. The

capacitance of a condenser is measured by the quantity of electricity put into it by a given voltage. The dielectric constant for a vacuum or dry air is unity, and the values for wood are all greater than unity. Since the structure and chemical composition of the cell walls of all species are essentially similar, it is not surprising that the dielectric constants are proportional to density at a given moisture content. The dielectric constant of wood increases with increase in density, and since the dielectric constant of water is approximately 81 as compared to 4.2 for oven-dry wood, it is evident that the dielectric constant of wood also increases with increase in moisture content. Variations in moisture content have a greater effect on the dielectric constant than do variations in density. The parallel-to-grain dielectric constant of wood is significantly greater than the corresponding perpendicular-to-grain constant. The dielectric constant of wood decreases with an increase in frequency of the oscillating current.

The power factor of wood is the ratio of the power absorbed in the wood per cycle of oscillation of an electric current to the total apparent power stored in the wood during that cycle. The power factor of wood is less dependent on density than is the dielectric constant but generally increases with increase in moisture content. At moisture content values of 0 to 7 percent, the parallel-to-grain power factors are greater than the corresponding perpendicular-to-grain power factors. The power factor varies with the frequency of the oscillating current and is greater at high frequencies when the wood is at a moisture content of 15 percent or lower.

9-6 LITERATURE CITED

- Berendt, R. D., Winzer, G. E., and Burroughs, C. B.
1968. A guide to airborne, impact, and structure borne noise; control in multifamily dwellings. A report to the Federal Housing Administration by the National Bureau of Standards. 414 pp.
- Bererek, L. L., (Ed.).
1960. Noise reduction. 752 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Brown, H. P., Panshin, A. J., and Forsaith, C. C.
1952. Textbook of wood technology. Vol. II, 783 pp. N.Y.: McGraw-Hill.
- Chang, Y. P., and Mitchell, R. L.
1955. Chemical composition of common North American pulpwood barks. TAPPI 38: 315-320.
- Clarke, L. N., and Kingston, R. S. T.
1950. Equipment for the simultaneous determination of thermal conductivity and diffusivity of insulating materials using a variable-state method. Australian J. Appl. Sci. 1(2): 172-187.
- Cremer, L.
1953. Calculation of sound propagation in structures. Acustica 3: 317-335.
- Dunlap, F.
1912. The specific heat of wood. USDA Forest Serv. Bull. 110, 28 pp.
- Dunlap, M. E., and Bell, E. R.
1947. Electrical moisture meters for wood. USDA Forest Serv. Forest Prod. Lab. Rep. R1660, 14 pp. Madison, Wis.
- Federal Housing Administration.
1963. Impact noise control in multifamily dwellings. Fed. Housing Admin. 750, 86 pp. Wash., D.C.

- Galligan, W. L., and Courteau, R. W.
1965. Measurement of elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. *In* Proceedings of second symposium on the non-destructive testing of wood, pp. 223-244. Pullman, Wash.: Wash. State Univ.
- Godshall, W. D., and Davis, J. H.
1969. Acoustical absorption properties of wood-base panel materials. USDA Forest Serv. Res. Pap. FPL-104, 8 pp. Forest Prod. Lab., Madison, Wis.
- Grantham, J. B.
1970. Field measurement of sound insulation provided by wood-framed apartment walls. *Forest Prod. J.* 20(4): 51-59.
- Gray, V. R.
1963. The colour of wood and its changes. *Timber Res. and Develop. Assoc. Adv. Serv. Leaflet* 12, 2 pp.
- Gröber, H.
1910. Wärmeleitfähigkeit von Isolier- und Baustoffen. *Z. Ver. Deut. Ing.* 54: 1319-1324.
- Hasselblatt, M.
1926. [The aqueous vapor tension and the electrical conductivity of wood in relation to its water content.] *Z. Anorg. Allg. Chem.* 154: 375-385.
- Hearmon, R. F. S., and Burcham, J. N.
1955. Specific heat and heat of wetting of wood. *Nature* 176: 978.
- Hiruma, J.
1913. Experiments on the electrical resistance of wood. *Bul. Forest Exp. Sta., Meguro, Tokyo*, 10: 59-65.
- Hough, W. A.
1969. Caloric value of some forest fuels of the southern United States. USDA Forest Serv. Res. Note SE-120, 6 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Ingemansson, S., and Kihlman, T.
1959. Sound insulation of frame walls. *Chalmers Univ. Technol. Trans.* 222: 1-47. Gothenburg, Sweden.
- James, W. L.
1964. Vibration, static strength, and elastic properties of clear Douglas-fir at various levels of moisture content. *Forest Prod. J.* 14: 409-413.
- Jayne, B. A.
1959. Indices of quality—vibrational properties of wood. *Forest Prod. J.* 9: 413-416.
- Judd, D. B., and Wyszecki, G.
1963. Color in business, science and industry. Ed. 2, 500 pp. N.Y.: John Wiley & Sons, Inc.
- Kelsey, K. E., and Clarke, L. N.
1955. Effect of temperature and initial moisture content on the heat of wetting of wood. *Nature* 176: 83-84.
- Koch, P.
1969. Specific heat of oven-dry spruce pine wood and bark. *Wood Sci.* 1: 203-214.
- Koch, P., and Woodson, G. E.
1968. Laminating butt-jointed, log-run, southern pine veneers into long beams of uniform high strength. *Forest Prod. J.* 18(10): 45-51.
- Kollmann, F.
1934. Über die wärmetechnischen Eigenschaften der Hölzer. *Gesundheits-Ing.* 57(18): 224-227.
- Kollmann, F.
1951. Technologie des Holzes und der Holzwerkstoffe. Vol. 1, ed. 2. 1050 pp. Berlin: Springer-Verlag.
- Kollmann, F. F. P., and Côté, W. A., Jr.
1968. Principles of wood science and technology. I. Solid wood. 592 pp. N.Y.: Springer-Verlag New York, Inc.
- Kollmann, F., and Malmquist, L.
1956. Über die Wärmeleitfähigkeit von Holz und Holzwerkstoffen. *Holz als Roh und Werkstoff* 14: 201-204.
- Kosten, C. W.
1953. Behaviour of Absorbing materials. *In* Technical aspects of sound, Vol. 1, pp. 49-104. E. C. Richardson, ed. N.Y.: Elsevier Publishing Company.

- Lemoine, T. J., McMillin, C. W., and Manwiller, F. G.
1970. Wood variables affecting the friction coefficient of spruce pine on steel. *Wood Sci.* 2: 144-148.
- Lewis, W. C.
1967. Thermal conductivity of wood-base fiber and particle panel materials. USDA Forest Serv. Res. Pap. FPL-77, 12 pp. Forest Prod. Lab., Madison, Wis.
- Lewis, W. C.
1968. Thermal insulation from wood for buildings: effects of moisture and its control. USDA Forest Serv. Res. Pap. FPL-86, 43 pp. Forest Prod. Lab., Madison, Wis.
- London, A.
1949. Transmission of reverberant sound through single walls. *J. Res. Nat. Bur. Stand.* 42: 605-615.
- London, A.
1950. Transmission of reverberant sound through double walls. *J. Acoust. Soc. Amer.* 22: 270-279.
- Lyon, R. H., and Maidanik, G.
1964. Statistical methods in vibration analysis. *J. Amer. Inst. Aeron. and Astronaut.* 2: 1015-1024.
- MacLean, J. D.
1941. Thermal conductivity of wood. *Heating, Piping and Air Conditioning* 13: 380-391.
- MacLean, J. D.
1942. The rate of temperature change in wood panels heated between hot plates. USDA Forest Serv. Forest Prod. Lab. Rep. 1299, 38 pp.
- MacLean, J. D.
1943. Rate of temperature change in laminated timbers heated in air under controlled relative humidity conditions. USDA Forest Serv. Forest Prod. Lab. Rep. 1434, 30 pp.
- MacLean, J. D.
1946. Temperatures obtained in timbers when the surface temperature is changed after various periods of heating. USDA Forest Serv. Forest Prod. Lab. Rep. R1609, 45 pp. Madison, Wis.
- MacLean, J. D.
1951. Rate of disintegration of wood under different heating conditions. *Amer. Wood Preserv. Assoc. Proc.* 47: 155-169.
- MacLean, J. D.
1952. Effect of temperature on the dimensions of green wood. *Amer. Wood-Preservers' Assoc. Proc.* 48: 136-157.
- Madgwick, H. A.
1970. Caloric values of *Pinus virginiana* as affected by time of sampling, tree age, and position in stand. *Ecology* 51: 1094-1097.
- Mariner, T., and Hehmann, H. W. W.
1967. Impact-noise rating of various floors. *J. Acoust. Soc. Amer.* 41: 206-214.
- Marra, G. G., Pellerin, R. F., and Galligan, W. L.
1966. Nondestructive determination of wood strength and elasticity by vibration. *Holz als Roh- und Werkstoff* 10: 460-466.
- McMillin, C. W.
1969. Specific heat of oven-dry loblolly pine wood. *Wood Sci.* 2: 107-111.
- McMillin, C. W.
1970. Specific heat of some oven-dry chemical constituents of loblolly pine wood. *Wood Sci.* 3: 52-53.
- McMillin, C. W., Lemoine, T. J., and Manwiller, F. G.
1970a. Friction coefficient of oven-dry spruce pine on steel, as related to temperature and wood properties. *Wood and Fiber* 2: 6-11.
- McMillin, C. W., Lemoine, T. J., and Manwiller, F. G.
1970b. Friction coefficient of spruce on steel—a note on lubricants. *Wood Sci.* 3: 100-101.
- Miller, D. G.
1968. Nondestructive testing of joists by a vibrational technique. *Forest Prod. J.* 18(2): 25-28.
- Miller, D. G., and Tardif, Y.
1967. Development of a vibration grader and comparison of vibration grading with visual and mechanical grading. *Can. Dep. Forest. and Rural Develop. Pub.* 1208, 24 pp.

- Moslemi, A. A.
1967. Quantitative color measurement for black walnut wood. USDA Forest Serv. Res. Pap. NC-17, 16 pp. N. Cent. Forest Exp. Sta., St. Paul, Minn.
- Moslemi, A. A.
1969. Quantitative color characterization for loblolly pine veneer. *Wood Sci.* 2: 61-64.
- National Association of Home Builders Research Foundation.
1967. Field study of residential acoustics—acoustical performance of apartments and occupant's responses. 129 pp. Rockville, Md.: NAHB Research Foundation, Inc.
- Owens-Corning Fiberglas Corporation.
1969. Solutions to noise control problems in apartments, motels and hotels. Owens-Corning Fiberglas Corp. Pub. 1-BL-4589, 43 pp. Toledo, Ohio.
- Parkin, P. H., Purkis, H. J., and Scholes, W. E.
1960. Field measurements of sound insulation between dwellings. *Nat. Bldg. Stud. Res. Pap.* 33, 571 pp. London.
- Parr, S. W., and Davidson, C. N.
1922. The calorific value of American woods. *J. Ind. and Eng. Chem.* 14: 935-936.
- Pellerin, R. F.
1965. A vibrational approach to nondestructive testing of structural lumber. *Forest Prod. J.* 15: 93-101.
- Pew, J. C., and Connors, W. J.
1971. Color of coniferous lignin. *TAPPI* 54: 245-251.
- Poensgen, R.
1912. Ein technisches Verfahren zur Ermittlung der Wärmeleitfähigkeit plattenförmiger Stoffe. *Z. Ver. Deut. Ing.* 56: 1653-1658.
- Prestemon, D. R.
1970. Wood frame walls and floors as noise barriers. *Forest Prod. J.* 20(7): 47-48.
- Reiher, H., Goesele, K., and Jehle, R.
1960. Schalltechnische Untersuchungen an Holzbalkendecken. *In Schallschutz von Bauteilen*, pp. 47-57. Berlin: Wilhelm Ernst & Sohn.
- Rowley, F. B.
1933. The heat conductivity of wood at climatic temperature differences. *Heating, Piping and Air Conditioning* 5: 313-323.
- Schoch, A., and Feher, K.
1952. The mechanism of sound transmission through single leaf partitions, investigated using small scale models. *Acustica* 2: 189-204.
- Schultz, T. J.
1969. Acoustical properties of wood: a critique of the literature and a survey of practical applications. *Forest Prod. J.* 19(2): 21-29.
- Skaar, C.
1948. The dielectric properties of wood at several radio frequencies. N.Y. State Coll. Forest. at Syracuse Univ. Tech. Pub. 69, 36 pp.
- Stamm, A. J.
1927. Electrical resistance of wood as a measure of the moisture content. *Indus. and Engin. Chem.* 19: 1021-1025.
- Stamm, A. J.
1930. An electrical conductivity method for determining the moisture content of wood. *Indus. and Engin. Chem.* 2(3): 240-244.
- Stamm, A. J.
1964. Wood and cellulose science. 549 pp. N.Y.: Ronald Press Co.
- USDA Forest Products Laboratory.
1955. Wood handbook. *USDA Agr. Handbook* 72, 528 pp.
- Van Dusen, M. S.
1920. The thermal conductivity of heat insulators. *J. Amer. Soc. Heating and Ventilating Eng.* 26: 625-652.
- Wangaard, F. F.
1940. Transverse heat conductivity of wood. *Heating, Piping and Air Conditioning* 12: 459-464.
- Wangaard, F. F.
1943. The effect of wood structure upon heat conductivity. *Trans. Amer. Soc. Mech. Eng.* 65(2): 127-134.

- Wangaard, F. F.
1969. Heat transmissivity of southern pine wood, plywood, fiberboard, and particleboard. *Wood Sci.* 2: 54-60.
- Wangaard, F. F., Kellogg, R. M., and Brinkley, A. W.
1966. Variation of wood and fiber characteristics and pulp-sheet properties of slash pine. *TAPPI* 49: 263-277.
- Ward, R. J., and Skaar, C.
1963. Specific heat and conductivity of particleboard as functions of temperature. *Forest Prod. J.* 13: 31-38.
- Weatherwax, R. C., and Stamm, A. J.
1945. Electrical resistivity of resin-treated wood and paper-base plastics. *Elect. Engin.* 64: 833-838.
- Weatherwax, R. C., and Stamm, A. J.
1947. The coefficients of thermal expansion of wood and wood products. *Amer. Soc. Mech. Engr. Trans.* 69(44): 421-432.
- Zwikker, C., and Kosten, C. W.
1949. *Sound absorbing materials.* 174 pp. N.Y.: Elsevier Publishing Company.

10

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10

Mechanical Properties

The load that a block of wood can carry is strongly affected by the direction the force is applied with relation to the direction of tracheid alignment, the duration of the load, and the specific gravity, moisture content, and temperature of the wood. Under some conditions, the mechanical behavior of wood reflects the fact that it is a viscoelastic, time-dependent material rather than a purely elastic material. The explanation for such behavior lies in the heterogeneous amorphous-crystalline structure of the cell wall.

When lightly loaded for a short term, however, wood deforms according to Hooke's law; that is, the **strain** or deformation in a piece of wood is proportional to the applied **stress** or force per unit area. Within this elastic range, the ratio of stress/unit strain—an indication of stiffness—is termed the **modulus of elasticity**. Stress is commonly measured in pounds force per square inch of area, and strain is expressed as inch change in length per inch of length. Therefore modulus of elasticity has the units pounds/inch² ÷ inch/inch; i.e., pounds per square inch. When the limit of proportionality or **proportional limit** is exceeded, wood takes a permanent set. As the applied load is further increased, a maximum is reached and failure occurs; stress at failure is termed the **maximum strength** or simply **strength**.

For a specimen loaded in bending, the maximum fiber stress at failure (compression or tension) calculated from the applied load and sample dimensions is termed **modulus of rupture**.

10-1 ANATOMY IN RELATION TO THE STRUCTURAL FAILURE OF WOOD

Garland (1939) studied the nature of cell damage in green and dry shortleaf and loblolly pine wood loaded to failure in tension and compression parallel to the grain. Wardrop and Addo-Ashong (1963) made a more general review to include microscopic examinations of failure in compression perpendicular to the grain. Much of this section (10-1) is based on the observations of these authors.

Because tracheids comprise most of the volume in softwood, their behavior under stress strongly affects the mechanical behavior of whole

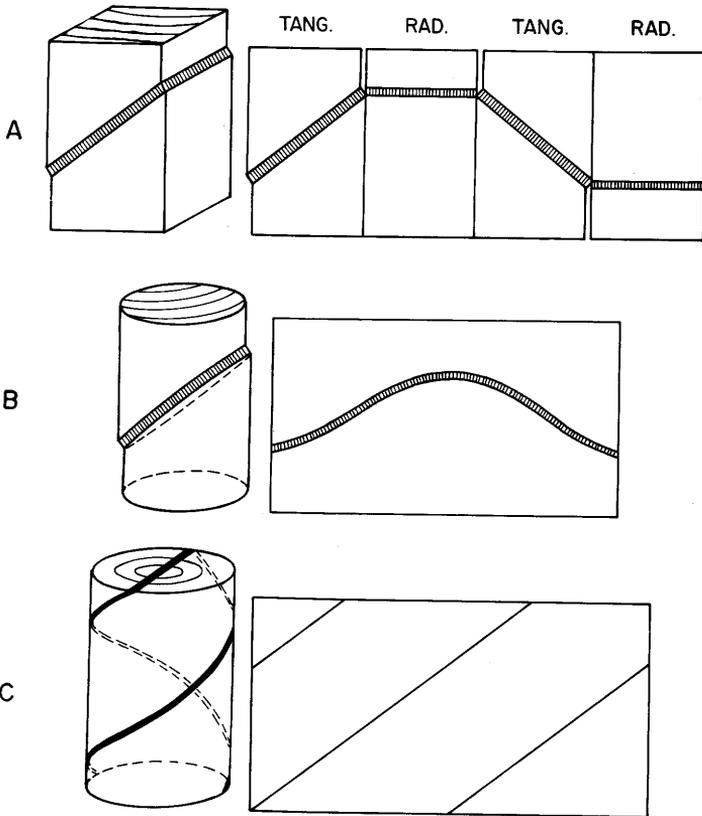


Figure 10-1.—Macroscopic buckling failures in wood specimens loaded in compression parallel to the grain. (A) Rectangular or square cross section. (B) Cylindrical with cut annual rings. (C) Cylindrical with complete annual rings. (Drawing after Frey-Wyssling 1953.)

wood. Since the tapered ends of tracheids overlap (fig. 5-6), and because the number of tracheids in any piece of structural wood is very large (billions per cubic foot), transfer of a load applied to wood must induce shear forces between adjacent cells.

FAILURE IN COMPRESSION

Southern pine loaded in compression parallel to the grain develops a visibly well-defined pattern of buckling failures. On the tangential faces of failed rectangular specimens, the lines of failure make an angle 45° to 60° to the axial direction; on radial faces, the lines are approximately perpendicular to the axial direction (fig. 10-1A). In round specimens, the failure lines form a single plane (fig. 10-1B) or double helix (fig. 10-1C).

These deformations are accompanied by shear stresses between adjacent cells; while separation along the middle lamella may occur, par-

ticularly in parenchyma cells, tracheids more commonly separate within the cell wall between the layers S_1 and S_2 (fig. 10-2).

The macroscopic buckling of tracheids (fig. 10-1) is preceded by the formation of minute deformations in the tracheid walls (fig. 10-2). According to Kissler and Steininger (1952), these deformations develop under loads approximately half that of the breaking load and thus provide the first microscopic indication of failure in compression. The deformations are most visible in the S_2 layer of the cell wall (fig. 10-2).

The strength and stiffness of wood loaded in compression parallel to the grain—as measured by the indices of maximum strength/specific gravity and modulus of elasticity/specific gravity—have a negative linear correlation with the sine of the fibril angle; i.e., the strength indices are lower for wood of high fibril angle than for wood of low fibril angle (fig. 10-3).

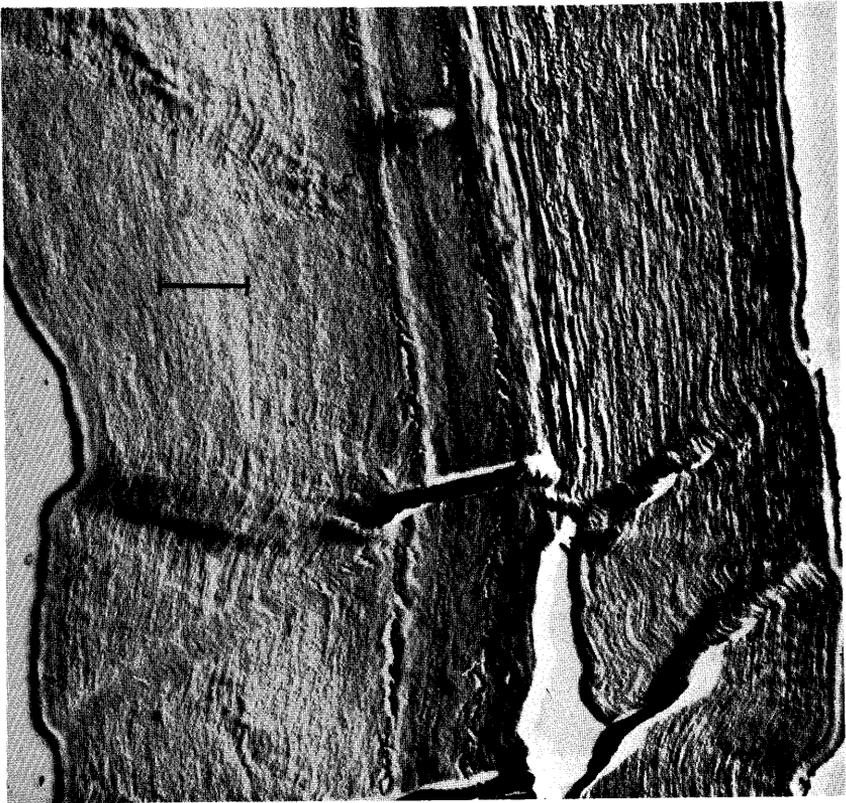


Figure 10-2.—Distortion of microfibrils in tangential tracheid cell wall in region of microscopic compression failure. Separation in cell wall near boundary between S_1 and S_2 layers is visible at bottom right. Latewood of eastern white pine (*Pinus strobus* L.). Scale mark shows 1 μm . (Photo from Keith and Côté 1968.)

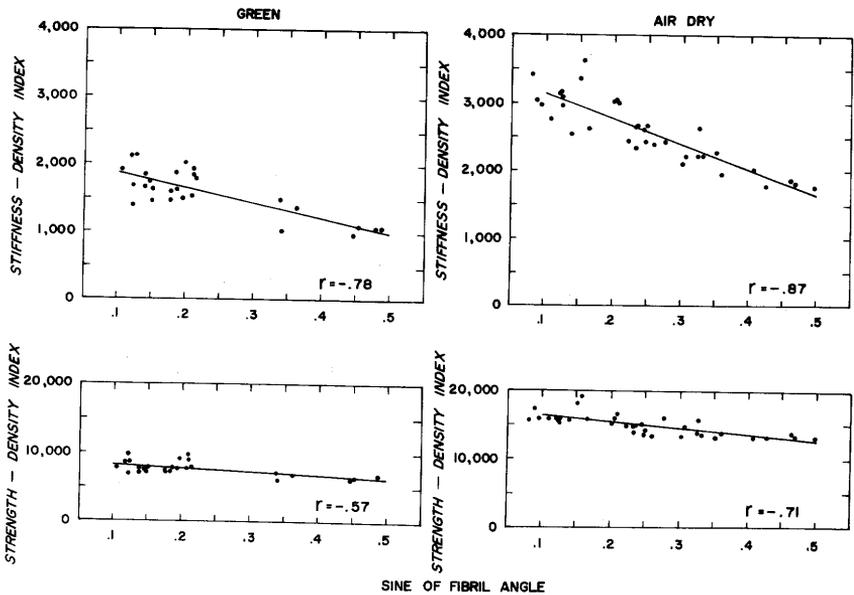


Figure 10-3.—Axial compression strength-density index (maximum compressive stress parallel to grain/specific gravity) and stiffness-density index ((modulus of elasticity)/(1,000 x specific gravity)) correlated with sine of average fibril angle in latewood for green (left) and air-dry (right) solid wood specimens of shortleaf and loblolly pine. Fibril angles were measured by the wall-check method. (Drawing after Garland 1939.)

Application of compressive force perpendicular to the grain direction causes tracheid walls to bend inward or distort sideways, altering the tracheid cross section (fig. 10-4). Consequently the modulus of elasticity in this direction is approximately one-tenth that in the longitudinal direction. As with compression parallel to the grain, when tracheids rupture, separation takes place between the layers S_1 and S_2 of the secondary wall.

FAILURE IN TENSION

When subjected to sufficient tension parallel to the grain, wood fractures and the tracheid walls are broken. Mark (1965) has provided a detailed stress analysis of coniferous tracheids under tension.

Although the tensile strength of dry whole wood is considerably greater than that of wood in the saturated or green condition, single wood tracheids are stronger in tension when wet than when dry (Wardrop 1951). The greater tensile strength of wet tracheids is attributed to a more equal distribution of load over the cellulose chains constituting the microfibrils. In the dry condition lateral bonding between chains leads to localized stress concentrations and rupture of the wall.

The tensile strength of wood tracheids is adversely affected by the helical arrangement of their microfibrils; therefore, long tracheids—whose fibril angles tend to be low—are stronger than short ones. Garland's (1939) work on solid specimens of shortleaf and loblolly pine demon-

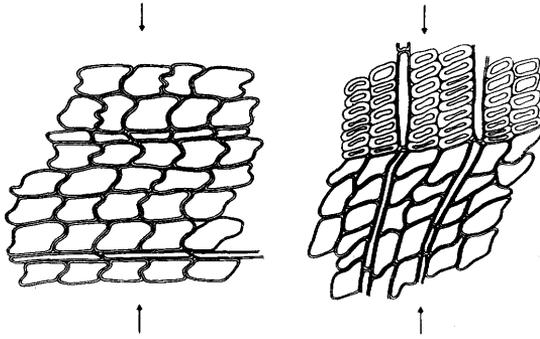


Figure 10-4.—Cell distortion in wood compressed (left) in the tangential and (right) in the radial direction. (Drawing after Frey-Wyssling and Stussi 1948.)

strated the magnitude of the effect (fig. 10-5). Manwiller and Godfrey¹, in their study of spruce pine, also observed a significant negative correlation between tensile strength of microtensile specimens and their fibril angle.

Tracheid failure ultimately involves slippage between the molecules comprising microfibrils, and between the microfibrils themselves. As with failure in compression, tension failure occurs within the tracheid walls rather than between tracheids—usually close to the plane of contact between the outer and middle layers of the secondary wall.

Individual, pulped, unbeaten, dry tracheids have been shown to have much higher tensile strength than dry whole wood. For example, Jayne (1960) observed a tensile breaking load for one individual slash pine tracheid of latewood that indicated a maximum stress of 196,000 p.s.i. (average 92,000 p.s.i. with modulus of elasticity averaging 3,113,000 p.s.i.); his data for slash pine earlywood fibers averaged 47,000 p.s.i. in tensile stress and 1,660,000 p.s.i. in modulus of elasticity. The fibers were loaded to failure when air-dry, and cross sectional areas were measured following desiccation to near oven-dry. These fiber strengths in slash pine can be compared to the data of Quirk et al. (1967) on the tensile strength of dry, match-stick-sized, earlywood and latewood specimens of slash pine.

Specimen	Tensile strength of dry slash pine specimens		Source
	Latewood	Earlywood	
	P.s.i.		
Individual dry tracheids.....	92,000	47,000	Jayne (1960)
Solid wood specimens $\frac{1}{16}$ -inch square at test section.....	45,590	8,465	Quirk et al. (1967)

¹ Manwiller, F. G., and Godfrey, P. R. Tensile properties of microspecimens of spruce pine as affected by position in stem and chemical degradation. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.7 dated May 1, 1972.

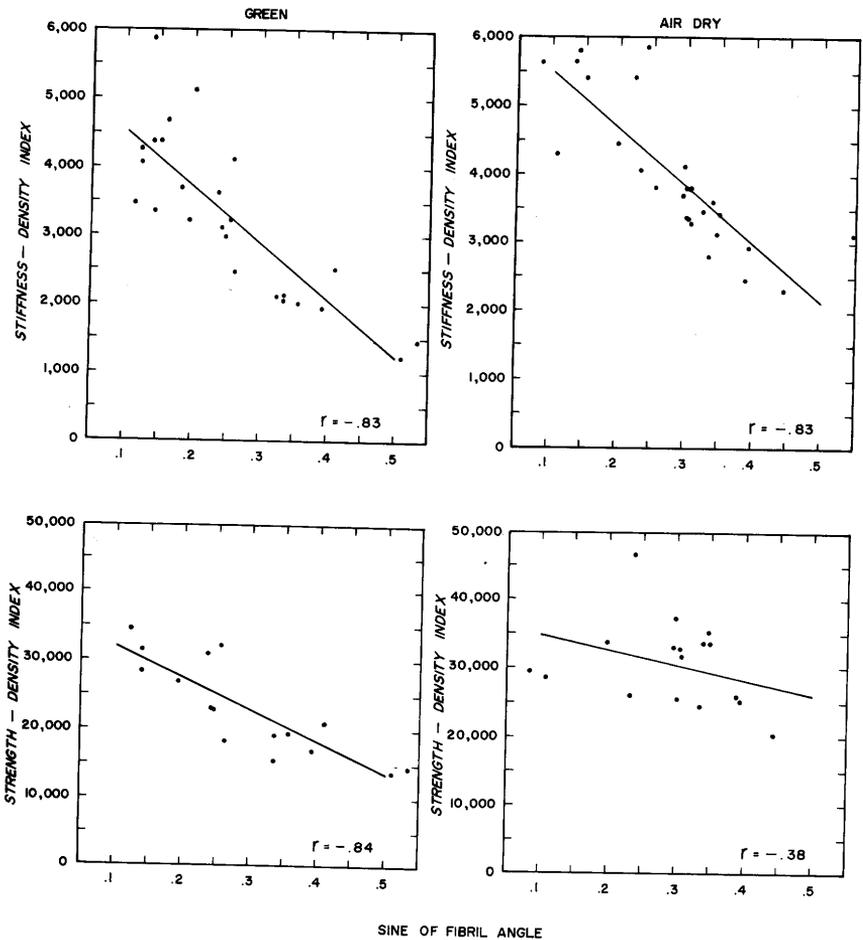


Figure 10-5.—Axial tension strength-density index (maximum tensile stress parallel to grain/specific gravity) and stiffness-density index ((modulus of elasticity)/(1,000 x specific gravity)) correlated with sine of average fibril angle in latewood for green (left) and air-dry (right) solid wood specimens of shortleaf and loblolly pine. Fibril angles were measured by the wall-check method. (Drawings after Garland 1939.)

FAILURE IN SHEAR

In specimens subjected to shear in the radial plane, lines of failure tend to follow the rays, but some tracheid walls are also ruptured. Shear stresses in the tangential plane may cause fractures to follow the junction of earlywood and latewood between annual rings; fracture of tracheid walls also occurs. Whether loaded in radial or tangential shear, failures within tracheid walls tend to occur between the layers S_1 and S_2 .

10-2 FACTORS AFFECTING STRENGTH OF CLEAR WOOD

The strength of wood is, in general, positively correlated with its specific gravity and negatively correlated with its moisture content and temperature and the duration of stress.

DURATION OF STRESS AND RATE OF STRAIN

The length of time a load acts on a wood member is negatively correlated with the load it can safely carry. A wood member continuously loaded for 10 years can carry only 60 to 65 percent of the load required to produce failure during a standard strength test of a few minutes duration; the long-time bending strength of wood is about $\frac{9}{16}$ that of the short-time value. Conversely, when a load is applied to a member in 1 second, its load-carrying capacity to rupture is increased nearly 25 percent over that indicated by standard strength tests (fig. 10-6).

Liska (1950) found that strength in compression parallel to the grain and strength in bending increased about 8 percent for every 10-fold in-

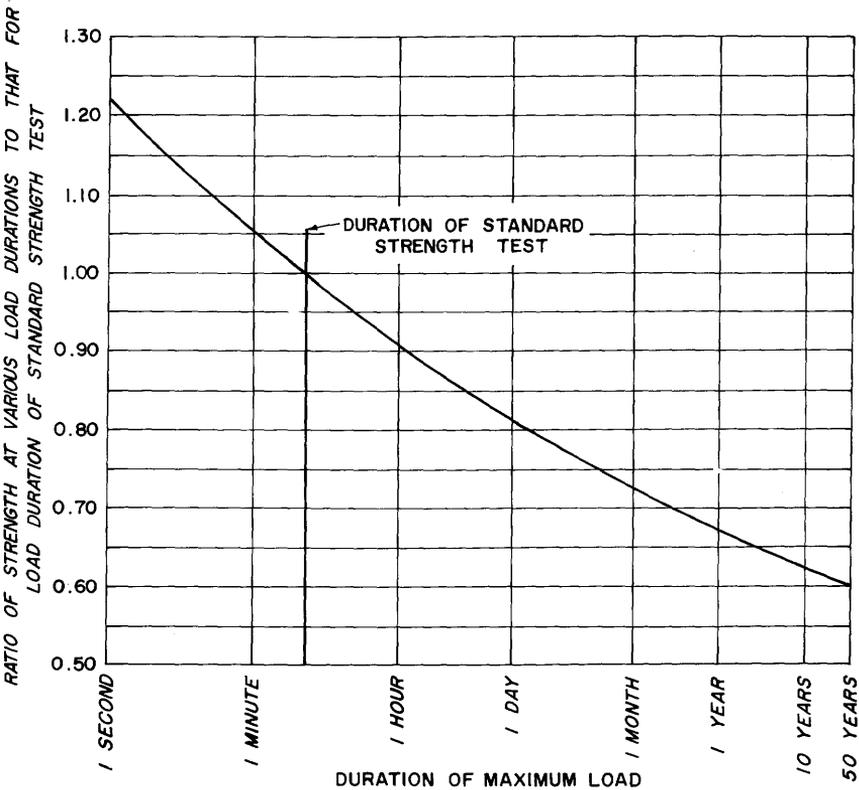


Figure 10-6.—Relation of clear-wood strength to duration of load. (Drawing after Liska, J. A. Strength properties of southern pine. Presentation at a symposium, "Utilization of the Southern Pines", Alexandria, La., November 6-8, 1969.)

crease in strain rate. James (1962) reported that this relationship held true for the modulus of rupture of air-dry wood (average of three species) for an increase in strain rate of 10^4 , i.e., increasing the loading head speed from 0.025 to about 250 inches per minute increased modulus of rupture by 31 percent. With saturated wood, the same increase in strain rate increased modulus of rupture 44 percent. Over the same range, modulus of elasticity increased about 14 percent, the increase being slightly higher for air-dry than for saturated wood, and work to maximum load increased by about 20 percent.

Thus wood structural elements have a built-in safety factor that allows them to resist without failure the overloads from short-time loading conditions such as snow, wind, earthquake, or blast.

TEMPERATURE

Wood tends to weaken with increasing temperature, and to become stronger when its temperature is lowered. The effect is immediate, and the magnitude of the change is positively correlated with moisture content in the wood. No data specific to southern pine wood are published, but the trends shown for modulus of rupture in figure 10-7 also apply generally to compression parallel to the grain and modulus of elasticity. The literature indicates that the slope of these curves increases with increasing wood specific gravity (Panshin et al. 1964, p. 194), e.g., it is probable that at elevated temperatures dense southern pine loses a higher proportion of compressive strength parallel to the grain than southern pine of lower density.

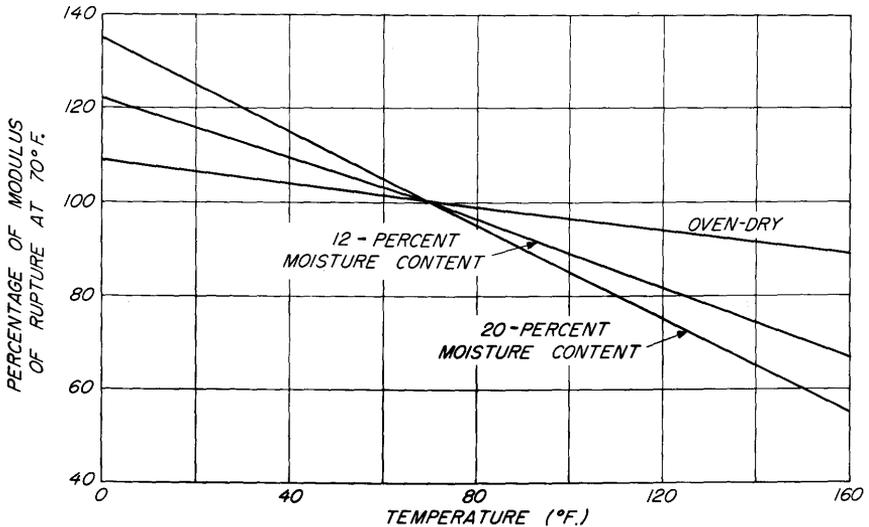


Figure 10-7.—Approximate immediate effect of temperature on modulus of rupture of softwoods at three moisture contents. (Drawing after USDA Forest Products Laboratory 1955, p. 90.)

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Temperature and moisture effects are interrelated and tend to be offsetting in their combined influence on wood strength properties. Generally, moisture is lost as the temperature is increased.

Air-dry wood can probably be exposed to temperatures below 150° F. for a year or more without a permanent loss in most strength properties, but its strength while heated will be temporarily reduced compared to its strength at normal temperatures (USDA Forest Products Laboratory 1955, p. 89).

When wood is exposed to temperatures of 150° F. or more for extended periods of time, it will suffer a permanent loss of strength related to the temperature, time, and exposure medium (see sec. 15-2).

SPECIFIC GRAVITY

Because specific gravity is an index of the amount of cell wall substance contained in a piece of wood, it is also related to the strength of wood. Liska (1965), in a review of the relationships between specific gravity and strength, observed that modulus of rupture, modulus of elasticity, compression strength parallel to the grain, and shear strength of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) have a positive linear correlation with specific gravity.

Pearson and Gilmore (1971), in a study of loblolly pine juvenile and mature wood, found that for stem heights above about 10 feet, a close linear relationship existed between wood specific gravity and modulus of rupture; also, specific gravity and modulus of elasticity were linearly

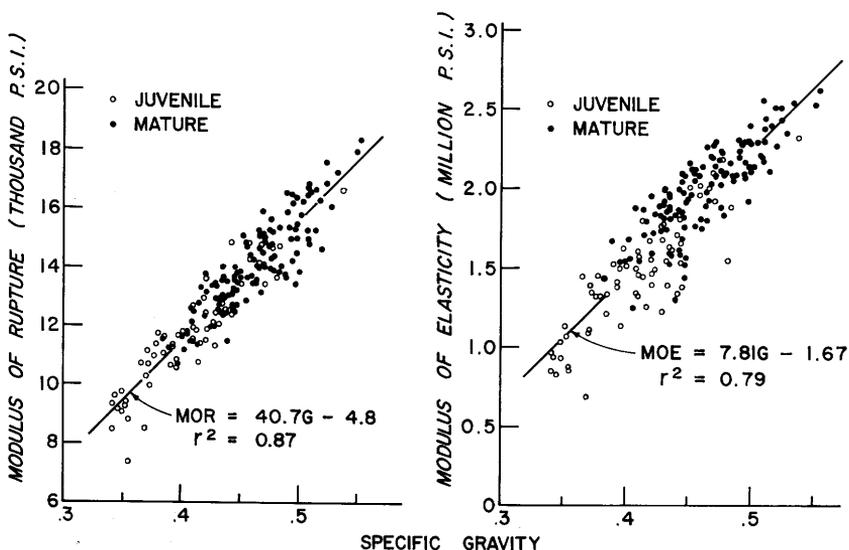


Figure 10-8.—Modulus of rupture (left) and modulus of elasticity (right) of loblolly pine juvenile and mature wood at 12-percent moisture content, related to specific gravity (G), basis of green volume and unextracted oven-dry weight. Data from butt logs were excluded from these plots. (Drawings after Pearson and Gilmore 1971.)

correlated (fig. 10-8). Wood taken from butt logs had lower moduli of elasticity and rupture than upper wood of equal specific gravity.

Biblis and Fitzgerald (1971) reported that for the loblolly pine they studied, relationships between shear strength parallel to the grain and specific gravity were slightly curvilinear (fig. 10-9).

Manwiller² found that strength properties of wood taken from various heights in 42 spruce pine trees cut throughout the major commercial range of the species were linearly correlated with specific gravity as shown in table 10-1 and figure 10-10.

Bendtsen and Ethington (1972) have developed linear regressions relating five major mechanical properties of green clear wood to specific gravity of loblolly, longleaf, shortleaf, and slash pine; correlation coefficients ranged from 0.38 to 0.87 (table 10-1).

² Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1 dated May 1, 1972.

TABLE 10-1.—*Linear relationships between certain clear-wood strength properties of five species of southern pine and specific gravity*

Property and moisture content	Constants ¹		Correlation coefficient	Standard error of the estimate
	a	b		
				<i>P.s.i.</i>
				LOBLOLLY PINE ²
Modulus of rupture				
Green.....	-418	16,189	0.72	793
Modulus of elasticity				
Green.....	1,000	2,905,000	.44	295,000
Compression strength par- allel to the grain, maximum				
Green.....	-448	8,207	.70	419
Shear strength, maximum				
Green.....	224	1,359	.58	86
Compression perpendicular to grain, proportional limit				
Green.....	-150	1,191	.53	98
				LONGLEAF PINE ²
Modulus of rupture				
Green.....	-501	16,478	.82	889
Modulus of elasticity				
Green.....	13,000	2,832,000	.66	249,000
Compression strength par- allel to the grain, maximum				
Green.....	-356	8,447	.79	522

See footnotes at end of table.

TABLE 10-1.—*Linear relationships between certain clear-wood strength properties of five species of southern pine and specific gravity—Continued*

Property and moisture content	Constants ¹		Correlation coefficient	Standard error of the estimate
	a	b		
				<i>P.s.i.</i>
Modulus of elasticity				
Green.....	-709,240	4,454,145	.58	312,940
12 percent.....	-1,373,376	6,259,895	.69	364,650
Compression strength parallel to the grain, maximum				
Green.....	-515	7,571	.77	340
12 percent.....	1,454	8,735	.59	710
Shear strength, maximum ⁵				
Green.....	124	1,675	.70	90
12 percent.....	201	2,134	.41	260

¹ The constants are from the expression $y = a + bx$; the equation expresses the strength property of interest, y , in p.s.i. In the equation, x is unextracted specific gravity, green volume and oven-dry weight basis.

² Data from Bendtsen and Ethington (1972).

³ Data from Manwiller; see text footnote².

⁴ The equations for spruce pine are applicable in the specific gravity range from 0.34 to 0.63.

⁵ Combined data from wood stressed in both radial and tangential directions.

The relationship between tensile strength and specific gravity is not completely resolved, and research data are limited. Ifju's (1969) data for green microtensile specimens (nominally 100 μm . thick) from six southern pines indicated a positive linear correlation between tensile strength and specific gravity; r values ranged from 0.33 for pitch pine to 0.80 for slash pine. His data also provided a family of linear regressions relating modulus for elasticity to specific gravity.

Although data from Biblis (1969b) show curvilinear relationships between tensile properties and specific gravity of microtensile specimens, his later (1969a) data for larger clear-wood tensile specimens cut from loblolly pine show linear (or very nearly linear) relationships between tensile properties (maximum strength and modulus of elasticity) and specific gravity. At 12-percent moisture content, tensile strength (p.s.i.) was equal to: $-7,036 + 50,717$ (specific gravity on basis of oven-dry volume and weight). Similarly, modulus of elasticity (p.s.i.) was equal to: $-785,878 + 5,393,379$ (specific gravity on basis of oven-dry volume and weight).

MOISTURE CONTENT

With the exception of toughness and shock resistance, wood weakens as

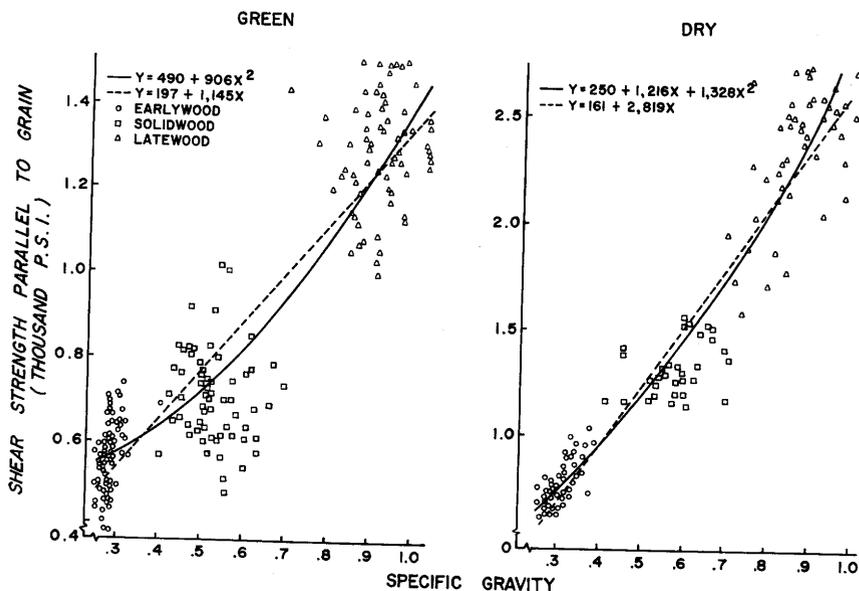


Figure 10-9.—Relationships between shear strength parallel to the grain and specific gravity (basis of green volume and unextracted oven-dry weight) of loblolly pine. Data are from earlywood, latewood, and solid whole wood in the green condition (left) and at 12-percent moisture content (right). The curvilinear expressions best fit the data. (Drawings after Biblis and Fitzgerald 1970.)

its moisture content is increased from oven-dry to approximately fiber saturation. Above this point its strength remains constant. Wilson (1932) has shown that strength properties in the range below an experimentally determined moisture content, M_p , can be expressed by the equation:

$$S = 10^{a-bM} \quad (10-1)$$

where S is a strength property, a and b are constants for each species, and M is the moisture content (percent) in the range up to and including M_p . For loblolly and longleaf pines, M_p has been determined to be 21 percent; for the remaining eight species of southern pine, M_p is commonly considered to be 25 percent (USDA Forest Products Laboratory 1955, p. 86).

From the values for green and dry southern pine wood shown in table 10-2, strength values at other moisture contents up to M_p (21 or 25 percent depending on species) can be calculated using the following equation derived from equation 10-1.

$$\ln S_i = \ln S_{12} + (12 - M_i) \frac{\ln \frac{S_{12}}{S_g}}{9} \quad (10-2)$$

where S_{12} and S_g are the values of a particular strength property of

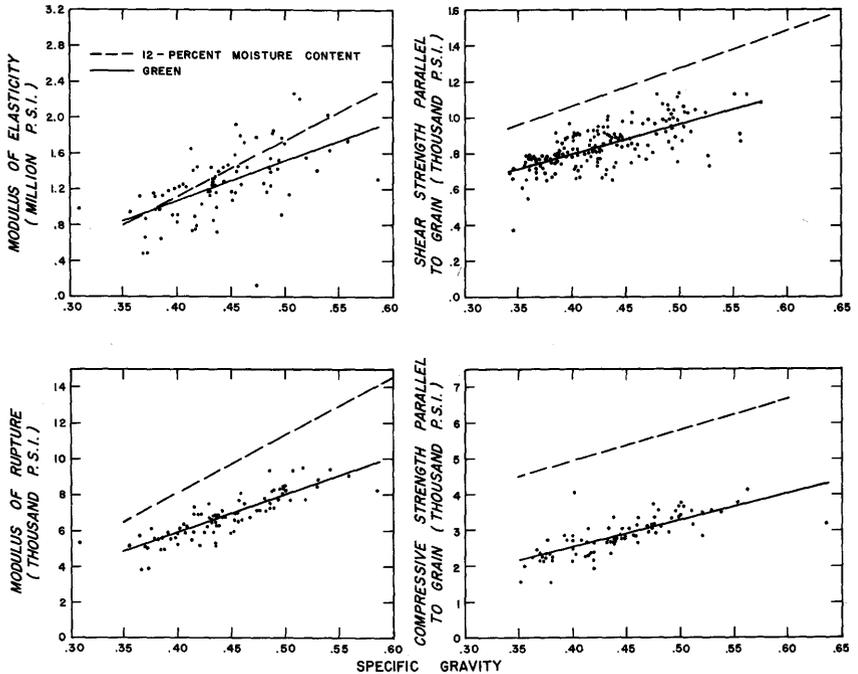


Figure 10-10.—Relationships between four strength properties of green and dry spruce pine wood and unextracted specific gravity (basis of green volume and oven-dry weight). Plotted points are for green wood only. (Drawing after Manwiller².)

southern pine at 12-percent moisture content and when green; S_1 is the desired strength at M_1 moisture content, percent.

If moisture content exceeds M_p , the green wood values in table 10-2 apply.

10-3 SPECIES-AVERAGE STRENGTH VALUES FOR CLEAR WOOD

Table 10-2 shows the important average mechanical properties of six of the species of southern pine, in the green condition and at 12-percent moisture content, based on tests of small, clear, straight-grained specimens. The properties and patterns of variation differ among species; longleaf and slash pine are the strongest, while spruce pine is weakest in all properties except shear strength.

The values shown in table 10-2 are averages for the tested samples; they represent the species average to the extent that the tested samples were representative. As the geographic distribution, age classes, and seed sources of the population of each tree species changes with time, average specific gravity and strength may also change.

Bendtsen and Ethington (1972) have provided data on variability of five strength properties in clear green wood of the four major southern pine species. Average values of modulus of rupture, modulus of elasticity, compression strength parallel to the grain (maximum) and shear strength (maximum) are shown in table 10-2. By the regression method, they estimated corresponding values for standard deviation as follows:

Property	Standard deviation for pine species of			
	Loblolly	Longleaf	Shortleaf	Slash
	----- P.s.i. -----			
Modulus of rupture.....	1,318	1,696	1,387	1,429
Modulus of elasticity.....	350,000	352,000	303,000	324,000
Compression strength parallel to grain, maximum.....	679	906	678	628
Shear strength parallel to grain, maximum.....	123	147	159	140
Compression strength perpendicular to grain, proportional limit.....	125	166	111	159

10-4 WITHIN-SPECIES VARIATION IN CLEAR WOOD STRENGTH³

A tree of any species can be classified by age class, growth rate, and geographic location. All three factors may be correlated with the strength properties of wood cut from the tree. This variation can be illustrated with a single species, spruce pine, which—for this purpose—has been sampled throughout its major commercial range. Trees 30 and 45 years old of slow and fast growth (more or less than 6 rings per inch 1 foot above ground level) were cut in four geographic regions of the species range. With three replications, a total of 48 trees were cut (but only 42 used because 6 trees were too small to yield good specimens) to provide strength data for static bending, compression and shear parallel to the grain, compression and tension perpendicular to the grain, hardness, and toughness. Data were recorded for clear wood tested green and at 12-percent moisture content.

GROWTH RATE

Standard test specimens cut from trees averaging more than 6 rings per

³ Data for sec. 10-4 are from Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1, dated May 1, 1972.

TABLE 10-2.—Average clear wood strength properties of six species of southern pines (data from Bendtsen and Ethington 1972, and from USDA, Forest Products Laboratory, Madison, Wis., January 27, 1972)

Pine species and moisture content	Specific gravity ¹	Static bending			Impact bending; height of drop causing complete failure (50-pound hammer)	Compression parallel-to-grain		Compression perpendicular to grain; fiber stress at proportional limit	Shear parallel to grain; maximum shearing strength	Tension perpendicular to grain; maximum tensile strength	Side hardness; load required to embed an 0.444-inch ball to 1/2 its diameter	
		Fiber stress at proportional limit	Modulus of Rupture	Elasticity ²		Work to maximum load	Fiber stress at proportional limit					Maximum crushing strength
		<i>P.s.i.</i>	<i>P.s.i.</i>	<i>1,000 P.s.i.</i>	<i>In.-lb. per cu. in.</i>	<i>In.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>Lb.</i>
Loblolly												
Green-----	0.47	4,100	7,200	1,370	8.2	30	2,550	3,420	410	860	260	450
12 percent---	.51	7,800	12,600	1,750	10.4	30	4,820	6,940	840	1,390	470	690
Longleaf												
Green-----	.53	5,200	8,400	1,550	8.9	35	3,430	4,210	470	1,040	330	590
12 percent---	.58	9,300	14,300	1,930	11.8	34	6,150	8,260	950	1,510	470	870
Shortleaf												
Green-----	.47	3,900	7,400	1,400	8.2	30	2,500	3,530	330	900	320	440
12 percent---	.51	7,700	13,100	1,770	11.0	33	5,090	7,270	750	1,390	470	690

TABLE 10-2.—Average clear wood strength properties of six species of southern pines (data from Bendtsen and Ethington 1972, and from USDA, Forest Products Laboratory, Madison, Wis., January 27, 1972)—Continued

Pine species and moisture content	Specific gravity ¹	Static bending			Impact bending; height of drop causing complete failure (50-pound hammer)	Compression parallel-to-grain		Compression perpendicular to grain; stress at proportional limit	Shear parallel to grain; maximum shearing strength	Tension perpendicular to grain maximum tensile strength	Side hardness; load required to embed an inch ball to ½ its diameter	
		Fiber stress at proportional limit	Modulus of Rupture	Elasticity ²		Work to maximum load	Fiber stress at proportional limit					Maximum crushing strength
		<i>P.s.i.</i>	<i>P.s.i.</i>	<i>1,000 P.s.i.</i>	<i>In.-lb. per cu. in.</i>	<i>In.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>P.s.i.</i>	<i>Lb.</i>
Slash												
Green.....	.53	5,100	8,700	1,530	9.5	36	3,040	3,820	520	960	400	630
12 percent...	.58	9,800	16,300	1,980	12.6	36	6,280	8,140	1,010	1,680	570	1,010
Spruce												
Green.....	.41	2,900	6,000	1,000	-----	-----	-----	2,840	280	900	-----	450
12 percent...	.44	5,100	10,400	1,230	-----	-----	-----	5,650	730	1,490	-----	660
Virginia												
Green.....	.45	4,000	7,300	1,220	10.9	34	2,500	3,420	390	890	400	540
12 percent...	.48	7,100	13,000	1,520	13.7	32	3,820	6,710	910	1,350	380	740

¹ Based on unextracted weight when oven-dry and volume when green or at 12-percent moisture content.

² Modulus of elasticity measured from a simply-supported, center-loaded beam. The modulus can be corrected for the effect of shear deflection by increasing it 10 percent.

inch at the 1-foot level differed significantly in a few strength properties from those cut from trees averaging less than 6 rings per inch, as follows:

<u>Moisture condition and strength property</u>	<u>Slow grown</u>	<u>Fast grown</u>
	----- P.s.i. -----	
Green		
Modulus of rupture -----	7,250	6,470
Modulus of elasticity -----	1,430,000	1,130,000
Maximum tensile stress perpendicular to grain (tangential) -----	270	340
12-percent moisture content		
Modulus of elasticity -----	1,800,000	1,410,000

Also, a significant difference in hardness was noted; to embed an 0.444-inch ball half its diameter into the side grain of air-dry wood from slow-grown trees required more force (840 pounds) than similar embedment into side grain of air-dry wood from fast-grown trees (700 pounds).

As was noted in section 7-5, tree-average specific gravity of the slow-grown trees was slightly higher than that of the fast-grown trees. The specific gravity of test specimens used to determine mechanical properties, however, generally did not differ significantly between fast- and slow-grown trees; specimens averaged 0.44 on the basis of green volume and oven-dry weight, and 0.48 on the basis of volume at 12-percent moisture content and oven-dry weight.

AGE CLASS

Standard test specimens cut from 30-year-old trees differed significantly in only two strength properties from those cut from 45-year-old trees.

<u>Strength property</u>	<u>Tree age</u>	
	<u>30 years</u>	<u>45 years</u>
Work to maximum load measured on green wood, in. lbs. per cu. in. -----	12.3	9.2
Hardness, i.e., force to embed an 0.444-inch ball to half its diameter in side grain of air-dry wood, lbs. -----	837	703

The general lack of correlation between spruce pine tree age and strength properties is likely attributable to the fact that tree-average specific gravities of 30-year-old and 45-year-old spruce pine trees proved not significantly different (see sec. 7-5). For the major southern pine species, the correlation between tree age and wood strength may be positive and more pronounced.

GEOGRAPHIC LOCATION

Differences in wood strength correlated with latitude and longitude were not significant in Manwiller's study of spruce pine.

The major southern pine species, however, have much broader ranges than spruce pine. It is likely that the tree-average specific gravity variation evident from figures 7-1, 7-2, 7-3, and 7-4, is reflected in geographic variability in some wood strength properties of loblolly, longleaf, shortleaf, and slash pines.

AMONG TREES

Specimens from each of 42 spruce pine trees were tested. Variability among tree averages was substantial, as shown by table 10-3. The mean of Manwiller's tree-average specific gravities was 0.42 (basis of green volume and oven-dry weight); this compares closely with the species-average value (0.41) shown for spruce pine in table 10-2. His strength values (table 10-3), however, differ somewhat from the values for spruce pine shown in table 10-2 because his clear test specimens were necessarily selected from lower portions of stems and therefore averaged high in specific gravity, i.e., 0.44 on a green volume oven-dry weight basis, and 0.48 on the basis of volume at 12-percent moisture content and oven-dry weight. Also, the sample of trees in Manwiller's experiment was stratified by age class and growth rate; the values in table 10-2 were based on an unstratified random sample of the spruce pine population.

10-5 WITHIN-TREE VARIATION IN CLEAR WOOD TENSILE STRENGTH

Because specific gravity, fibril angle, and chemical constituents in stem-wood may vary across each annual ring, between adjacent rings, with radial position in the stem, and with height above ground, it is reasonable that strength properties should vary greatly with location within trees. The literature contains many observations on this variation, e.g., much of the range in modulus of elasticity reported by Koch (1967a) and Koch and Woodson (1968) for thin laminae of slash and loblolly pines (under 1 million to over 3 million p.s.i.) is attributable to within-tree variation.

Because tensile properties are more readily measured on microspecimens than most other strength properties, published information on variability within individual southern pine trees is largely limited to tensile strength and modulus of elasticity. The other strength properties also vary substantially within individual trees, but documentation is meager.

WITHIN ANNUAL INCREMENT

Ifju (1969) and Biblis (1969a, b) have studied the variation in tensile properties across individual annual rings in southern pine. Ifju examined one breast-height disk taken from a single tree of each of six species (loblolly, longleaf, pitch, shortleaf, slash, and Virginia pines). His trees ranged from 9½ to 13½ inches d.b.h. and from 21 to 48 years old with

TABLE 10-3.—Among-tree variation in tree-average values of clear wood properties of spruce pine based on a 42-tree, range-wide sample stratified by age class, growth rate, and geographic location (data from Manwiller, see text footnote³)

Strength property	Tree-average values					
	Green			12-percent moisture content		
	42-tree average	Range	Standard deviation	42-tree average	Range	Standard deviation
Static bending						
Fiber stress at proportional limit, p.s.i.---	2,830	1,640-4,360	691	4,880	2,710-7,780	1,223
Modulus of rupture, p.s.i.-----	6,820	3,890-9,480	1,211	10,200	5,530-14,120	2,132
Modulus of elasticity, p.s.i.-----	1,260,000	480,000-2,240,000	384,000	1,580,000	900,000-3,560,000	500,000
Work to proportional limit, in.-lb. per cu. in.-----	0.40	0.12-1.01	0.18	0.93	0.28-1.66	0.34
Work to maximum load, in.-lb. per cu. in.-----	10.54	5.55-19.60	3.54	9.22	0.84-23.30	4.18
Compression parallel to the grain						
Fiber stress at proportional limit, p.s.i.---	1,960	1,160-2,730	337	3,660	2,340-5,430	702
Maximum crushing strength, p.s.i.-----	2,840	1,580-3,940	497	5,670	4,430-7,320	742
Compression perpendicular to the grain						
Fiber stress at proportional limit, p.s.i.---	375	245-529	64	796	470-4,705	160
Maximum shear stress parallel to the grain						
Radial, p.s.i.-----	846	659-1,065	110	1,244	622-1,741	263
Tangential, p.s.i.-----	841	537-1,048	108	1,214	793-1,631	201

Maximum tensile stress perpendicular to grain						
Radial, p.s.i.-----	288	128-418	63	371	199-583	92
Tangential, p.s.i.-----	312	123-462	69	397	270-558	79
Hardness (load required to embed an 0.444-inch ball to one-half its diameter)						
Side grain, lb.-----	535	373-789	107	741	436-1,385	202
End grain, lb.-----	562	375-889	124	1,064	738-1,620	201
Toughness (specimen 2 cm. square tested over a 24 cm.- span with load applied to radial and tangential faces)						
Radial, in.-lb.-----	394	109-652	177	148	53-299	56
Tangential, in.-lb.-----	373	74-648	170	181	49-314	70

2 to 4.5 rings per inch growth rate; latewood percentage ranged from 27 to 55 percent. Biblis studied a single 38-year-old loblolly tree having growth rings about $\frac{1}{4}$ -inch wide with earlywood and latewood zones approximately equal in width. Both evaluated microtensile specimens in the saturated condition.

Ifju tested 100- μ m.-thick specimens with a 2-cm. span; specimens were taken from the 8th-9th-10th, 18th-19th-20th, and the three most recent increments. As was the case with Ifju's data on specific gravity (see equation 7-4 and fig. 7-6), his regression equations for both ultimate tensile strength and modulus of elasticity are of the form:

$$Y = a + b \arctan\left(\frac{x+s}{10} - 10\right) \quad (10-3)$$

where:

Y = tensile strength (p.s.i.) or modulus of elasticity at point of interest (p.s.i. $\times 10^{-3}$).

a is a constant

b is a regression coefficient

x = percent of distance across the increment

s = percent latewood

In general, the equations accounted for about 50 percent of the variation, with a standard error of the estimate of 3,500 to 7,600 p.s.i. for tensile strength and 120,000 to 400,000 p.s.i. for modulus of elasticity. The Virginia pine values were based on 60 observations; 120 to 215 observations established each of the other five equations.

Figure 10-11 illustrates the curve form for juvenile and mature wood of shortleaf pine; curves for the other species are similar. When observations from all increments were grouped for each species, the constants for equation 10-3, together with R and standard error of the estimate (S_e) values, were as follows:

Pine species	Tensile strength				Modulus of elasticity			
	a	b	R	S_e	a	b	R	S_e
				<i>P.s.i.</i>				<i>P.s.i.</i>
Loblolly.....	8,064	3,323	0.693	3,950	379	177	0.625	253,000
Longleaf.....	13,349	5,518	.711	5,945	727	323	.737	325,000
Pitch.....	7,308	1,153	.367	3,496	316	102	.578	122,000
Shortleaf.....	13,942	6,382	.667	7,600	694	335	.667	399,000
Slash.....	12,418	5,738	.713	5,904	633	285	.674	327,000
Virginia.....	9,768	4,124	.637	5,746	395	169	.603	258,000
Data for all species pooled.....	11,766	5,126	.683	6,170	586	284	.683	342,000

R	S _e	n	ANNUAL RINGS			R	S _e	n
			18-19	20	8-9-10			
0.72	6.4	72	----	----	----	0.80	268	42
.82	5.2	46	----	----	----	.81	310	46

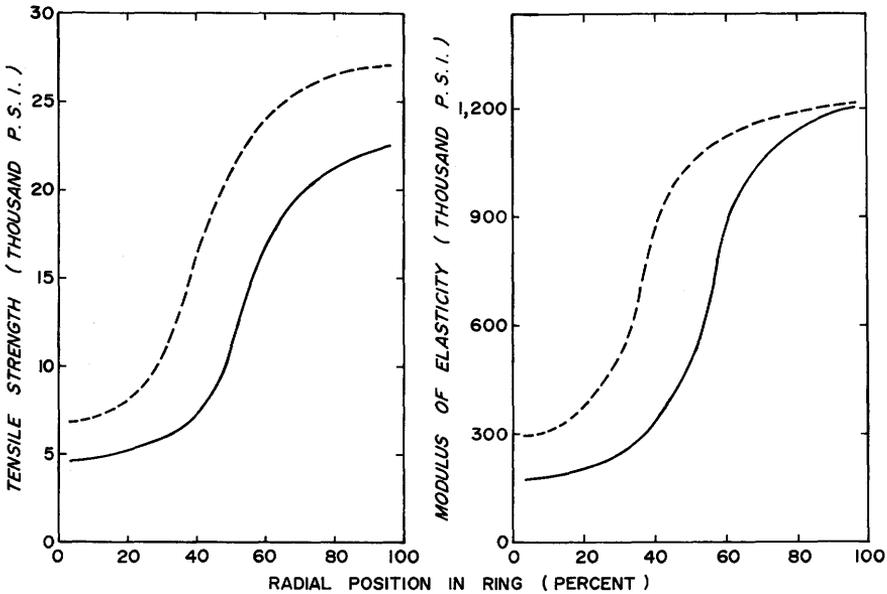


Figure 10-11.—Intra-increment patterns for tensile strength and modulus of elasticity observed in breast-height, saturated wood from a single shortleaf pine tree. R is correlation coefficient; S_e is standard error of estimate; n is number of samples. (Drawing after Ifju 1969.)

While the absolute values of tensile properties determined from microtensile specimens must be interpreted with caution (Davies 1968; Biblis 1969a, 1970; Kennedy and Chan 1970; Manwiller and Godfrey¹), the trends shown in figure 10-11 are of interest. It is seen that mature wood is stronger and stiffer than juvenile wood throughout the increment. While latewood specific gravity should not vary much between the ninth and 19th rings, earlywood in the ninth ring should be somewhat more dense than earlywood in the 19th ring (fig. 7-7). It is possible that the higher fibril angle of wood from the ninth ring compared to wood from the 19th ring (fig. 5-44) adversely affects earlywood tensile strength in the ninth ring.

Biblis' (1969b) data from a single loblolly pine show the same trend of tensile strength variation across growth increments evident in Ifju's (1969) data. The following comparison (Biblis 1969a) of matched saturated microtensile specimens and larger all-earlywood or all-latewood specimens casts doubt, however, on the quantitative values obtainable from microtensile specimens:

Type of specimen and tensile property	Earlywood	Latewood
Microtensile (100 μ m. thick)		
Maximum tensile stress (range), p.s.i.-----	3,270-4,950	8,620-13,710
Modulus of elasticity (range), p.s.i.-----	150,700-258,900	777,630-1,076,820
Macrotensile (approx. $\frac{3}{8}$ - by $\frac{3}{16}$ -inch cross section)		
Maximum tensile stress, p.s.i.-----	9,230	28,390
Modulus of elasticity, p.s.i.-----	805,400	3,424,560

Data taken by Manwiller and Godfrey¹ on 300- to 400- μ m.-thick microtome-cut specimens of spruce pine showed ratios between earlywood and latewood of 0.424 and 0.458 for ultimate tensile strength and modulus of elasticity. The 1,296 specimens were drawn from 18 locations in each of 72 trees and tested at about 9-percent moisture content.

Quirk et al. (1967) tested 15 earlywood and 15 latewood specimens of slash pine in tension. They were milled to measure $\frac{1}{16}$ -inch in cross section and tested dry. He found that the latewood was more than five times stronger than earlywood; latewood had a tensile strength of 45,590 p.s.i., whereas earlywood averaged 8,465 p.s.i.

WITH POSITION IN TREE

Most strength properties of whole wood should vary with height and radial position in a tree in proportion to wood specific gravity at the location (figs. 10-8, 10-9, and 10-10).

Data relating strength of entire earlywood or latewood increments to position in the tree are sparse and not conclusive. In one of the few studies on the subject, Manwiller and Godfrey¹ found that height above ground and number of annual rings from the pith explained virtually none of the variation observed in tensile properties of 300- to 400- μ m.-thick specimens taken from earlywood and latewood of spruce pine trees.

10-6 DESIGN STRESS VALUES

Design stress or allowable stress values for southern pine, to be used by engineers and architects, are derived from data for green, clear wood (table 10-2) through procedures outlined in American Society for Testing and Materials (ASTM) Designation D245 titled *Tentative methods for establishing structural grades for lumber*. Following is a brief description of the procedure.

Allowable properties are derived from the experimentally determined data (table 10-2) by making certain reductions reflecting an assessment of variability in clear wood, permitted strength-reducing features in the grade, degree of hazard related to the specific property, duration of the load, and a factor of safety of about 1.3. It assumes an accumulation of 10 years under full design load.

While small clear specimens of wood may show—for some strength properties—appreciable increase in strength with drying, it has been found that in structural lumber the gain in strength from drying is partially or completely offset by the development of drying defects. Therefore, the conditions under which allowance may be made for benefit from drying are explained in Designation D245.

A distinction is made between **dense** and **medium-grained** southern pine. Dense lumber averages, on one end or the other, not less than 6 annual rings per inch and one-third or more latewood; pieces that average not less than 4 annual rings per inch are accepted as dense if they average one-half or more latewood. Medium-grained lumber is weaker than dense lumber; it averages, on one end or the other, not less than 4 rings per inch. **Wide-ringed** lumber has less than 4 rings per inch and can at best qualify for the lower structural grades of lumber.

STRENGTH RATIO

The **strength ratio** of a piece (or grade) of structural lumber represents the hypothetical strength remaining after allowance is made for knots, cross grain, or other strength-reducing features present. A strength ratio of 75 percent is applied to a piece or a grade in which the maximum reduction in strength from that of clear wood is 25 percent. Strength reduction from knots and cross grain generally are not cumulative; thus, if the ratio from knots is 75 percent and that from cross grain 69 percent, the combined strength ratio is 69 percent.

Strength ratios are applied to stresses in transverse bending, tension, and compression parallel to the grain, and horizontal shear in beams. As an example, a one-inch knot located in the middle third of the length on the narrow face of a 2 by 6 joist (standard size 1½ by 5½ inches) results in a bending strength ratio of 49 percent.

Modulus of elasticity and compression perpendicular to the grain are assumed little affected by knots, and strength ratios for these properties are assumed to be 100 percent for all grades; for the contrary view that modulus of elasticity in southern pine may be grade dependent see Gerhards (1970).

DESIGN STRESS

The architect or engineer can find convenient tabulations of design stresses in *Standard grading rules for southern pine lumber* published by the Southern Pine Inspection Bureau, Pensacola, Fla. Because the information in these rules is under more or less continuous revision, the reader is referred to them as the source. Tabulations will be found for structural lumber 2 inches and thicker, of various degrees of dryness and with various strength ratios.

To give some idea of the range of values, the 1970 edition (p. 64 and

part C of Supplement No. 1) shows that Dense Select Structural kiln-dried southern pine dimension lumber 2 to 4 inches thick and 2 to 4 inches wide has the highest design stress, and Stud grade dry lumber has the lowest design stress (for comparable lumber size) of the tabulated grades, as follows:

<u>Property</u>	<u>Dense</u>	
	<u>Select Structural</u>	<u>Stud</u>
	----- P.s.i. -----	
Bending -----	2,650	750
Tension parallel to grain -----	1,550	425
Compression parallel to grain -----	2,150	600
Horizontal shear -----	95	75
Compression perpendicular to grain -----	475	345
Modulus of elasticity -----	2,000,000	1,400,000

As a further convenience for designers, a simplified system for determining allowable joist and rafter spans for southern pine lumber has been published by the Southern Forest Products Association, New Orleans, La. (SFPA Technical Bulletin No. 2, *Southern pine maximum spans for joists and rafters*). The allowable spans in the tables are based on American Softwood Lumber Standard (PS 20-70) sizes for dressed lumber at 19-percent maximum moisture content, as follows:

<u>Nominal size</u>	<u>Dressed size</u>
<i>Inches</i>	<i>Inches</i>
2 x 4	1½ x 3½
2 x 6	1½ x 5½
2 x 8	1½ x 7¼
2 x 10	1½ x 9¼
2 x 12	1½ x 11¼

From table 10-2 it is evident that wood from some of the minor species—for example spruce pine—is significantly weaker than wood from the four major species, i.e., loblolly, longleaf, shortleaf, and slash pines. Since marketing considerations and difficulties of identification indicate the desirability of marketing several of the southern pine species as a group, the design properties must be determined on a group basis. This can be done by consideration of average properties and standing timber volumes of each species in the group according to the procedures of ASTM Designation D2555 titled *Tentative methods for establishing clear wood strength values*. This procedure is used by the Southern Pine Inspection Bureau in the establishment of their grading rules.

NONDESTRUCTIVE TESTING

The procedures previously outlined in this section represent current practice for visually graded lumber. Nondestructive mechanical grading is an alternative to visual grading procedures. Most southern pine dimension

lumber is used in light-frame construction, primarily housing. In some of the major structural elements of a house, e.g., joists and beams, span length is generally determined by limitations on deflection rather than by strength in bending. Deflection is governed by modulus of elasticity. It is technically possible to measure, at production speeds, the modulus of elasticity of every piece of lumber sold, and to stamp this value on the lumber. It is likely that in the future operational procedures and quality control techniques will be sufficiently improved to permit lumber to be segregated into 200,000 p.s.i. classes from 1 million to over 2 million p.s.i.; the value stamped on each piece could then be a guaranteed minimum or an average for the class. Since this measured value is independent of species, all material of a given modulus of elasticity class could then be used regardless of species for identical spans subject to the same limitations on deflection.

There are uses—as in some glued-laminated beams, trusses, and decking—where the strength of dimension lumber is greater in importance than its stiffness. For these uses, lumber can be mechanically graded for modulus of elasticity and visually graded for strength. Combination of both systems permits greater precision in predicting the actual strength of lumber than either system alone. It is probable that a totally nonvisual method of nondestructively and accurately evaluating both modulus of rupture and modulus of elasticity will be developed before many years pass; such a development, if exploited by industry, would greatly increase the efficiency with which wood is used in structures.

For the reader interested in further study of nondestructive testing, following are a few pertinent references:

- | | |
|--|------------------------------|
| USDA Forest Products Laboratory (1964) | Marra et al. (1966) |
| Galligan (1965) | Doyle (1968) |
| Galligan and Courteau (1965) | Hoyle (1968, 1970) |
| Pellerin (1965) | Koch and Woodson (1968) |
| Doyle and Markwardt (1966, 1967) | Miller (1968) |
| Hilbrand and Miller (1966) | Orosz (1968) |
| Koch (1966, pp. 31-32; 1967ab) | Walters and Westbrook (1970) |

DESIGN STRESSES FOR PRODUCTS OTHER THAN LUMBER

Wood in forms other than lumber is being used with increasing efficiency as a structural material. Many of the criteria for determination of design stresses are in a state of flux at this time, but some comment is in order.

Poles.—Design stress data for poles are under continual review by the American National Standard Institute Committee (ANSI) 05. Pole specifications were last revised on the basis of research reported by Wood et al. (1960) and Wood and Marquardt (1965); this research covered the 5 major pole species and included the major southern pine species. The requirements for poles are given in the current edition of ANSI Standard

05.1 (formerly ASA Standard) *Specifications and dimensions for wood poles*. The engineered stress in bending for the major southern pine species is 8,000 p.s.i.; this is a near ultimate value and is reduced by design engineers according to importance of use and hazard from failure.

Piles.—Foundation piles are used to support structures resting on soils having insufficient bearing strength to support footings for any but the lightest loads. Current practice is to design wood piles for loads of 15 to 25 tons when load tests are not conducted and for loads of 40 to 50 tons when justified by load test. These higher loads produce stresses that approach the allowable stresses for green sawn timbers.

Wilkinson (1968), in a study of strength properties in compression parallel to the grain and in bending, determined that southern pine piles had an average tip-end crushing strength of 1,820 p.s.i., an average modulus of elasticity of 1,340,000 p.s.i., and an average modulus of rupture of 4,580 p.s.i. This rather low modulus of rupture may have been attributable to the steam conditioning to which the piles were subjected (15 hours at 245° F.). Kiln-drying of southern pine piles caused a reduction in crushing strength of about 12 percent over that of green piles when both were evaluated with moisture contents above the fiber saturation point. Kiln-drying of southern pine piles did not affect the modulus of elasticity measured in compression.

The physical characteristics of timber piles are described in *Standard specifications for timber piles*, ASTM Designation D25-70. Basic principles for establishing design stress values are given in *Tentative method of test for establishing design stress for round timber piles*, ASTM Designation D2899-70T.

Laminated beams.—Beams having outer laminae of upper grades of nominal 1- and 2-inch-thick, kiln-dry, southern pine lumber are assigned maximum allowable design stresses as follows:

Modulus of elasticity	1,800,000 p.s.i.
Stress in bending	2,600 p.s.i.
Stress in horizontal shear	200 p.s.i.

By selective placement of laminae, it is possible to increase both modulus of elasticity and modulus of rupture of southern pine laminated beams, and at the same time reduce their variability. The principle of using modulus of elasticity to locate laminations within a beam has been investigated by Koch (1964, 1967ab, 1971), Koch and Bohannon (1965), and Koch and Woodson (1968). In each of these studies, thin ($\frac{1}{8}$ - to $\frac{1}{4}$ -inch-thick) southern pine veneers were used to fabricate beams from 7 to 18 inches deep. Veneers were so arranged that the stiffest veneers were near the outer faces of the beam and veneer stiffness was gradually decreased toward the neutral axis.

In the study by Koch and Woodson (1968), butt-jointed southern pine veneers were located by stiffness and fabricated into beams. The beams,

which were 2 inches wide, 18 inches deep, and 25 feet long, had an average modulus of elasticity of 2.1×10^6 p.s.i. Average modulus of rupture was 9,020 p.s.i. with a 95-percent exclusion limit of 7,650 p.s.i.

Koch and Bohannon (1965) evaluated laminated southern pine beams in which the veneer laminations were arranged by four different methods: specific gravity, stiffness, appearance, and random. They found that the modulus of elasticity of small beams which had their laminae arranged by stiffness averaged 31 percent higher than those which had their laminae arranged randomly. The accompanying increase in average modulus of rupture was from 6,630 p.s.i. to 10,200 p.s.i., a 54-percent increase. The five beams they assembled by appearance were considerably stronger and stiffer than those randomly laid up, but they were not as strong and stiff as those laid up using stiffness as the criterion. This research showed that small beams with thin laminae arranged by stiffness were stronger than beams assembled by other means.

Thick laminations, if selectively placed, also yield beams of improved strength and stiffness. With finger-jointed, $8/4$, southern pine laminations assembled into beams $5\frac{1}{4}$ inches wide, $2\frac{3}{8}$ inches deep, and 40 feet long, Moody and Bohannon (1970) studied the effect of using modulus of elasticity in addition to visual grades as criteria for the positioning of laminations in laminated beams. They found that the average modulus of elasticity of the beams manufactured using both visual and stiffness criteria was 12 percent higher than that for beams using only visual criteria; and the average modulus of rupture was 14 percent higher than that for the visual-only beams. The minimum-strength of beams in each group, however, was approximately equal.

A detailed presentation of design stresses for laminated beams should include lamination layup data to be meaningful. Current design stress information can be obtained from the American Institute of Timber Construction, Englewood, Colo.

Plywood.—The source of standards for design stresses applicable to southern pine plywood is the American Plywood Association, Tacoma, Wash. As these standards are more or less continuously revised, they are not reproduced here.

10-7 LITERATURE CITED

- | | |
|---|---|
| <p>Bendtsen, B. A., and Ethington, R. L.
1972. Properties of major southern pines: Part II—Structural properties and specific gravity. USDA Forest Serv. Res. Pap. FPL 177.</p> | <p>Biblis, E. J.
1969b. Transitional variation and relationships among properties within loblolly pine growth rings. Wood Sci. and Technol. 3: 14-24.</p> |
| <p>Biblis, E. J.
1969a. Tensile properties of loblolly pine growth zones. Wood and Fiber 1: 18-28.</p> | <p>Biblis, E. J.
1970. Effect of thickness of microtome sections on their tensile properties. Wood & Fiber 2(1): 19-30.</p> |

- Biblis, E. J., and Fitzgerald, J. D.
1970. Shear properties of loblolly pine growth zones. *Wood Sci.* 2: 193-202.
- Davies, G. W.
1968. Microscopic observations of wood fracture. *Holzfor-schung* 22: 177-180.
- Doyle, D. V.
1968. Properties of No. 2 dense kiln-dried southern pine dimension lumber. USDA Forest Serv. Res. Pap. FPL-96, 24 pp. Forest Prod. Lab., Madison, Wis.
- Doyle, D. V., and Markwardt, L. J.
1966. Properties of southern pine in relation to strength grading of dimension lumber. USDA Forest Serv. Res. Pap. FPL-64, 64 pp. Forest Prod. Lab., Madison, Wis.
- Doyle, D. V., and Markwardt, L. J.
1967. Tension parallel-to-grain properties of southern pine dimension lumber. USDA Forest Serv. Res. Pap. FPL-84, 36 pp. Forest Prod. Lab., Madison, Wis.
- Frey-Wyssling, A.
1953. [Fine structure of slip lines in overstressed wood.] *Holz als Roh- und Werkstoff* 11: 283-288.
- Frey-Wyssling, A., and Stussi, F.
1948. [Stability and deformation of softwood when under pressure perpendicular to the grain.] *Schweiz. Z. Für Forstwesen* 99(3): 106-114.
- Galligan, W. L., editor.
1965. Proceedings of the second symposium on nondestructive testing of wood. 543 pp. Pullman, Wash.: Wash. State Univ.
- Galligan, W. L., and Courteau, R. W.
1965. Measurements of elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. *In* Proceedings of second symposium on the non-destructive testing of wood, pp. 223-244. Pullman, Wash.: Wash. State Univ.
- Garland H.
1939. A microscopic study of coniferous wood in relation to its strength properties. *Ann. Mo. Bot. Gard.* 26: 1-95.
- Gerhards, C. C.
1970. Dependence of MOE on strength ratio and specific gravity: 4-inch-thick southern pine. *Forest Prod. J.* 20(6): 37-38.
- Hilbrand, H. C., and Miller, D. G.
1966. Machine grading—theory and practice. *Forest Prod. J.* 16(11): 28-34; (12): 36-40.
- Hoyle, R. J.
1968. Background to machine stress grading. *Forest Prod. J.* 18(4): 87-97.
- Hoyle, R. J., editor.
1970. Proceedings of the third short course on nondestructive testing of wood. 197 pp. Pullman, Wash.: Wash. State Univ. Press.
- Ifju, G.
1969. Within-growth-ring variation in some physical properties of southern pine wood. *Wood Sci.* 2: 11-19.
- James, W. L.
1962. Dynamic strength and elastic properties of wood. *Forest Prod. J.* 7: 253-260.
- Jayne, B. A.
1960. Some mechanical properties of wood fibers in tension. *Forest Prod. J.* 10: 316-322.
- Keith, C. T., and Côté, W. A.
1968. Microscopic characterization of slip lines and compression failures in wood cell walls. *Forest Prod. J.* 18(3): 67-74.
- Kennedy, R. W., and Chan, C. K.
1970. Tensile properties of microsections prepared by different microtomy techniques. *J. Inst. Wood Sci.* 25(5:1): 39-42.
- Kisser, J., and Steinger, A.
1952. [Macroscopic and microscopic structural changes in wood subjected to bending stress.] *Holz als Roh- und Werkstoff* 10: 415-421.

- Koch, P.
1964. Strength of beams with laminae located according to stiffness. *Forest Prod. J.* 14: 456-460.
- Koch, P.
1966. Straight studs from southern pine veneer cores. USDA Forest Serv. Res. Pap. SO-25, 37 pp. Southern Forest Exp. Sta., New Orleans, La.
- Koch, P.
1967a. Location of laminae by elastic modulus may permit manufacture of very strong beams from rotary-cut southern pine veneer. USDA Forest Serv. Res. Pap. SO-30, 12 pp. South. Forest Exp. Sta., New Orleans, La.
- Koch, P.
1967b. Super-strength beams laminated from rotary-cut southern pine veneer. *Forest Prod. J.* 17(6): 42-48.
- Koch, P.
1971. Process for producing laminated structures. (U.S. Pat. No. 3,580,760) U.S. Pat. Off., Wash., D.C.
- Koch, P., and Bohannan, B.
1965. Beam strength as affected by placement of laminae. *Forest Prod. J.* 15: 289-295.
- Koch, P., and Woodson, G. E.
1968. Laminating butt-jointed, log-run, southern pine veneers into long beams of uniform high strength. *Forest Prod. J.* 18(10): 45-51.
- Liska, J. A.
1950. Effect of rapid loading on the compressive and flexural strength of wood. USDA Forest Serv. Forest Prod. Lab. Rep. R1767, 17 pp.
- Liska, J. A.
1965. Research progress on the relationships between density and strength. Proc., Symp. on Density . . . A Key to Wood Quality, pp. 89-97. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
- Mark, R.
1965. Tensile stress analysis of the cell walls of coniferous tracheids. In *Cellular ultrastructure of woody plants*, pp. 493-533. W. A. Côté, Jr., ed. Syracuse: Syracuse Univ. Press.
- Marra, G. G., Pellerin, R. F., and Galigan, W. L.
1966. Nondestructive determination of wood strength and elasticity by vibration. *Holz als Roh- und Werkstoff* 10: 460-466.
- Miller, D. G.
1968. Nondestructive testing of joists by a vibrational technique. *Forest Prod. J.* 18(2): 25-28.
- Moody, R. C., and Bohannan, B.
1970. Flexural properties of glued-laminated southern pine beams with laminations positioned by visual-stiffness criteria. USDA Forest Serv. Res. Pap. FPL 127, 20 pp. Forest Prod. Lab., Madison, Wis.
- Orosz, I.
1968. Some nondestructive parameters for prediction of strength of structural lumber. USDA Forest Serv. Res. Pap. FPL 100, 6 pp. Forest Prod. Lab., Madison, Wis.
- Panshin, A. J., DeZeeuw, C., and Brown, H. P.
1964. Textbook of wood technology. 643 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Pearson, R. G., and Gilmore, R. C.
1971. Characterization of the strength of juvenile wood of loblolly pine (*Pinus taeda* L.). *Forest Prod. J.* 21(1): 23-31.
- Pellerin, R. F.
1965. A vibrational approach to nondestructive testing of structural lumber. *Forest Prod. J.* 15: 93-101.
- Quirk, J. T., Kozlowski, T. T., and Blomquist, R. F.
1967. Effects of adhesive formulation and age on strength of bonded butt joints. USDA Forest Serv. Res. Note FPL-0178, 16 pp. Forest Prod. Lab., Madison, Wis.

- USDA Forest Products Laboratory.
 1955. Wood handbook. USDA Agr. Handbook 72, 528 pp.
- USDA Forest Products Laboratory.
 1964. Symposium on nondestructive testing of wood. USDA Forest Serv. Res. Note FPL-040, 56 pp. Forest Prod. Lab., Madison, Wis.
- Walters, E. O., and Westbrook, R. F.
 1970. Vibration machine grading of southern pine dimension lumber. Forest Prod. J. 20(5): 24-32.
- Wardrop, A. B.
 1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. Australian J. Sci. Res. 4B: 391-414.
- Wardrop, A. B., and Addo-Ashong, F. W.
 1963. The anatomy and fine structure of wood in relation to its mechanical failure. In Symposium on fracture, 32 pp. Proc., Melbourne Univ. Eng. Dep.
- Wilkinson, T. L.
 1968. Strength evaluations of round timber piles. USDA Forest Serv. Res. Pap. FPL-101, 44 pp. Forest Prod. Lab., Madison, Wis.
- Wilson, T. R. C.
 1932. Strength-moisture relations for wood. USDA Tech. Bull. 282, 88 pp.
- Wood, L. W., and Markwardt, L. J.
 1965. Derivation of fiber stresses from strength values of wood poles. USDA Forest Serv. Res. Pap. FPL-39, 8 pp. Forest Prod. Lab., Madison, Wis.
- Wood, L. W., Erickson, E. C. O., and Dohr, A. W.
 1960. Strength and related properties of wood poles. Amer. Soc. for Testing Mater. Wood Pole Res. Program Final Rep., 83 pp.

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11

Defects and grades of trees and logs

The southern pines have many attributes that contribute to their ready conversion into wood products; they also have a few undesirable characteristics. On the credit side—the trees of the major species tend to be self pruning in fully-stocked stands (fig. 3-14) so that degrade from knots is less than that in many other conifers, stems are not excessively tapered and most are fairly straight, spiral grain is usually absent or minor, attack by wood borers or birds is infrequent in living trees and freshly cut logs, growth stresses are minor, mineral streaks or frost cracks virtually never develop, and shake, decay, and worm holes are seldom found in young trees. On the debit side—cankers are common in some stands, some trees have crooked or forked stems, in open-grown trees and in some of the minor species numerous thick branches may cause large knots in the stem (fig. 3-20), pitch pockets and streaks are common in wood cut from some stands, most trees contain some compression wood, all contain a central zone of inferior juvenile wood, and some are so fast growing that their utility for some purposes is reduced.

11-1 DEFECTS

Uniformity is much desired by most users of pine. From this standpoint, extreme variations in gross and minute anatomy (ch. 5), chemical constituents (ch. 6), and specific gravity (ch. 7) could be considered as defects. These variations are, however, omitted from the following discussion of factors that degrade logs and trees because they are not recognized by grading rules except those applicable to poles and piling and to some grades of structural lumber which specify a minimum number of rings per inch and a minimum percentage of latewood.

STEM CROOK, FORK, AND TAPER

The utility of a pine tree is strongly influenced by the form of the stem. Crooked, forked, and excessively tapered stems are not suitable for poles or piling; if converted to lumber or veneer their yield is lower in both quantity and quality than that from straight stems with little taper.

Crooked pulpwood stacks poorly for transport and is more difficult to debark than straight wood.

Some stem deformations in southern pine are traceable to environmental causes such as sleet storms, or attack on terminal shoots by insects such as *Dioryctria larvae* (Merkel et al. 1965); frequency of deformations varies among species (compare figs. 3-14 and 3-10). The major factors controlling stem straightness are probably hereditary (Mergen 1955; Barber 1961, p. 101; Goddard and Strickland 1964; Gansel 1966; Nikles 1966). Progeny from crooked and forked trees tend also to be crooked and forked (fig. 11-1).

Ultimately, it is hoped that the incidence of stem crook in southern pine will be greatly reduced through control of genetic variation and seed source. For the present, wood loss due to stem crook can be reduced by judicious cutting of trees into logs.

Factors influencing taper in stems have been extensively reviewed by Larson (1963). In brief, the stem within the crown is strongly tapered. In open-grown trees with long, vigorous crowns, the rapid stem taper either continues or diminishes rather slowly down the branch-free bole. As the base of the crown recedes and the clean bole elongates with increasing age or stand closure, the stem becomes more cylindrical.

KNOTS

Knots are the major cause of degrade in saw logs and veneer bolts; in boards or veneer they are associated with grain distortions, local areas of weakness, unsightly appearance, resin exudation, compression wood, and the machining defect of torn grain. The pulp industry also has difficulty with knotty wood because it is very dense, chips nonuniformly, has a high resin content, and is associated with compression wood.

While branches are living, the cambium adds layers of wood that are continuous over both stem and branch; knots so formed are tight (fig. 11-2, Left). When the branch dies and is shed, the stub of the dead branch is slowly embedded in stemwood; this usually results in an encased knot (fig. 11-2, Center) that will ultimately be overgrown with clear wood. Should flat-sawn lumber be cut through the encased knot, it may loosen sufficiently to cause a knot hole.

In a clear-boled southern pine, therefore, there are three zones of knot occurrence. The inner zone or core contains tight knots. The second zone—variable in radial thickness depending on the rate of pruning—contains encased or loose knots; this loose-knot zone extends to the bark in the portion of the stem lying above the clear wood zone and below the live crown. In trees of sufficient age, the clear wood zone is the outermost sheath and extends from ground level part way to the live crown. If branches are smoothly pruned close to a young stem, clear wood will soon grow over the wound (fig. 11-2, Right), expediting production of clear lumber and veneer.

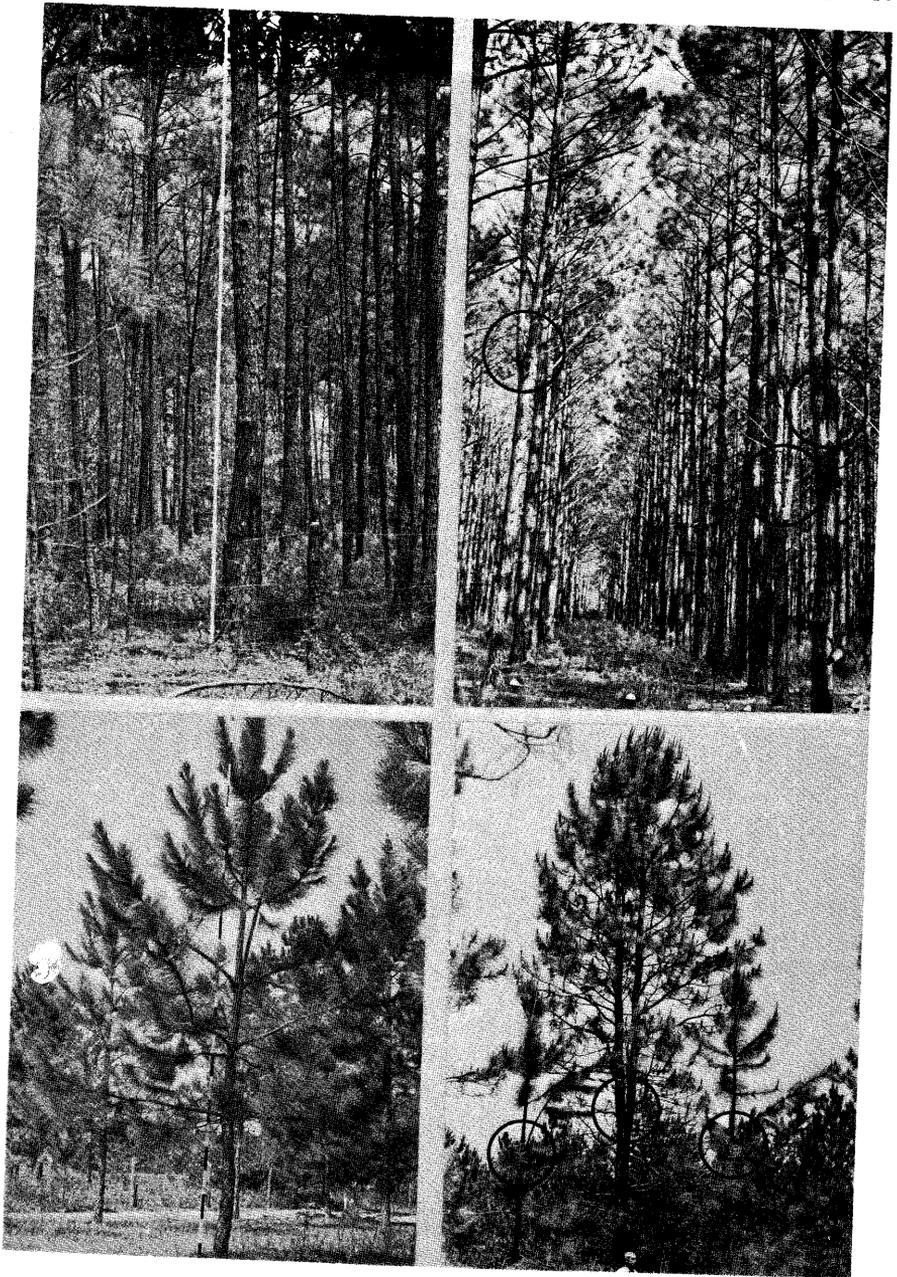
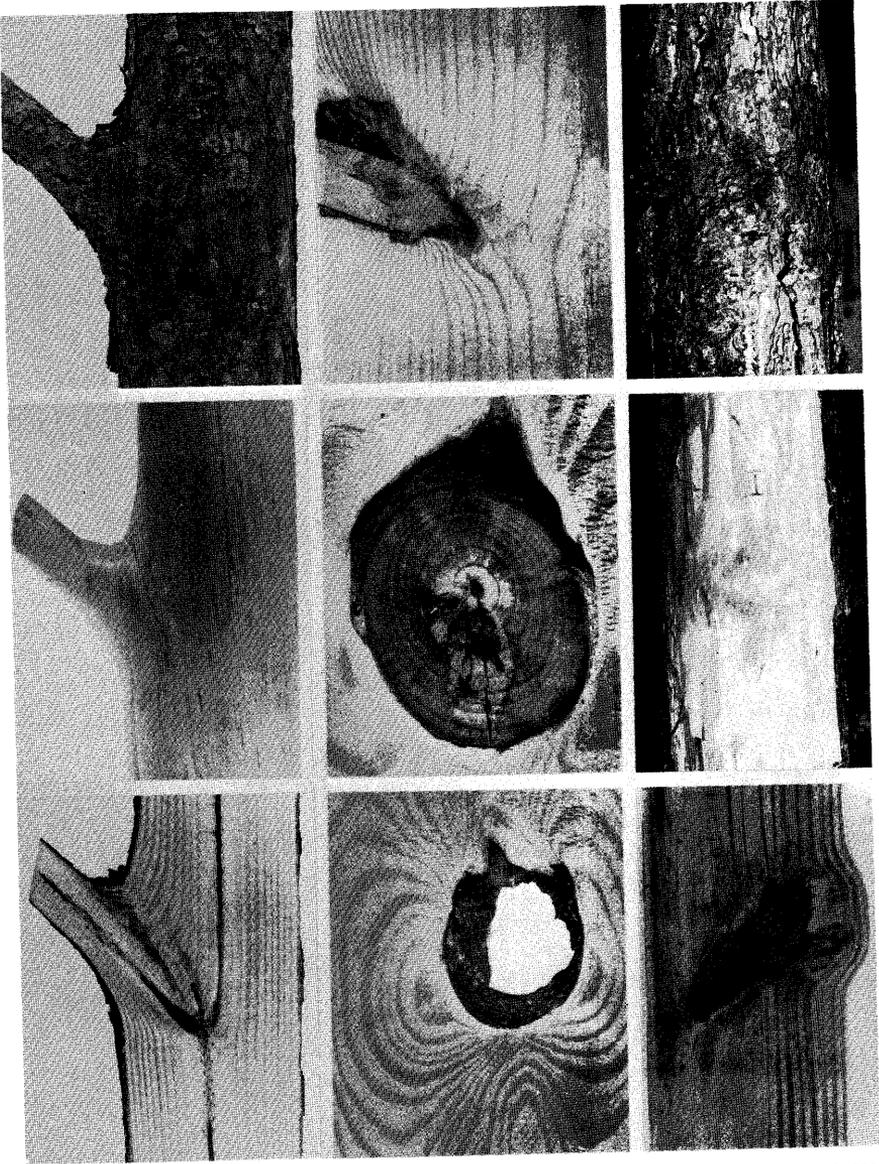


Figure 11-1.—Trees with forked or crooked stems tend to have progeny with similar defects. (Top left) Parent slash pine with sweep and twist. (Bottom left) Crooked wind-pollinated progeny from tree above. (Top right) Forking of trees in this plantation was frequent and probably due to the seed source. (Bottom right) Natural regeneration under slash pine with forks similar to that of the older pine which was probably the seed source. (Photos from Mergen 1955.)



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Figure 11-2.—Knots in slash pine. (Left) Live branch with tight knot, stem surface after peeling, same branch in radial section. (Center) Dead branch stub with encased knot, tangential section of another encased knot, typical knot hole. (Right) Bark scars, stem surface after peeling, and clear wood formed 6 years after pruning limb flush with stem.

Mode of branching.—In his study of branch characteristics of longleaf pines, Snyder (1961) noted three types of branch growth. At the top, branches are almost as thick as the leader and competing with it; their attachment angles are acute. Next comes a series of two to seven whorls where there is an equilibrium in growth among the branches and between

them and the main stem. Branches tend to thicken progressively toward the ground but in proportion to the thickening of the main stem; angles are less sharp. This zone of growth equilibrium is an appropriate place to sample for branch characters. Below it is a senescence zone where branches are smaller and are not growing in proportion to the main stem.

Persistence of branches and knot length.—Paul (1938) analyzed 10 to 19 trees of each of the four major southern pine species for knot characteristics. Stands from North Carolina, Florida, and Mississippi were sampled. He found that branches on the lower 20 feet of the stem remained alive 7 to 9 years after origin and the intergrown tight knots formed while the branch was alive averaged 1 inch long.

He also observed that dead branches persisted for the longest time in shortleaf pine, but the average length of the dead portion of encased knots was about the same for all four species—1 inch for knots $\frac{1}{2}$ -inch in diameter or less, and 2 inches for knots more than $\frac{1}{2}$ -inch in diameter.

<u>Pine species</u>	<u>Persistence of dead branches</u>
	<i>Years</i>
Shortleaf -----	12
Loblolly -----	8
Slash and longleaf -----	6

Paul found that branches of small diameter (less than $\frac{1}{2}$ -inch) may persist for as much as 50 years because they are too dry to support growth of wood-destroying fungi. Generally speaking, however, he concluded that in stands of high density natural pruning to a height of 20 feet takes place within 6 to 15 years after the branches die.

Of the four major southern pine species, shortleaf pine appears to have the least inherent tendency for natural pruning. Pruning of southern pines to improve timber quality is not widely practiced because of the expense of the operation and the difficulty of selling pruned trees at appropriately high prices.

Knot volume.—In shortleaf pine, Davis (1931) found that knots were fewer and smaller in log-run boards from virgin-growth than from second-growth trees. These data indicate that knots comprise less of the total volume of old trees than of young.

<u>Source of shortleaf pine boards</u>	<u>Knots per 8 bd. ft. of lumber</u>	<u>Average knot size</u>
	<i>Number</i>	<i>Sq. in.</i>
Virgin growth	3.8	0.8
Second growth	5.7	1.1

In a sample of forty 8- and 11-year-old, plantation-grown loblolly pines, knots comprised 1.1 percent of the total stem volume inside bark. The top 5-foot merchantable bolt (to 4-inch top diameter) in 11-year-old

loblolly pines averaged 2.3 percent knot volume, with 5-foot bolts immediately above and below this having 2.6 and 2.3 percent respectively (Wedel et al. 1968).

Knot number.—Paul’s (1938) study showed that all four major species usually had two to four knots per whorl and that whorls with more than five knots were rare. Wedel et al. (1968) observed an average of 3.9 branches per whorl (31 branches per tree) on thirty-two 8-year-old plantation-grown loblolly pines.

Paul further noted that the average number of branches on the lower 20 feet of the stem varied with species.

<u>Pine species</u>	<u>Range of tree age</u>	<u>Branches on lower 20 feet</u>
	<i>Years</i>	<i>Number</i>
Shortleaf -----	40-51	11
Loblolly -----	21-72	7
Slash -----	18-49	5
Longleaf -----	20-30	4

It is believed that southern pine trees with few branches tend to have progeny with few branches. Trees with the fewest branches may not, however, have the smallest knot volume (Wedel et al. 1968).

Knot diameter.—The size of knots is closely related to the size of branches. In young trees the size of visible branches provides a good indication of knot size within the bole. In older trees, knot size in clear stems is influenced by the size attained by branches before they were overgrown.

Paul’s (1938) study of trees 18 to 72 years old showed that shortleaf and loblolly pines had the smallest branches in the lowest 20 feet of the stem, while slash and longleaf pines had the largest.

<u>Pine species</u>	<u>Average branch diameter</u>	<u>Maximum branch diameter</u>
	----- <i>Inches</i> -----	
Shortleaf -----	0.4	1.7
Loblolly -----	.4	2.0
Slash -----	.5	3.0
Longleaf -----	.6	2.0

He failed to find a strong correlation between stand density and average knot diameter.

A study of eight trees from an 11-year-old loblolly pine plantation showed that there was an increase in branch diameter up to 25 feet above ground level, while from 25 to 40 feet the branch diameter remained almost constant; above this level branch diameter decreased. When 32 loblolly pines 8 years of age were measured, average branch diameter was 0.69 inch for trees that averaged 5.7 inches in diameter at breast height. The ratio of branch diameter to bole diameter at point of attachment was 0.12. Branch diameter was greatest in the fastest grow-

ing trees, in trees with small branch angles, and in trees with small numbers of branches (Wedel et al. 1968).

It has been shown that southern pine trees with large-diameter branches tend to have progeny also having branches of large diameter (Gansel 1966; Strickland and Goddard 1966; Wedel et al. 1968; Stephenson and Snyder 1969).

Branch angle.—The cross-sectional area of knots exposed by flat-sawing or rotary-peeling increases as the square of the diameter of the branch causing the knot; it also increases (into an ellipsoid shape) as the angle between branch and stem approaches zero (fig. 11-3).

Gansel (1966) and Barber (1961) found that slash pine branches making a large angle with the stem were generally thinner and shorter than those making a small angle. The thirty-two 8-year-old loblolly pines studied by Wedel et al. (1968) had an average branch angle of 58° from vertical; those with the largest angle tended to have branches of small diameter.

Branch angle appears to be an inherited characteristic (Strickland and Goddard 1966; Wedel et al. 1968; Stephenson and Snyder 1969). Figure 11-4 illustrates genetic variation of those branch characters that affect the percentage of knot volume in stemwood.

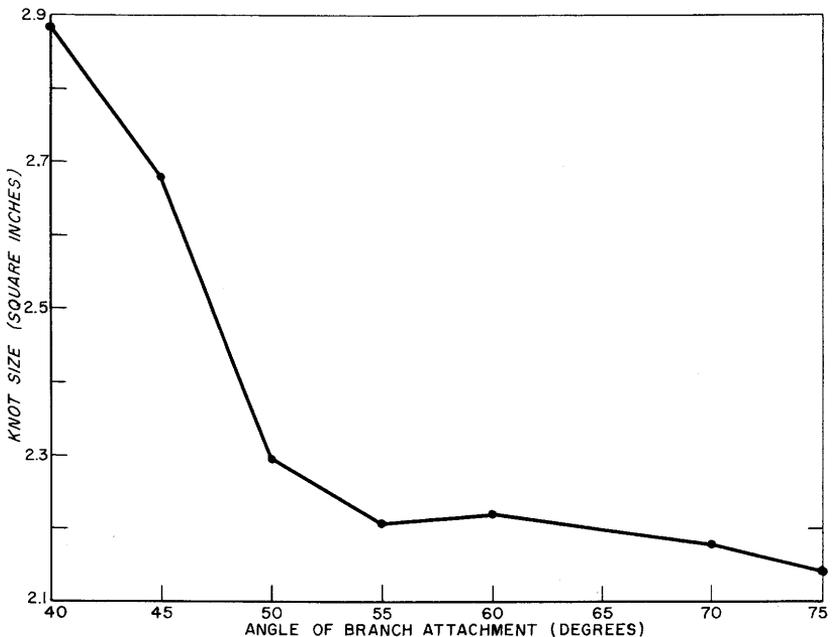


Figure 11-3.—Relationship of angle between branch and stem and cross-sectional area of longleaf pine knots exposed by bark removal. Knot area is adjusted to the mean branch size of 48 trees (showing 16 to 29 rings at breast height) sampled in south Mississippi. (Drawing after Snyder 1961.)



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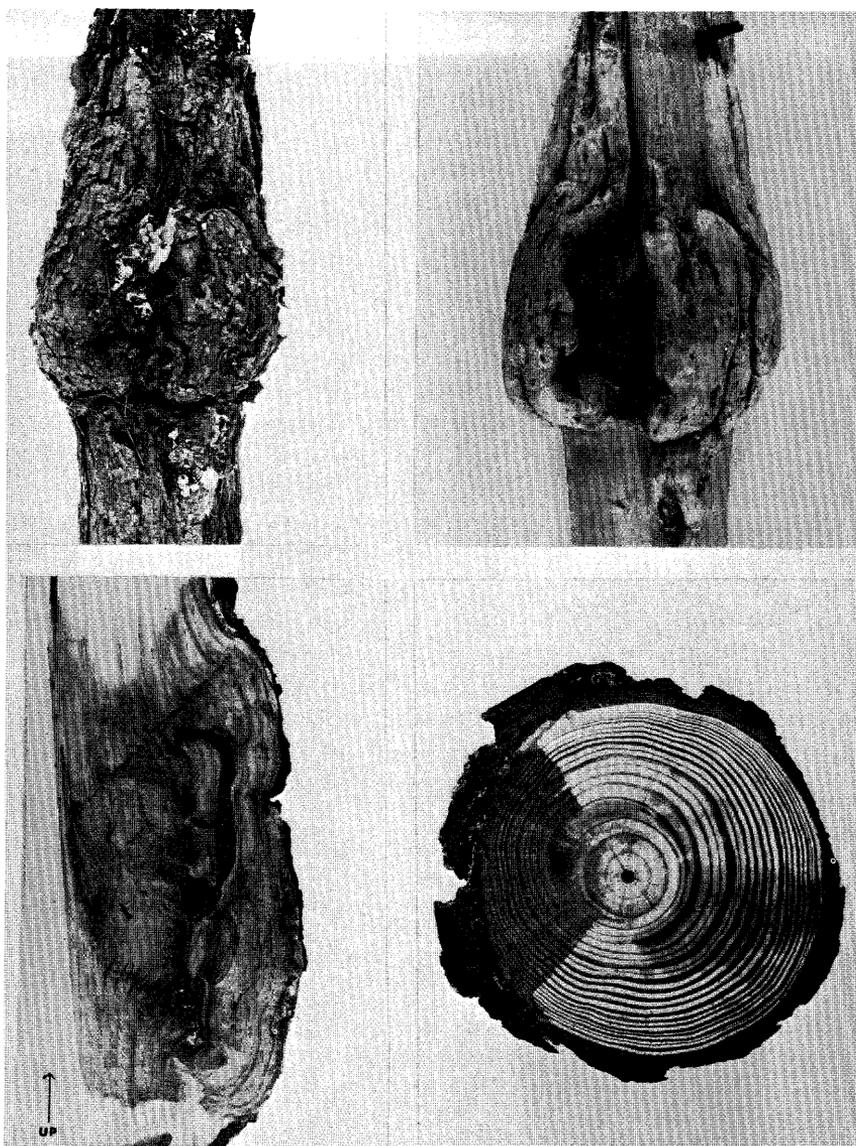
Figure 11-4.—Genetic variation in southern pine branches. (Left) At age 7, limbs on the tree at top are much larger, both absolutely and relative to tree diameter than those at the bottom. The trait is heritable. (Center) Trees in photo at bottom have inherited a desirable tendency for branches to join the trunk at right angles, forming small knots. More low-quality wood will grow at the base of the upward-trending branches of trees in photo at top. (Right) Trees with fewer-than-average branches have better-than-average wood. (Photos from Stephenson and Snyder 1969.)

CANKERS¹

Fusiform rust, caused by *Cronartium fusiforme* Hedgc. & Hunt ex. Cumm., a serious killer of pine seedlings, causes galls and cankers of unusable material which degrade product values by reducing volume, and by limiting saleable portions of trees to less than optimum lengths (fig. 11-5). These defects also subject trees to excessive wind breakage.

The rust lives from year to year in the living bark of pine branches and stems, causing galls that are typically spindle shaped. Old galls, particu-

¹ Except for the illustrations of fusiform rust cankers, this information on rust disease is taken from Verrall (1958).



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Figure 11-5.—Fusiform-rust cankers cut from loblolly and slash pine stems. (Top) Canker with bark in place and with bark removed; cut from 11-year-old loblolly pine. Stem is 5.5 inches in diameter below canker. (Bottom left) Longitudinal section of a canker cut from a 9-year-old, 4.4-inch-diameter loblolly pine stem. (Bottom right) Cross section through a canker removed from a slash pine stem shows typical discoloration on left side.

larly on slash pine, sometimes die on one side and form flat or depressed cankers that may exude large amounts of resin. At least some of this resin exudation is caused by secondary infections of the pitch canker fungus *Fusarium lateritium* f. *pini*.

Fusiform rust is most prevalent in the longleaf pine belt and in the

southern part of the shortleaf-loblolly-hardwood forest type. Loblolly and slash pines are particularly susceptible to this fungus. Pitch and pond pines are also attacked, while longleaf pine is moderately resistant and shortleaf pine highly so. Pines of all ages are susceptible; damage is worst in young stands. Genetic variation may ultimately enable control because resistance to the fusiform rust disease is transmissible and can be incorporated in tree breeding programs (Stephenson and Snyder 1969). Readers interested in additional information on fusiform rust will find the papers by Czabator (1971) and Dinus and Schmidting (1971) useful.

Eastern gall rust (*Cronartium cerebrum*), while much less destructive than fusiform rust, is common in shortleaf, Virginia, sand, and spruce pines. It occasionally occurs on loblolly and slash pines. The globose galls of the eastern rust, with their distinct "collars" of bark at each end, can usually be distinguished from fusiform rust galls that usually are spindle-shaped and only occasionally ball-shaped.

CROSS GRAIN

A piece of pine has **cross grain** whenever its tracheids are not aligned parallel to its longitudinal axis.

Cross grain can be caused by **spiral grain** in the standing tree. In southern pine the angle of spiral reaches a maximum in the second or next few rings from the pith and then decreases rapidly in succeeding rings. This helical angularity of tracheids has been observed by Dadswell and Nicholls (1959) to be as high as 11° in some growth rings of slash pine; however, they did not consider it a marked defect in any of the 13 trees (aged 15 to 30 years) examined. In a study of 1,043 4-year-old loblolly pine trees, Zobel et al. (1968) only rarely found a tree with spirality bad enough to cause serious degrade; 19 had a spirality of 7° or more, and only two had spirality as great as 9° . The average was 2.8° .

While extensive data have not been published, it appears that spiral grain is not a serious defect in the major southern pine species. The scarcity of pronounced helical patterns of weathering in southern pine poles supports this contention.

More serious and much more prevalent in southern pine lumber is the cross grain caused by grain distortions around knots, by sawing crooked logs, and by sawing, edging, or ripping boards so that the saw lines are not parallel to tracheid alignment. Similarly, logs having crook or pronounced taper, if rotary-cut, will produce cross-grained veneer.

Cross grain is usually expressed in terms of slope, i.e., as a ratio of the distance of grain deviation from one edge of the piece to length along the grain. When two adjacent surfaces both exhibit cross grain, the true angularity is greater than that shown on either face and is equal to the square root of the sum of squares of the slopes on the two adjacent faces. In the southern pines, alignment of the resin canals usually permits quick

evaluation of severity of cross grain. Other methods for easily measuring slope of grain are given in Anderson et al. (1945).

Wood with cross grain is weaker than straight-grained wood—particularly in tension parallel to the longitudinal axis of the member. The strength of wood members with various grain slopes is compared below to the strength of a straight-grained member (USDA Forest Products Laboratory 1955, p. 97):

Maximum slope of grain in member	Static bending		Impact bending—height of drop causing complete failure (50-pound hammer)	Compression parallel to grain—maximum crushing strength
	Modulus of rupture	Modulus of elasticity		
	----- <i>Percent</i> -----			
Straight-grained.....	100	100	100	100
1 in 25.....	96	97	95	100
1 in 20.....	93	96	90	100
1 in 15.....	89	94	81	100
1 in 10.....	81	89	62	99
1 in 5.....	55	67	36	93

COMPRESSION WOOD

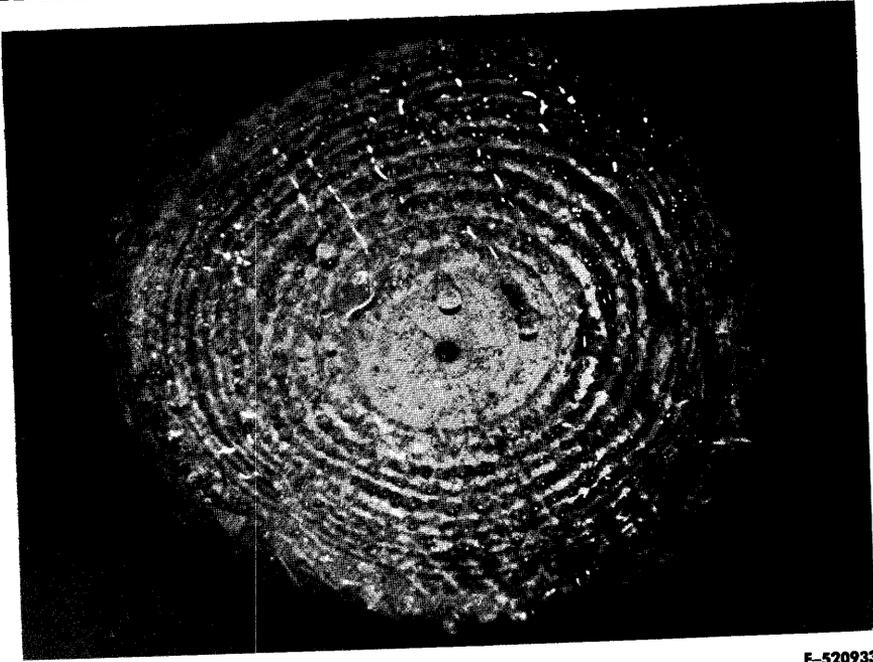
Lumber containing compression wood warps excessively and is weaker in most properties than normal wood of the same specific gravity. For this reason the rules governing the selection of upper grades of southern pine finish and stress grades of lumber exclude compression wood if "in a readily identifiable and damaging form", in the lower grades, e.g., D finish, timbers not stress rated, and the board grades, there is no restriction on compression wood (Southern Pine Inspection Bureau 1970). Similarly, veneer that contains excessive proportions of compression wood will cause plywood panels to warp.

Section 5-6 describes the anatomy, location, and frequency of occurrence of compression wood.

PITCH

Freshly crosscut southern pine logs often exude large amounts of resin (fig. 11-6); this copious exudation, which causes hands and gloves to become uncomfortably sticky, reflects the high resin content of southern pine wood. Southern pine with excessive pitch concentrations does not finish well, and is unsatisfactory for uses where it must be painted or varnished.

Pitch streak.—Lumber grading rules (Southern Pine Inspection Bureau



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Figure 11-6.—Pitch exudation on end of freshly crosscut slash pine log.

1970) define pitch streak (fig. 11-7 top left) as a well-defined accumulation of pitch in a more or less regular streak. The severity of its occurrence in lumber ranges from that termed "very small" (not over $\frac{3}{8}$ -inch wide and not over 15 inches long) to very large (over one-fourth the width by one-half the length of the board surface. In general, pitch streaks are severely limited only in the appearance grades of southern pine lumber. Pitch streaks—not more than $\frac{3}{8}$ -inch wide—that blend with the color of the wood are permitted in Grade "A" veneer and veneer to be given natural finish (American Plywood Association 1966).

In addition to the occurrence of pitch in more or less regular streaks, it also occurs in irregular patches (fig. 11-7 top right). The Southern Pine Inspection Bureau (1970) recognizes **pitch** in degrees of severity ranging from "light" (light but evident) to "heavy" (very evident accumulation of pitch showing by its color and consistency).

Pitch pocket.—Cavities, usually occurring within the limits of an annual ring or between annual rings, that hold liquid or dry pitch are termed **pitch pockets**. When exposed in tangential section these pockets are usually elliptical in shape with the long axis of the ellipse aligned with the pith of the tree (fig. 11-7 bottom). The Southern Pine Inspection Bureau (1970) recognizes degrees of severity ranging from "very small" (not over $\frac{1}{8}$ -inch wide by 2 inches long) to "very large" (over 4 sq. in. in area); a **closed** pitch pocket has an opening on one surface only, whereas a **through** pitch pocket has an opening to the opposite surface. Only closed

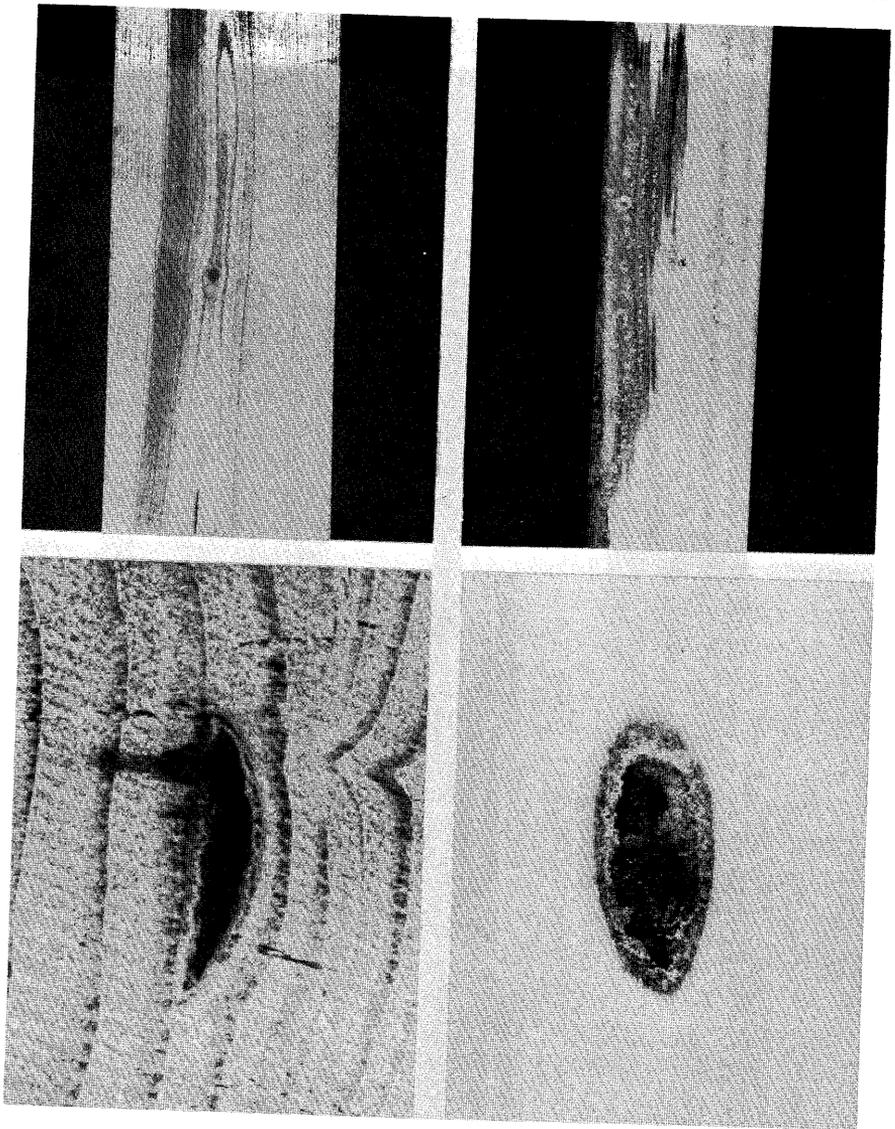


Figure 11-7.—Pitch in southern pine lumber. (Top left) Pitch streak. (Top right) Irregular patch of pitch. (Bottom) Pitch pocket in transverse section (left) and tangential section (right). F-520934

pitch pockets of very small size are allowed in the upper grades of finish lumber.

Effect of pitch on strength.—Tests have shown that resin in southern pine slightly increases some strength properties, but the additional strength is very small compared to that which normally would result from an equal weight of wood substance (USDA Forest Products Laboratory 1955, p. 102).

COMPRESSION FAILURES

The Gulf and Atlantic Coast regions are repeatedly subjected to hurricanes that cause much breakage of stems in stands of southern pine. It is reasonable to suppose that gusts of wind at times stress stems into some degree of compression failure but not to the point of complete failure accompanied by stem breakage. When these trees are later logged, they still contain wood having minute compression failures, and lumber cut from them is, to some degree, weaker than normal. There are no published data reporting the prevalence of compression failures in living southern pine trees that have been exposed to hurricane winds; it would make an interesting study.

SHAKE

According to Meyer and Leney (1968), **shake** is a naturally occurring defect of standing trees caused primarily by the separation of contiguous latewood tracheids along their compound middle lamellae; the failure tends to occur among the last-formed cells of the growth increment, usually within 10 cells of the ring boundary. Shakes tend to remain in only one ring but may also pass through two or more rings by following a short, abrupt, radial path between rings. In their work with western conifers they found partially or completely loosened fibers and deposits of extraneous material in all shakes obtained from standing trees.

In present-day forests of young southern pine, shake in standing trees is not a common defect.

WIDE RINGS

Wide-ringed lumber is defined by the Southern Pine Inspection Bureau (1970) as having less than four rings per inch; it is excluded from the important structural grade of Number 1 Common dimension lumber as being too fast grown. Most mature southern pine wood has four or more rings per inch, but in the juvenile core near the pith annual rings frequently are wider than $\frac{1}{4}$ -inch and latewood content is low.

Results from two studies of southern pine 8-foot 2 by 4's give an idea of the proportion of wide-ringed lumber yielded by the juvenile core (Koch 1966, p. 11; 1971).

Number of 2 by 4's	Source	Region	Percent with less than 4 rings per inch
144	Veneer cores	Central Louisiana	15
144	6- to 8-inch logs	East Texas	20
336	Veneer cores	Central Louisiana	59

INSECT DAMAGE AND STAIN

Insects of the species *Platypus flavicornis* (ambrosia beetle), *Buprestis apricans* (turpentine borer), and *Monochamus titillator* (southern pine sawyer) all attack injured, weakened, or dying southern pine trees and make galleries in the wood. *Dendroctonus frontalis* (southern pine beetle) attacks the inner bark rather than the woody stem; it carries with it, however, a blue-stain fungus that infects the woody stem, hastens the death of the tree, and lowers the value of lumber cut from the tree.

Chapter 17 contains discussions of each of these insects; aspects included are: habits, signs of attack, illustration of damage, and control.

DECAY

Decay, mostly heart rot, originating in the standing tree is a declining problem in southern pine because young age classes with little heartwood predominate. Decay is ordinarily not an important factor until age 100 years in longleaf pine (Wahlenberg 1946), age 75 in loblolly (Wahlenberg 1960), 60 years in Virginia pine (Fenton and Berry 1958), and 75 years in pitch pine (Walker 1967). In older trees, or on poorer sites where heartwood may form earlier than normal, heart rot may cause serious degrade or loss of wood.

Most heart rot in southern pines is red heart or red ring rot caused by *Fomes pini* (Hepting and Chapman 1938; Gruschow and Trousdell 1958). In southern pine veneer production, red heart sometimes makes it difficult, or impossible, to hold the log in the lathe chucks; i.e., as the veneer knife engages, the log spins out because the chucks lose their grip.

In dead trees or logs *Fomes pini* may continue to develop slightly (Boyce 1961), but there is no evidence of continued growth in converted products (Fritz and Atwell 1941; Wood 1955; Boyce 1961). Firm red heart is admitted without limit in southern pine dimension lumber; the incipient stage (no white-pocket decay) probably causes less than 15-percent reduction in modulus of rupture in bending and compression strength parallel to the grain (Scheffer et al. 1941; Wood 1955). Advanced decay, however, causes marked weakening (Scheffer et al. 1941; Atwell 1948).

Red-brown butt rot caused by *Polyporus schweinitzii* is considerably less common and affects primarily the base of the bole. A brown rotter, it causes significant reduction in toughness even when infections are detectable only by microscopic or cultural techniques (Scheffer et al. 1941). When decay is visually obvious, strength reductions are great.

The development of decay and stain in wood products is discussed in chapter 16; preservative treatments are described in chapter 22.

11-2 TREE GRADES

Tree grades—based on lumber outturn and applicable to merchantable,

standing, loblolly, shortleaf, longleaf, and slash pines—have been developed and adopted by the USDA Forest Service (Schroeder et al. 1968b). To be considered under these rules, trees must have a minimum diameter at breast height of 9.6 inches outside bark and a minimum merchantable height of two 16-foot logs with top diameter not less than 6 inches inside bark. One-log trees should be graded by the log grading system detailed by Schroeder et al. (1968a) and described in the following text section 11-3.

Trees are graded mainly on the external characteristics of the butt 16-foot log. The number of **clear faces**, together with evaluation of the amount of sweep and rot, determines the tree grade. A **face** is one-fourth the tree circumference and extends the full length of the 16-foot grading section. Clear faces are those free of knots measuring more than $\frac{1}{2}$ -inch in diameter, overgrown knots of any size, and holes more than $\frac{1}{4}$ -inch in diameter. Faces may be rotated, if necessary, to obtain the maximum number of clear faces.

Grading trees involves three steps. First, determine the number of clear faces on the butt 16-foot grading section. Usually the grading section is taken from a 12-inch stump height, but it can be moved up as high as 4 feet to avoid including a fire scar or similar defect. Include as many defects as possible in one face so the maximum number of clear faces is obtained. If the grading section has three or more clear faces, classify it a tentative Grade A; if one or two clear faces, tentative Grade B; and if it has no clear face, tentative Grade C.

Next, examine the grading section for sweep. If sweep in the lower 12 feet of the grading section amounts to 3 inches or more *and* is equal to or greater than one-fourth the diameter at breast height, lower the grade of the tree one grade if it was tentative Grade A or B after the clear face examination.

The third step in grading is to examine the entire tree for evidence of heart rot. If either conks, massed hyphae, or punk knots are found anywhere on the stem, reduce the tree one grade as was done for sweep. Tentative Grade C trees are dropped to cull if total scalable defect, including sweep, exceeds two-thirds the gross scale of the tree.

Yields of rough, green lumber, by grade (Southern Pine Inspection Bureau 1968), are presented in tables 11-1, 11-2, and 11-3 for longleaf and slash pines and in tables 11-4, 11-5, and 11-6 for loblolly and shortleaf pines.

In the tables grade 1D includes No. 1 dimension and No. 1 dense; grade 2D includes No. 2 dimension, No. 2 dense, and "Special"; grade 3D includes No. 3 dimension and No. 3 dense. The grades 1C, 2C, 3C, and 4C are grades of 1-inch boards.

Because the tabulated results are Southwide averages, it is unlikely that they will be comparable to the yields of any single mill. If, for example, a mill is producing 90 percent of its lumber in 2-inch dimension, it obvi-

TABLE 11-1.—*Grade-yield of rough green lumber from longleaf and slash pine trees of grade A (Schroeder et al. 1968b)*

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade A, two-log trees										
10										
12	3	14	20	13	3	1	40	3	3	0
14	5	12	20	24	3	1	26	4	4	1
16	5	11	21	32	3	1	18	5	3	1
18	5	9	22	38	3	1	14	5	3	0
20	3	7	23	44	3	0	14	5	1	0
22	1	5	24	47	2	0	16	5	0	0
Grade A, three-log trees										
10										
12	5	10	22	9	0	0	47	7	0	0
14	8	10	22	18	2	0	31	8	1	0
16	8	10	22	25	2	0	23	8	2	0
18	9	11	22	29	2	0	18	7	2	0
20	7	11	23	33	2	0	17	6	1	0
22	6	11	23	36	2	0	17	5	0	0
24	4	10	24	37	2	0	20	3	0	0
26	1	9	25	39	1	0	23	2	0	0
Grade A, four-log trees										
10										
12										
14	10	8	23	12	0	0	37	10	0	0
16	12	10	23	17	1	0	27	10	0	0
18	12	12	22	21	1	0	22	9	1	0
20	12	14	22	23	2	0	19	7	1	0
22	11	16	22	24	2	0	19	5	1	0
24	10	18	23	24	2	0	20	3	0	0
26	8	20	23	24	2	0	23	0	0	0

ously will not get the board-dimension mix shown in the tables. In this case the mill can readily conduct its own mill study by grading a sample of standing trees in each of the three tree grades. A tally—by grade, thickness, and width—of their yield of rough green lumber can then be the basis of the mill's yield table. The data behind tables 11-1 through 11-6 have been analyzed by Yandle (1968) to show—for each lumber grade—the lumber width distribution, i.e., the percentage of lumber in widths 3, 4, 5, 6, 8, 10, and 12 inches. This distribution is of interest because lumber prices generally increase with increasing lumber widths. Tables 11-7 (tree grade A), 11-8 (tree grade B), and 11-9 (tree grade C) give the distribution by board width within each lumber grade for tree diameter classes of 10 (9.0-11.9), 13 (12.0-14.9), 16 (15.0-17.9), 19 (18.0-20.9), and 22+ (21.0 and over) inches. The tables present actual (uncurved)

TABLE 11-2.—Grade-yield of rough green lumber from longleaf and slash pine trees of grade B (Schroeder et al. 1968b)

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade B, two-log trees										
10	3	7	24	21	0	0	38	7	0	0
12	3	10	20	29	0	0	27	11	0	0
14	4	11	18	34	1	0	19	13	0	0
16	5	12	17	37	2	0	14	13	0	0
18	7	11	17	39	3	0	11	12	0	0
20	9	10	16	40	5	0	9	11	0	0
22	11	9	17	40	6	0	8	9	0	0
Grade B, three-log trees										
10										
12	3	9	22	25	0	0	31	9	1	0
14	4	10	20	30	1	0	23	11	1	0
16	5	11	19	33	2	0	18	11	1	0
18	7	10	19	35	3	0	15	10	1	0
20	9	10	19	35	5	0	13	9	0	0
22	11	9	19	36	6	0	12	7	0	0
24	14	7	19	36	8	0	11	5	0	0
26	16	5	20	36	9	0	11	3	0	0
Grade B, four-log trees										
10										
12	3	8	22	21	1	1	31	11	2	0
14	3	10	20	26	1	1	24	13	2	0
16	5	10	19	29	2	1	19	13	2	0
18	7	9	18	31	4	1	16	12	2	0
20	9	9	18	32	5	1	13	11	2	0
22	11	8	19	33	6	1	12	9	1	0
24	14	6	19	33	8	0	12	7	1	0
26	16	5	20	32	9	0	12	5	1	0

yield data for 157,769 bd. ft. of rough green lumber manufactured South-wide. Of the total lumber in the studies, 61 percent was in boards and 39 percent was in dimension. A mill producing substantially different proportions of boards and dimension would not necessarily produce the distribution of lumber widths given in tables 11-7, 11-8, and 11-9.

When pine trees are sawn into 1-inch lumber, the width of lumber yielded is a function of tree diameter at breast height (table 11-10).

11-3 LOG GRADES

Grades for southern pine saw logs—based on external characteristics of the log and applicable to loblolly, shortleaf, longleaf, and slash pine species—have also been developed and adopted by the USDA Forest

TABLE 11-3.—*Grade-yield of rough green lumber from longleaf and slash pine trees of grade C (Schroeder et al. 1968b)*

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade C, two-log trees										
10	2	6	17	31	0	0	32	11	1	0
12	2	6	16	39	0	0	23	14	0	0
14	1	6	16	45	1	0	16	15	0	0
16	1	6	15	50	2	0	11	14	1	0
18	1	6	13	54	4	0	7	12	3	0
20	1	6	11	57	6	0	4	9	6	0
22	1	6	9	59	9	0	2	5	9	0
Grade C, three-log trees										
10										
12	4	7	18	32	0	0	25	13	1	0
14	4	7	17	38	1	0	18	14	1	0
16	4	7	16	43	2	0	13	13	2	0
18	4	7	14	47	4	0	9	11	4	0
20	3	8	12	50	6	0	6	8	7	0
22	3	8	10	52	9	0	3	4	10	1
24	3	8	7	54	11	0	2	0	14	1
Grade C, four-log trees										
10										
12	7	8	22	21	0	0	23	19	0	0
14	6	8	21	27	0	0	17	21	0	0
16	6	8	20	32	2	0	11	20	1	0
18	6	8	18	36	3	0	7	18	4	0
20	6	8	16	39	6	0	4	15	6	0
22	6	8	14	41	8	0	2	10	10	1
24	5	9	11	43	11	0	0	6	14	1
26	5	9	8	45	14	0	0	0	18	1

Service (Schroeder et al. 1968a). To be considered under these rules, logs must be 8 to 20 feet long and at least 6 inches in diameter inside bark at the small end, and their net scale must be at least one-third their gross scale. The system is also used for grading trees that contain only one 16-foot saw log.

Logs are graded on the external appearance of the **faces**; the number of **clear faces**, together with evaluation of the amount of sweep and rot in the log determines its grade. A face is one-fourth the circumference of the log surface and extends the full length of the log. Clear faces are those free from knots measuring more than 1/2-inch in diameter, overgrown knots of any size, and holes more than 1/4-inch in diameter.

Grading logs involves three steps. First, determine the number of clear faces on the log. Include as many defects as possible in one face

TABLE 11-4.—Grade-yield of rough green lumber from loblolly and shortleaf pine trees of grade A (Schroeder 1968b)

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade A, two-log trees										
10	3	4	12	11	2	1	53	11	2	1
12	7	7	15	16	2	1	35	14	2	1
14	11	7	16	19	3	1	23	16	3	1
16	12	7	16	21	5	1	13	18	6	1
18	14	6	16	22	7	1	6	19	8	1
20	14	4	15	23	10	1	1	20	11	1
22	14	2	12	23	12	2	0	20	14	1
Grade A, three-log trees										
10										
12	5	6	15	19	2	0	39	12	2	0
14	8	8	17	21	2	0	28	14	2	0
16	11	8	17	23	3	0	20	15	3	0
18	12	8	16	23	5	1	14	16	5	0
20	13	7	15	23	7	1	10	16	7	1
22	13	6	14	23	9	1	7	17	9	1
24	14	4	12	23	11	1	5	17	12	1
26	14	3	10	22	13	1	4	17	15	1
Grade A, four-log trees										
10										
12	3	5	15	21	0	0	43	11	2	0
14	6	8	16	23	0	0	34	12	1	0
16	9	9	17	24	1	0	27	12	1	0
18	10	10	17	24	2	0	23	13	1	0
20	11	10	16	24	4	0	20	13	2	0
22	12	10	15	23	5	1	18	12	4	0
24	12	9	13	22	7	1	18	12	5	1
26	12	9	12	21	9	1	17	11	7	1

so the maximum number of clear faces are obtained. If the log has three or more clear faces, classify it a tentative Grade 1; if it has one or two clear faces, a tentative Grade 2; and if it has no clear face, a tentative Grade 3.

The second step is to examine the log for sweep. If sweep in the log amounts to 3 inches or more *and* equals or exceeds one-third the scaling diameter, lower the grade of tentative Grade 1 or 2 logs by one grade.

Finally, examine the log for evidence of rot. If conks, massed hyphae, punk knots, or other evidence of rot are found on the log, reduce the grade of the log one grade as was done for sweep.

The yields of rough green lumber by lumber grade (Southern Pine Inspection Bureau 1968) for graded longleaf and slash pine logs are given

TABLE 11-5.—Grade-yield of rough green lumber from loblolly and shortleaf pine trees of grade B (Schroeder 1968b)

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade B, two-log trees										
10	2	2	11	20	4	0	30	27	4	0
12	4	4	14	23	2	0	27	23	3	0
14	6	4	15	25	2	1	23	20	4	0
16	7	4	16	27	4	1	18	17	6	0
18	9	3	15	28	7	2	13	14	8	1
20	10	2	14	30	11	2	7	12	11	1
22	12	1	14	31	16	2	0	9	13	2
Grade B, three-log trees										
10										
12	4	3	15	20	3	1	27	22	5	0
14	5	4	16	22	2	1	25	20	5	0
16	6	5	16	23	3	1	22	19	5	0
18	7	5	16	24	5	1	18	18	7	0
20	8	5	13	25	8	1	14	17	8	1
22	9	5	11	26	12	1	9	16	10	1
24	10	4	10	26	14	2	4	16	12	2
26	11	3	7	27	19	2	0	15	14	2
Grade B, four-log trees										
10										
12	5	1	17	18	4	0	27	20	7	1
14	5	4	17	19	2	0	26	21	6	0
16	6	6	16	19	2	0	25	21	5	0
18	6	7	14	20	3	0	23	22	5	0
20	6	8	12	20	5	0	20	23	6	0
22	6	9	9	20	7	1	18	24	6	0
24	7	9	6	20	10	1	15	25	7	0
26	7	9	4	20	13	1	12	26	8	0

in table 11-11 and for graded loblolly and shortleaf pine logs in table 11-12. Yields from pond pine trees and logs are similar to those from loblolly and shortleaf, but according to current grading rules (Southern Pine Inspection Bureau 1970), all pond pine lumber—as well as lumber from the five other minor species—must be classified as open-grained or wide-ringed (less than 4 rings per inch) regardless of actual rings per inch or percent latewood; this excludes the lumber of these species from some of the stress grades.

In tables 11-11 and 11-12—as in the tables relating to tree grades—grade 1D includes No. 1 dimension and No. 1 dense; grade 2D includes No. 2 dimension, No. 2 dense, and “Special”; grade 3D includes No. 3 dimension and No. 3 dense.

TABLE 11-6.—*Grade-yield of rough green lumber from loblolly and shortleaf pine trees of grade C (Schroeder 1968b)*

Tree grade and d.b.h. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade C, two-log trees										
10	0	1	8	18	3	0	29	24	15	2
12	2	2	12	24	1	0	21	24	13	1
14	3	2	12	28	2	0	16	23	13	0
16	3	3	12	29	4	0	13	22	14	0
18	4	3	10	30	7	0	10	20	16	0
20	5	3	7	29	10	0	10	18	18	0
22	5	3	4	28	14	0	9	16	21	0
Grade C, three-log trees										
10										
12	1	1	5	20	2	0	23	30	18	0
14	2	2	7	23	2	0	18	29	17	0
16	3	3	8	24	3	0	14	28	17	0
18	4	3	8	24	5	0	12	27	17	0
20	4	4	7	23	8	0	11	25	18	0
22	5	4	6	21	11	0	10	23	19	1
24	5	5	4	18	14	0	10	21	21	2
26	6	5	2	16	18	0	10	19	22	2
Grade C, four-log trees										
10										
12	0	0	0	15	2	0	14	35	24	0
14	1	2	2	17	2	0	19	36	21	0
16	2	3	5	18	2	0	15	35	20	0
18	3	4	7	17	4	0	13	33	19	0
20	4	5	8	15	5	0	12	32	18	1
22	4	6	8	13	8	0	11	30	18	2
24	5	7	8	10	10	0	10	28	18	4
26	6	7	8	7	13	0	10	26	18	5

The lumber grade-yields tabulated are Southwide averages. An individual mill can develop its own yield data by selecting approximately 50 logs of each grade and making a tally by grade, width, and thickness, of the rough green lumber produced from each grade and diameter class of logs.

In this section and in section 11-2 grade yields have been stated in terms of rough green lumber. The considerable degrade occurring when southern pine lumber is dried and surfaced is discussed in chapter 20.

When pine logs are sawn into 1-inch lumber, the width of lumber yielded is a function of log diameter as shown by table 11-13 (McClay 1954). These data are in agreement with a later study by Applefield (1958).

TABLE 11-7.—*Distribution of lumber from grade A southern pine trees, by lumber grades and board widths, according to tree diameter class (Yandle 1968)*

Board width (inches)											All grades
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D	
----- Percent -----											
10-INCH D.B.H. (TOTAL VOLUME 3,064 BD. FT., DIMENSION 59 PERCENT)											
3	5	18	6	18	0	23	0	0	0	0	5
4	55	52	36	43	100	77	23	42	0	100	33
5	19	8	10	10	0	0	0	0	0	0	4
6	21	22	43	21	0	0	73	44	100	0	52
8	0	0	5	4	0	0	4	14	0	0	5
10	0	0	0	0	0	0	0	0	0	0	0
12+	0	0	0	4	0	0	0	0	0	0	1
13-INCH D.B.H. (TOTAL VOLUME 9,649 BD. FT., DIMENSION 44 PERCENT)											
3	5	6	3	6	7	18	0	0	0	0	3
4	27	18	16	26	16	35	2	6	23	0	13
5	25	15	7	11	14	0	0	1	0	0	7
6	33	37	43	34	20	19	58	57	50	100	46
8	10	24	30	23	43	28	40	36	27	0	31
10	0	0	0	0	0	0	0	0	0	0	0
12+	0	0	1	0	0	0	0	0	0	0	0
16-INCH D.B.H. (TOTAL VOLUME 18,022 BD. FT., DIMENSION 34 PERCENT)											
3	1	2	2	1	2	9	0	0	0	0	1
4	12	8	6	11	16	49	2	1	0	0	7
5	11	9	4	7	4	0	0	0	0	0	4
6	38	32	23	31	24	18	23	35	27	0	29
8	35	38	55	43	46	24	58	58	59	100	49
10	3	9	10	7	8	0	16	6	14	0	9
12+	0	2	0	0	0	0	1	0	0	0	1

11-4 VENEER BLOCK GRADES

Walters (1967) studied the yield of ninety 8-foot southern pine veneer logs (called "blocks") in an effort to relate veneer volume and grade recovery to visible log characteristics. He devised three block grades based on block diameter, evidence of knots, sweep, and growth rate, which he termed A (high), B (intermediate), and C (low). Thirty blocks of each grade (comprised of 10 each in diameter classes of 11, 13, and 15 inches) were collected in east Texas and peeled into 1/10-inch veneer. His results,

TABLE 11-7.—*Distribution of lumber from grade A southern pine trees, by lumber grades and board widths, according to tree diameter class*
(Yandle 1968)—Continued

Board width (inches)	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D	All grades
----- Percent -----											
19-INCH D.B.H. (TOTAL VOLUME 22,650 BD. FT., DIMENSION 33 PERCENT)											
3	0	1	1	1	1	2	0	0	0	0	1
4	5	5	4	7	11	17	0	0	1	45	4
5	7	8	3	4	4	7	0	0	0	0	3
6	23	24	15	18	26	15	7	11	8	0	16
8	36	38	42	44	25	52	50	54	67	55	45
10	23	12	25	22	24	7	39	29	21	0	25
12+	6	12	10	4	9	0	4	6	3	0	6
22-INCH D.B.H. (TOTAL VOLUME 30,763 BD. FT., DIMENSION 35 PERCENT)											
3	0	0	0	0	0	0	0	0	0	0	0
4	6	3	4	4	9	12	0	1	1	6	4
5	6	4	4	3	5	5	0	0	0	0	3
6	18	18	12	11	14	9	1	4	9	37	10
8	35	29	27	25	21	9	26	16	23	17	25
10	21	22	18	25	18	24	53	42	33	7	28
12+	14	24	35	32	33	41	20	37	34	33	30

extended by regression to include 10- and 16-inch-diameter blocks, were as follows:

- There was no significant difference in the volume of green veneer recovery between block grades of the same diameter class. Output of completed panels was lower for the lower grade blocks.
- Cubic feet of panels produced varied from 26.6 percent of block input for 10-inch C blocks to 50 percent for 16-inch A and B blocks.
- Square feet of $\frac{3}{8}$ -inch plywood averaged 2.75 per board foot log-scale input for all block diameters in grades A and B when scaled by the Doyle rule; with C-grade blocks, the ratio was 2.66 sq. ft. per board foot for the largest diameters and 2.33 for the smallest. When the International $\frac{1}{4}$ -inch log rule was the basis, these recovery ratios were lower for small-diameter logs than for those of large diameter; they ranged from 1.67 to 2.36 in A and B blocks and from 1.43 to 2.27 in C blocks.
- Veneer grade recovery was related to block grade and diameter. Grade A blocks produced 36 to 49 percent of high-grade face veneer, while Grade C blocks produced none.

TABLE 11-8.—*Distribution of lumber from grade B southern pine trees, by lumber grades and board widths, according to tree diameter class (Yandle 1968)*

Board width (inches)	Percent										All grades
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D	
----- Percent -----											
10-INCH D.B.H. (TOTAL VOLUME 3,288 BD. FT., DIMENSION 56 PERCENT)											
3	9	7	10	8	0	0	0	0	0	0	4
4	61	42	39	52	43	25	29	63	30	0	43
5	20	8	12	3	26	0	0	0	0	0	4
6	10	31	36	30	12	75	67	34	56	100	44
8	0	12	3	7	19	0	4	3	14	0	5
10	0	0	0	0	0	0	0	0	0	0	0
12+	0	0	0	0	0	0	0	0	0	0	0
13-INCH D.B.H. (TOTAL VOLUME 7,577 BD. FT., DIMENSION 38 PERCENT)											
3	3	3	1	3	7	10	0	0	0	0	1
4	36	28	20	30	48	70	2	9	13	0	19
5	10	13	5	3	0	20	0	0	0	0	4
6	29	44	47	48	21	0	59	74	75	0	52
8	22	12	27	16	24	0	39	17	12	0	24
10	0	0	0	0	0	0	0	0	0	0	0
12+	0	0	0	0	0	0	0	0	0	0	0
16-INCH D.B.H. (TOTAL VOLUME 14,122 BD. FT., DIMENSION 36 PERCENT)											
3	1	2	1	1	2	7	0	0	0	0	1
4	19	11	8	13	23	14	1	2	14	27	9
5	16	9	7	4	7	0	0	0	0	0	4
6	45	38	29	34	21	35	25	29	49	73	32
8	19	37	49	44	28	5	59	57	22	0	46
10	0	3	6	4	14	39	15	12	13	0	8
12+	0	0	0	0	5	0	0	0	2	0	0
19-INCH D.B.H. (TOTAL VOLUME 17,020 BD. FT., DIMENSION 42 PERCENT)											
3	0	1	1	0	1	4	0	0	0	0	0
4	9	7	5	9	12	11	1	1	1	62	5
5	8	6	3	4	3	7	0	0	0	0	3
6	25	24	15	21	17	8	4	12	19	38	16
8	36	38	41	39	26	41	37	52	43	0	40
10	16	19	27	21	29	29	55	32	34	0	31
12+	6	5	8	6	12	0	3	3	3	0	5

Walters' (1967) block grades, while useful for special yield studies, are too complex for routine application at plywood plants and are not further described here.

Schroeder and Clark (1970) have developed a method for predicting veneer grade yields based on scaling diameter and number of **knot-**

TABLE 11-9.—*Distribution of lumber from grade C southern pine trees, by lumber grades and board widths, according to tree diameter class (Yandle 1968)*

Board width (inches)	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D	All grades
----- Percent -----											
10-INCH D.B.H. (TOTAL VOLUME 3,492 BD. FT., DIMENSION 52 PERCENT)											
3	3	6	6	7	9	0	0	0	0	0	3
4	50	66	40	59	91	100	24	67	47	0	46
5	0	0	7	10	0	0	0	0	0	0	4
6	30	28	47	24	0	0	68	33	53	0	45
8	0	0	0	0	0	0	8	0	0	0	2
10	17	0	0	0	0	0	0	0	0	0	0
12+	0	0	0	0	0	0	0	0	0	0	0
13-INCH D.B.H. (TOTAL VOLUME 10,816 BD. FT., DIMENSION 45 PERCENT)											
3	8	2	3	2	4	29	0	0	0	0	1
4	69	31	21	29	40	45	3	13	15	0	20
5	0	8	6	5	3	0	0	0	0	0	3
6	23	45	39	44	37	26	45	59	60	100	48
8	0	14	31	20	16	0	52	28	25	0	28
10	0	0	0	0	0	0	0	0	0	0	0
12+	0	0	0	0	0	0	0	0	0	0	0
16-INCH D.B.H. (TOTAL VOLUME 10,280 BD. FT., DIMENSION 40 PERCENT)											
3	0	1	0	0	2	0	0	0	0	0	0
4	25	17	12	14	32	45	1	1	3	0	10
5	1	6	4	2	0	0	0	0	0	0	1
6	44	45	34	30	33	0	11	34	60	100	32
8	30	31	42	43	26	55	63	36	24	0	41
10	0	0	8	11	7	0	22	29	13	0	15
12+	0	0	0	0	0	0	3	0	0	0	1
19-INCH D.B.H. (TOTAL VOLUME 7,081 BD. FT., DIMENSION 52 PERCENT)											
3	0	0	0	0	1	0	0	0	0	0	0
4	7	11	8	12	28	39	0	1	2	0	7
5	0	9	3	2	1	0	0	0	0	0	1
6	48	35	26	24	28	7	5	9	31	0	20
8	40	34	53	46	34	54	22	20	40	0	35
10	5	11	10	16	8	0	73	70	22	100	37
12+	0	0	0	0	0	0	0	0	5	0	0

associated defects of each block. Knot-associated defects are defined as knots, limb stubs, overgrown knots, bark distortions, and knot clusters; not included are adventitious twigs, splits, or mechanical damage, bird peck, or other less common defects.

Their data, based on a total of 405 blocks, are applicable to loblolly

TABLE 11-10.—*Lumber widths yielded (percentage of board feet, rough green) by loblolly and shortleaf pine trees of various diameters when sawn into 1-inch boards on circular mills*
(McClay 1953)

D.b.h. ¹ (inches)	Board width in inches					
	4	5	6	8	10	12
	----- Percent -----					
10	28	18	52	2		
12	18	11	54	17		
14	10	5	37	43	5	
16	7	3	27	37	26	
18	5	2	21	28	40	4
20	3	1	16	19	38	23
22	2	1	12	16	34	35
24	2	1	8	13	21	55

¹ Outside bark.

pine peeled to 1/10-inch thickness. Some of the blocks were cut in southeastern Louisiana. The balance were from Washington County, N.C.

The dry veneer was graded according to American Plywood Association (1966) rules and tallied by grade for each of four size categories—full 4- by 8-foot sheet, half-sheet, strip, and fishtail. Grades tallied for full- and half-sheet veneer were A, A-patch, B, B-patch, C, and D. A-patch veneer permitted a maximum of six patches per sheet, and B-patch veneer permitted a maximum of 12 patches per sheet. Although the grading rules allow 18 patches in A-patch and an unlimited number in B-patch veneer, industry practice indicates the restrictions are economically realistic. Only grades C and D were recorded for strip and fishtail veneer.

From their study, Schroeder and Clark (1970) developed regression equations that provided the grade-yield data shown in table 11-14. Because thickness of veneer peeled and mill variations can have a great effect on veneer yields, mills wishing to use the system should test approximately 150 blocks to determine the applicability of table 11-14 to their operations.

11-5 GRADES OF POLES AND PILING

Beltz and Christopher (1968) have surveyed pole and piling production in the United States and conclude that in 1964 over half the Nation's treated poles and piling were harvested in the Midsouth. Their publication shows that Alabama, Mississippi, Louisiana, and Arkansas were the foremost producing states and that most utility poles and piling sold were in length classes from 30 to 50 feet.

TABLE 11-11.—*Grade-yield of rough green lumber sawn from longleaf and slash pine logs of grades 1, 2, and 3 (Schroeder et al. 1968a)*

Log grade and d.i.b. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade 1 logs (Rough-green, basis: 113 logs)										
6										
8	3	19	21	3	0	1	52	1	0	0
10	11	16	23	6	1	1	38	2	1	1
12	16	16	25	8	1	1	29	2	1	1
14	18	18	26	8	1	1	24	2	1	1
16	18	22	28	8	2	0	21	1	0	0
18	18	25	29	7	2	0	19	0	0	0
20	16	29	30	6	2	0	17	0	0	0
Grade 2 logs (Rough-green, basis: 136 logs)										
6	3	6	24	21	0	0	35	11	0	0
8	4	11	24	16	1	0	35	8	1	0
10	5	14	26	14	1	0	32	7	1	0
12	7	16	27	14	1	0	27	7	1	0
14	10	17	29	14	1	0	22	7	0	0
16	13	17	30	16	0	0	17	7	0	0
18	15	17	32	18	0	0	11	7	0	0
20	18	17	33	20	0	0	5	7	0	0
Grade 3 logs (Rough-green, basis: 645 logs)										
6	0	1	21	37	1	0	18	20	2	0
8	1	2	14	44	2	0	18	18	1	0
10	2	3	12	47	3	0	17	15	1	0
12	2	5	13	48	3	0	15	12	2	0
14	3	7	16	47	4	0	12	9	2	0
16	3	8	21	46	4	0	9	6	3	0
18	3	11	26	44	4	0	6	2	4	0
20	4	13	31	41	4	0	3	0	4	0

The use of wooden poles has steadily increased in response to expansion of power lines. Demand for poles in farm and other types of construction has also been rising. The South has dominated the nation's pole market for a long time and will continue to do so (Christopher 1969).

A recent study in loblolly pine stands near Crossett, Arkansas indicates that returns from stands managed for pulpwood and sawtimber alone were only 62 percent of returns from the same stands managed for pulpwood, sawtimber, and poles (Bassett 1967). Williston's (1957) guide for pole growers provides a convenient compilation of volume tables.

Poles and piling are harvested, graded, and marketed on a piece-basis. They are classed first by species and secondly by dimension into definite grades.

TABLE 11-12.—Grade-yield of rough green lumber sawn from loblolly and shortleaf pine logs of grades 1, 2, and 3 (Schroeder et al. 1968a)

Log grade and d.i.b. (inches)	Lumber grade									
	B & B	C	D & 1C	2C	3C	4C	1D	2D	3D	4D
----- Percent -----										
Grade 1 logs (Rough-green, basis: 267 logs)										
6	0	0	15	22	6	0	51	4	2	0
8	6	7	20	15	2	0	45	4	1	0
10	13	12	22	10	1	0	37	4	1	0
12	18	14	23	9	1	0	30	4	1	0
14	21	14	23	9	2	1	25	4	1	0
16	23	14	22	10	4	1	20	4	2	0
18	25	13	21	12	6	1	15	4	3	0
20	26	12	20	15	8	1	11	4	3	0
Grade 2 logs (Rough-green, basis: 320 logs)										
6	0	0	7	15	2	1	46	23	6	0
8	2	3	15	18	1	1	40	16	4	0
10	6	6	19	19	1	0	34	12	3	0
12	8	7	20	20	3	0	29	10	3	0
14	10	8	20	19	4	1	25	10	3	0
16	12	9	19	19	5	1	20	11	4	0
18	13	9	18	19	7	1	17	12	4	0
20	14	9	16	19	8	2	13	14	5	0
Grade 3 logs (Rough-green, basis: 1,091 logs)										
6	0	0	8	26	3	1	21	30	10	1
8	0	1	8	34	4	0	15	28	10	0
10	1	1	8	35	5	0	12	27	11	0
12	2	2	8	34	6	1	10	26	11	0
14	2	3	8	30	8	1	10	25	12	1
16	3	4	7	26	10	2	10	24	13	1
18	4	4	7	21	12	3	11	23	13	2
20	5	5	7	15	15	3	12	22	14	2

POLES

Pole specifications are published by the American Standards Association (1963); poles meeting these specifications are grouped into classes according to the load (applied laterally at the top) required to break them.

Class	Breaking load
	<i>Pounds</i>
1	4,500
2	3,700
3	3,000
4	2,400

Class	Breaking load
	Pounds
5	1,900
6	1,500
7	1,200
9	740
10	370

TABLE 11-13.—Lumber widths yielded (percentage of board feet, rough green) by loblolly and shortleaf pine logs of various diameters when sawn on circular mills into 1-inch borads (McClay 1954)

Scaling diameter ¹ (inches)	Board width in inches				
	4	6	8	10	12
	----- Percent -----				
6	100				
7	90	10			
8	43	57			
9	31	69			
10	25	64	11		
11	15	41	44		
12	11	24	65		
13	7	22	63	8	
14	4	17	35	42	2
15	4	14	22	53	8
16	3	11	17	44	25
17	3	7	15	21	55
18	3	7	13	16	62
19	2	5	11	14	67
20	1	5	9	15	70
21	1	5	8	14	72
22	1	5	9	14	71

¹ Inside bark.

Since the allowable fiber stress in loblolly, longleaf, shortleaf, and slash pine poles is 8,000 p.s.i. (Wood and Markwardt 1965), it is possible to define the pole classes in terms of length and circumference at top and 6 feet from the butt (table 11-15). For more ready use by foresters, Bassett (1967) translated the circumferences shown in table 11-15 into tree diameters at breast height (table 11-16).

The American Standards Association (1963) specification defines prohibited defects. In brief: the outer wood zone at the butt must show at least 6 rings per inch although poles showing 4 rings per inch are acceptable if they have 50-percent or more latewood; poles cannot have the defects of cross breaks, decay, dead knots, streaks of dead wood in the

sapwood, holes, hollow butts or tops, or marine borer damage. The specification also limits the amount of shake and split in a pole and excludes trees with excessive sweep or crook. Both outer and inner bark must be removed from all poles. Spiral grain is limited according to pole length. For poles 30 feet or shorter, the maximum is one complete twist in any 10 feet; for 35 to 40 feet inclusive, one twist is allowed in any 16 feet; and for poles 50 feet and longer, one twist is permitted in any 20 feet.

Chapter 29 contains some mensurational data on poles; see figure 29-5 and tables 29-51 and 29-52.

TABLE 11-14.—*Predicted veneer grade-yields for loblolly pine peeler blocks by diameter and number of knot-associated defects (Schroeder and Clark 1970)*

Block scaling diameter (inches)	Knot-associated defects	Veneer grade yields			
		A ¹	B ²	C	D
	<i>Number</i>	<i>Percent</i>			
8 ³	0	0	23	77	0
	2	0	12	88	0
	4	0	0	100	0
10	0	11	21	68	0
	2	10	18	72	0
	4	9	13	69	9
	6	6	8	61	25
	8	3	5	53	39
	10	0	4	44	52
	12	0	0	37	63
14	0	0	32	68	
12	0	11	23	65	1
	2	9	19	60	12
	4	8	14	55	23
	6	5	10	49	36
	8	4	7	42	47
	10	1	4	36	59
	12	0	3	29	68
14	0	0	24	76	
14	0	10	24	58	8
	2	9	20	54	17
	4	8	16	49	27
	6	6	13	44	37
	8	4	9	39	48
	10	3	5	33	59
	12	0	2	28	70
14	0	0	22	78	

Table 11-14.—*Predicted veneer grade-yields for loblolly pine peeler blocks by diameter and number of knot-associated defects (Schroeder and Clark 1970)*—Continued

Block scaling diameter (inches)	Knot-associated defects	Veneer grade yields			
		A ¹	B ²	C	D
	<i>Number</i>	<i>Percent</i>			
16	0	10	26	53	11
	2	8	23	50	19
	4	8	19	46	27
	6	6	15	42	37
	8	5	11	37	47
	10	4	7	32	57
	12	2	3	26	69
18 ³	0	9	28	50	13
	2	8	25	47	20
	4	7	22	44	27
	6	7	18	40	35
	8	6	14	36	44
	10	5	10	30	55
20	0	9	30	47	14
	2	8	28	44	20
	4	8	24	42	26
	6	7	21	38	34
	8	6	17	34	43
	10	5	12	30	53
22	0	8	33	45	14
	2	8	30	43	19
	4	8	27	40	25
	6	7	23	37	33
	8	7	19	33	41
	10	6	15	29	50
24	0	8	35	43	14
	2	8	32	41	19
	4	8	29	39	24
	6	7	26	36	31
	8	7	22	32	39
	10	6	18	28	48
26	0	8	36	42	14
	2	8	34	40	18
	4	7	32	37	24
	6	7	29	34	30
	8	7	25	31	37
	10	7	21	27	45

¹ Includes A and A-patch veneer.

² Includes B and B-patch veneer.

³ Diameter classes: 7.6 to 8.5 = 8 inches, etc.

TABLE 11-15.—*Length and circumference specifications for the nine classes of southern pine poles (American Standards Association 1963)*¹

Pole class	1	2	3	4	5	6	7	9	10	
Min. circumference at top in inches	27	25	23	21	19	17	15	15	12	
Pole length	Groundline distance from butt ²		Minimum circumference at 6 feet from butt							
	<i>Feet</i>	<i>Inches</i>								
20	4	31.0	29.0	27.0	25.0	23.0	21.0	19.5	17.5	14.0
25	5	33.5	31.5	29.5	27.5	25.5	23.0	21.5	19.5	15.0
30	5.5	36.5	34.0	32.0	29.5	27.5	25.0	23.5	20.5	
35	6	39.0	36.5	34.0	31.5	29.0	27.0	25.0		
40	6	41.0	38.5	36.0	33.5	31.0	28.5	26.5		
45	6.5	43.0	40.5	37.5	35.0	32.5	30.0	28.0		
50	7	45.0	42.0	39.0	36.5	34.0	31.5	29.0		
55	7.5	46.5	43.5	40.5	38.0	35.0	32.5			
60	8	48.0	45.0	42.0	39.0	36.0	33.5			
65	8.5	49.5	46.5	43.5	40.5	37.5				
70	9	51.0	48.0	45.0	41.5	38.5				
75	9.5	52.5	49.0	46.0	43.0					
80	10	54.0	50.5	47.0	44.0					
85	10.5	55.0	51.5	48.0						
90	11	56.0	53.0	49.0						
95	11	57.0	54.0	50.0						
100	11	58.5	55.0	51.0						
105	12	59.5	56.0	52.0						
110	12	60.5	57.0	53.0						
115	12	61.5	58.0							
120	12	62.5	59.0							
125	12	63.5	59.5							

¹ Table values are based on fiber stress of 8,000 p.s.i. Classes and lengths for which circumferences at 6 feet from the butt are listed inside brackets are the preferred standard sizes. Those shown outside brackets are included for engineering purposes only.

² Use figures in this column only when a definition of groundline is necessary in order to apply requirements relating to scars, straightness, etc.

TABLE 11-16.—*Minimum breast-height tree diameter (outside bark) to meet specifications for various classes of southern pine poles (Bassett 1967)*

Pole length (feet)	Pole class and minimum top diameter ¹ in inches						
	² 1 8.8	2 8.1	3 7.5	4 6.9	5 6.2	6 5.6	7 5.0
	----- Inches -----						
16	-----	-----	-----	-----	-----	7.2	6.8
18	-----	-----	-----	-----	-----	7.7	7.2
20	-----	-----	-----	-----	-----	8.0	7.5
25	-----	-----	-----	10.8	10.0	9.0	8.2
30	-----	-----	-----	11.4	10.6	9.7	9.0
35	-----	-----	13.0	12.1	11.3	10.4	9.6
40	15.6	14.6	13.6	12.8	11.9	11.0	-----
45	16.4	15.3	14.2	13.4	12.4	11.5	-----
50	17.1	16.0	14.8	14.0	12.9	-----	-----
55	17.7	16.6	15.4	14.5	13.5	-----	-----
60	18.2	17.2	16.0	15.0	13.9	-----	-----

¹ Minimum top diameter may not be exceeded by more than 3 inches.

² Class 1 minimum d.b.h. may not be exceeded by more than 1 inch.

PILES

Specifications for piles based on their bearing value are given in Designation D25-58 of the American Society for Testing and Materials (1968). Under this specification, timber piles are classified according to their intended use: Class A, for heavy use (e.g., railroad bridges), calls for a minimum butt diameter sufficient for timber caps 14 inches in width; Class B piles for docks, wharves, bridges, building or other foundations, and general construction must have a butt diameter sufficient for use of timber caps 12 inches in width; and Class C piles for foundations that will always be completely submerged, for cofferdams, falsework, or light construction.

The dimensions of southern pine piles in each of the three classes are given in table 11-17. Generally specifications regarding defects are more stringent than those for poles. Spiral grain is limited to one-half of a complete twist in any 20 feet of length. For Class A and B piles the straightness requirement calls for a straight line from the center of the butt to the center of the tip to lie entirely within the body of the pile; and crooks in short sections of the pile are sharply limited. Generally, piles must be sound, free from decay, red heart, and insect attack. Limits on hole size, as well as knot size, grouping, and soundness are specified. In Class A and B piles, splits cannot be longer than the butt diameter; shake cannot exceed one-third the butt circumference.

TABLE 11-17.—Circumferences, diameters, and lengths of southern pine piles¹ (American Society for Testing and Materials 1968)

Length in feet	Class A						Class B						Class C					
	3 ft. from butt				At tip, min.		3 ft. from butt				At tip, min.		3 ft. from butt				At tip, min.	
	Min.		Max.		Circumference	Diameter	Min.		Max.		Circumference	Diameter	Min.		Max.		Circumference	Diameter
Circumference	Diameter	Circumference	Diameter	Circumference			Diameter	Circumference	Diameter	Circumference			Diameter	Circumference	Diameter	Circumference			Diameter
Under 40.....	44	14	57	18	28	9	38 ²	12 ²	63	20	25	8	38 ³	12 ³	63	20	25	8
40 to 50 incl.....	44	14	57	18	28	9	38	12	63	20	22	7	38	12	63	20	19	6
55 to 74 incl.....	44	14	57	18	25	8	41	13	63	20	22	7	38	12	63	20	19	6
75 to 90 incl.....	44	14	63	20	22	7	41	13	63	20	19	6	38	12	63	20	19	6
Over 90.....	44	14	63	20	19	6	41	13	63	20	16	5	38	12	63	20	16	5

¹ Circumferences and diameters (approx.) are given in inches.

² In Class B piles, a minimum circumference of 34 inches or diameter of 11 inches at a point 3 feet from the butt may be specified for lengths of 25 feet and under.

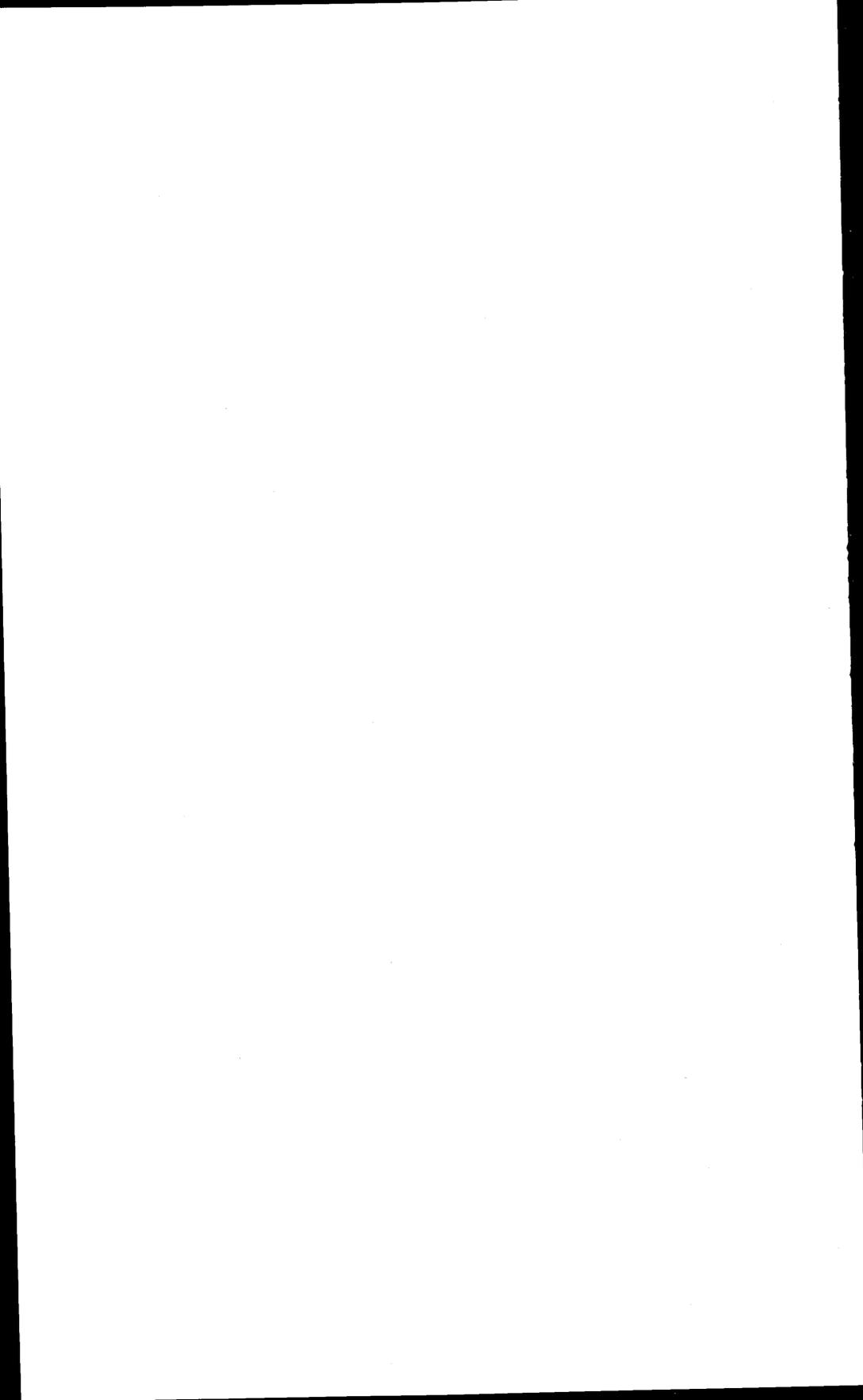
³ In Class C piles, a minimum circumference of 31 inches or diameter of 10 inches at least 3 feet from the butt may be specified for lengths of 25 feet and under.

11-6 LITERATURE CITED

- American Plywood Association.
1966. U.S. Product Standard PS 1-66 for softwood plywood, construction and industrial. 28 pp. Tacoma, Wash.: American Plywood Assoc.
- American Society for Testing and Materials.
1968. Standard specifications for round timber piles. ASTM Designation D25-58 (reapproved 1964). In ASTM Standards, part 16, pp. 45-49. Philadelphia: Amer. Soc. Testing and Mater.
- American Standards Association.
1963. American Standard specifications and dimensions for wood poles. Specif. 05.1-1963, 15 pp. N.Y.: American Standards Assoc., Inc.
- Anderson, E. A., Koehler, A., and Krone, R. H.
1945. Instruments for rapidly measuring slope of grain in lumber. USDA Forest Serv. Forest Prod. Lab. Rep. 1592, 12 pp.
- Applefield, M.
1958. The marginal sawlog for southern yellow pine. Tex. Forest Serv. Res. Note 21, 24 pp.
- Atwell, E. A.
1948. Red-stain and pocket-rot in jack pine: Their effect on strength and serviceability of the wood. Can. Dep. Mines and Resources. Dominion Forest Serv. Forest Prod. Lab. Circ. 63, 23 pp.
- Barber, J. C.
1961. Growth, crown form, and fusiform rust resistance in open-pollinated slash pine progenies. Sixth South. Forest Tree Impr. Conf. Proc. 1961: 97-104.
- Bassett, J. R.
1967. Pole production in natural loblolly pine stands near Crosssett, Arkansas. USDA Forest Serv. Res. Note SO-58, 5 pp. South. Forest Exp. Sta., New Orleans, La.
- Beltz, R. C., and Christopher, J. F.
1968. Pole and piling production in the Midsouth. USDA Forest Serv. Resource Bull. SO-13, 17 pp. South. Forest Exp. Sta., New Orleans, La.
- Boyce, J. S.
1961. Forest pathology. 600 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Christopher, J. F.
1969. Pole supply outlook. Forest Farmer 28(4): 6-7, 17.
- Czabator, F. J.
1971. Fusiform rust of southern pines—A critical review. USDA Forest Serv. Res. Pap. SO-65, 39 pp. South. Forest Exp. Sta., New Orleans, La.
- Dadswell, H. E., and Nicholls, J. W. P.
1959. Assessment of wood qualities for tree breeding. I. CSIRO Div. Forest Prod. Tech. Pap. 4, 16 pp.
- Davis, E. M.
1931. The defects and some other characteristics of virgin-growth and of second-growth commercial shortleaf pine lumber. J. Forest. 29: 54-63.
- Dinus, R. J., and Schmidting, R. C.
1971. Fusiform rust in loblolly and slash pines after cultivation and fertilization. USDA Forest Serv. Res. Pap. SO-68, 10 pp. South. Forest Exp. Sta., New Orleans, La.
- Fenton, R. H., and Berry, F. H.
1958. Red ring rot in Virginia pine in Maryland. J. Forest. 56: 280-284.
- Fritz, C. W., and Atwell, E. A.
1941. Decay in red-stained jack pine ties under service conditions. Can. Forest Serv. Forest Prod. Lab. Circ. 58, 26 pp.
- Gansel, C. R.
1966. Inheritance of stem and branch characters in slash pine and relation to gum yield. Eighth South. Forest Tree Impr. Conf. Proc. 1965: 63-67.
- Goddard, R. E., and Strickland, R. K.
1964. Crooked stem form in loblolly pine. Silvae Genet. 13: 155-157.

- Gruschow, G. F., and Trousdell, K. B.
1958. Incidence of heart rot in mature loblolly pine in coastal North Carolina. *J. Forest.* 56: 220-221.
- Hepting, G. H., and Chapman, A. D.
1938. Losses from heart rot in two shortleaf and loblolly pine stands. *J. Forest.* 36: 1193-2001.
- Koch, P.
1966. Straight studs from southern pine veneer cores. *USDA Forest Serv. Res. Pap. SO-25*, 37 pp. Southern Forest Exp. Sta., New Orleans, La.
- Koch, P.
1971. Process for straightening and drying southern pine 2 by 4's in 24 hours. *Forest Prod. J.* 21(5): 17-24.
- Larson, P. R.
1963. Stem form development of forest trees. *Forest Sci. Monogr.* 5, 42 pp.
- McClay, T. A.
1953. Estimating board widths obtainable from pine trees of different diameters. *USDA Forest Serv. Southeast. Forest Exp. Sta. Res. Note* 25, 2 pp.
- McClay, T. A.
1954. Lumber grade yields in the loblolly-shortleaf pine type by the southern pine log grades. *USDA Forest Serv. Southeast. Forest Exp. Stat., Sta. Pap.* 37, 12 pp.
- Mergen, F.
1955. Inheritance of deformities in slash pine. *South. Lumberman* 190(2370): 30-32.
- Merkel, E. P., Squillace, A. E., and Bengtson, G. W.
1966. Evidence of inherent resistance to *Dioryctria* infestation in slash pine. *Eighth South. Forest Tree Impr. Conf. Proc.* 1965: 96-99.
- Meyer, R. W., and Leney, L.
1968. Shake in coniferous wood—an anatomical study. *Forest Prod. J.* 18(2): 51-56.
- Nikles, D. G.
1966. Progeny tests of slash pine (*Pinus elliottii* Engelm.) in Queensland, Australia. *Eighth South. Forest Tree Impr. Conf. Proc.* 1965: 112-121.
- Paul, B. H.
1938. Knots in second-growth pine and the desirability of pruning. *USDA Forest Serv. Misc. Pub.* 307, 35 pp.
- Scheffer, T. C., Wilson, T. R. C., Luxford, R. F., and Hartley, C.
1941. The effect of certain heart rot fungi on the specific gravity and strength of Sitka spruce and Douglas-fir. *USDA Tech. Bull.* 779, 24 pp.
- Schroeder, J. G., Campbell, R. A., and Rodenbach, R. C.
1968a. Southern pine log grades for yard and structural lumber. *USDA Forest Serv. Res. Pap. SE-39*, 9 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Schroeder, J. G., Campbell, R. A., and Rodenbach, R. C.
1968b. Southern pine tree grades for yard and structural lumber. *USDA Forest Serv. Res. Pap. SE-40*, 15 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Schroeder, J., and Clark, A.
1970. Predicting veneer grade-yields for loblolly pine. *Forest Prod. J.* 20(2): 37-39.
- Snyder, E. B.
1961. Measuring branch characters of longleaf pine. *USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap.* 184, 4 pp.
- Southern Pine Inspection Bureau.
1968. Standard grading rules for southern pine lumber. 171 p. New Orleans, La.: Southern Pine Inspection Bureau.
- Southern Pine Inspection Bureau.
1970. Standard grading rules for southern pine lumber. 208 pp. Pensacola, Fla.: South. Pine Insp. Bur.
- Stephenson, G. K., and Snyder, E. B.
1969. Genetic variation—key to superior trees. *USDA Forest Serv. South. Forest Exp. Sta.*, 12 pp.
- Strickland, R. K., and Goddard, R. E.
1966. Inheritance of branching and crown characteristics in slash pine. *Eighth South. Forest Tree Impr. Conf. Proc.* 1965: 57-63.
- USDA Forest Products Laboratory.
1955. Wood handbook. *USDA Agr. Handbook* 72, 528 pp.

- Verrall, A. F.
1958. Fusiform rust of southern pines. USDA Forest Pest Leaflet 26, 4 pp.
- Wedel, K. W. von, Zobel, B. J., and Shelbourne, C. J. A.
1968. Prevalence and effect of knots in young loblolly pine. Forest Prod. J. 18(9): 97-103.
- Wahlenberg, W. G.
1946. Longleaf pine. 429 pp. Wash., D.C.: Charles Lathrop Pack Forest Found. in coop. with USDA Forest Serv.
- Wahlenberg, W. G.
1960. Loblolly Pine. 603 pp. N.C.: Duke Univ. Sch. Forest.
- Walker, L. C.
1967. Silviculture of the minor southern conifers. Stephen F. Austin State Coll. Sch. Forest. Bull. 15, 106 pp.
- Walters, E. O.
1967. Southern yellow pine block grade-veneer yield. Tex. Forest Serv. Tech. Rep. 14, 18 pp.
- Williston, H. L.
1957. Pole grower's guide. USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap. 153, 34 pp.
- Wood, L. W.
1955. Properties of white-pocket Douglas-fir lumber. USDA Forest Serv. Forest Prod. Lab. Rep. 2017, 44 pp.
- Wood, L. W., and Markwardt, L. J.
1965. Derivation of fiber stresses from strength values of wood poles. USDA Forest Serv. Res. Pap. FPL-39, 8 pp. Forest Prod. Lab., Madison, Wis.
- Yandle, D. O.
1968. Southern yellow pine tree overruns and lumber width distributions. USDA Forest Serv. Res. Pap. SE-41, 12 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Zobel, B., Stonecypher, R. W., and Browne, C.
1968. Inheritance of spiral grain in young loblolly pine. Forest Sci. 14: 376-379.



PART III— BARK, ROOTS, AND NEEDLES

<i>Chapter</i>	<i>Title</i>
12	BARK
13	ROOTS
14	NEEDLES

二

12

Bark

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12

Bark

12-1 ANATOMY¹

The functions of bark in the life process of a tree are briefly described at the beginning of chapter 4. Each growing season the vascular cambium forms a layer of **xylem** (wood) to the interior and a layer of **phloem** (conducting cells of the bark) to the exterior. The annual layer of phloem is one-tenth to one-sixth as thick as the annual layer of wood. Each new layer of phloem pushes the older layers outward from the enlarging stem.

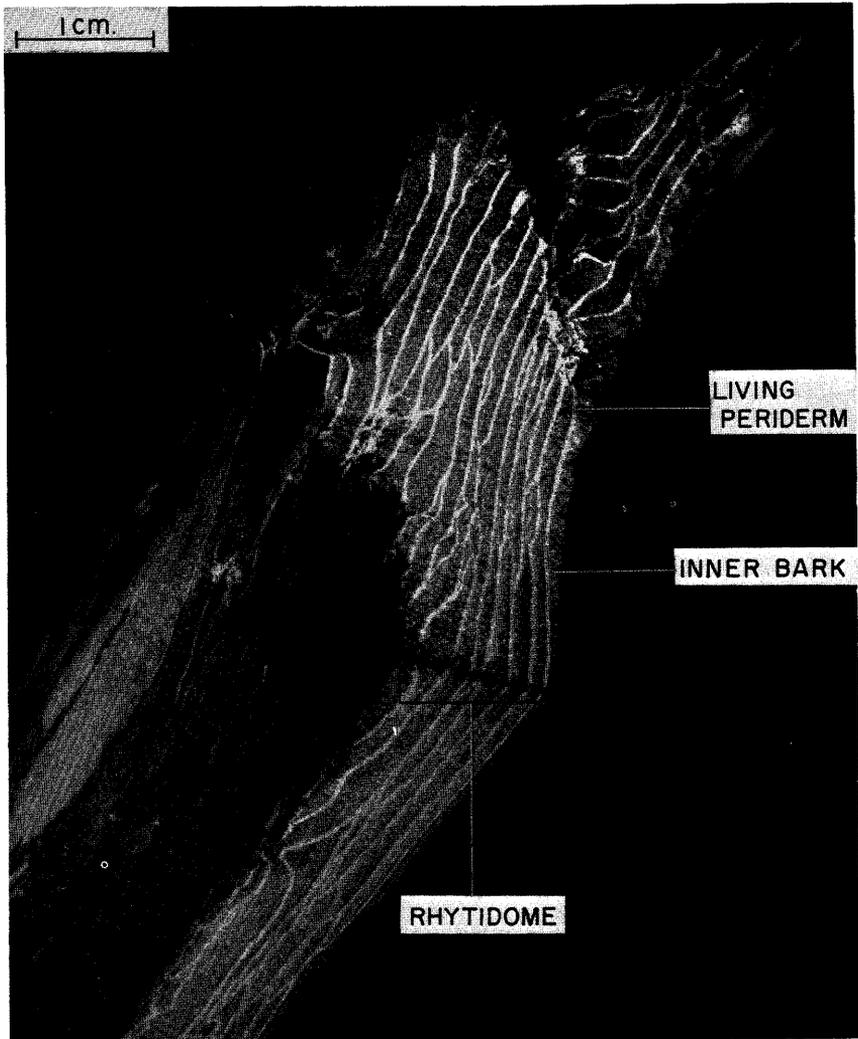
At some distance from the cambium, a new tissue—the **phellogen** or **cork cambium**—appears within the older phloem. The phellogen (a single layer of dividing cells) produces a tangentially oriented **periderm**, which protects the delicate phloem tissue from harmful external influences. Portions of older phloem are sealed off from interior supplies of moisture and nutrients by the impervious periderm layers (fig. 12-1); the cells of these isolated areas undergo striking changes and die. Each periderm and the phloem it isolates are in turn pushed outward; a new periderm arises further inward and the older periderm dies. Since outer layers are not sloughed off as rapidly as interior ones are formed, the thick, scaly bark typical of southern pines is eventually accumulated.

A cross sectional or radial cut through mature southern pine bark shows two distinct zones. The narrow, light-colored region next to the vascular cambium is the **inner bark**; it contains the living food-conducting and storage cells. The thick outer bark (**rhytidome**) consists of areas of dark, porous tissue (dead phloem) subdivided by relatively conspicuous, merging lines of periderm. The innermost periderm separates inner bark from rhytidome.

INNER BARK

Inner bark encompasses all the tissues from the vascular cambium outward to the innermost periderm. It includes the phloem produced during a number of years. In southern pines inner bark is relatively narrow; in

¹ Sec. 12-1 is taken with minor editorial changes from Howard (1971) by permission of Elaine T. Howard and the Forest Products Research Society. Howard studied all 10 southern pines; sampling included both races (or varieties) of sand pine and the south Florida variety of slash pine.



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Figure 12-1.—Cross-sectional and radial surfaces of slash pine bark. Light-colored periderm layers have curved ends in sectional view. The periderm adjacent to the inner bark is the only one composed of living cells. (Photo from Howard 1971.)

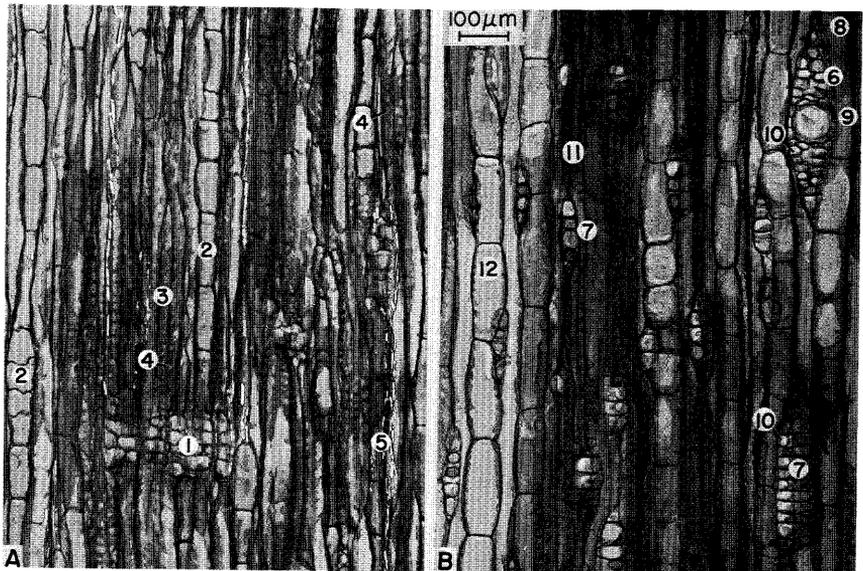
trees observed by Howard (1971), it ranged from 0.5 mm. to slightly over 2 mm. in width, and averaged about 1.5 mm. According to Huber (1958), only a very narrow band next to the cambium—perhaps 200 to 300 μm . in width—is active in conducting photosynthates downward from the leaves to the various areas of use or storage.

Most of the phloem cells are oriented longitudinally. Fusiform initials of the cambium produce the vertical phloem elements: sieve cells, longitudinal parenchyma, and some albuminous cells. There are no typical phloem fibers. Ray initials give rise to the horizontal system of ray cells:

ray parenchyma, albuminous cells, and, in fusiform rays, epithelial cells. Elements of southern pine phloem are illustrated in figure 12-2. Their xylem counterparts are as follows:

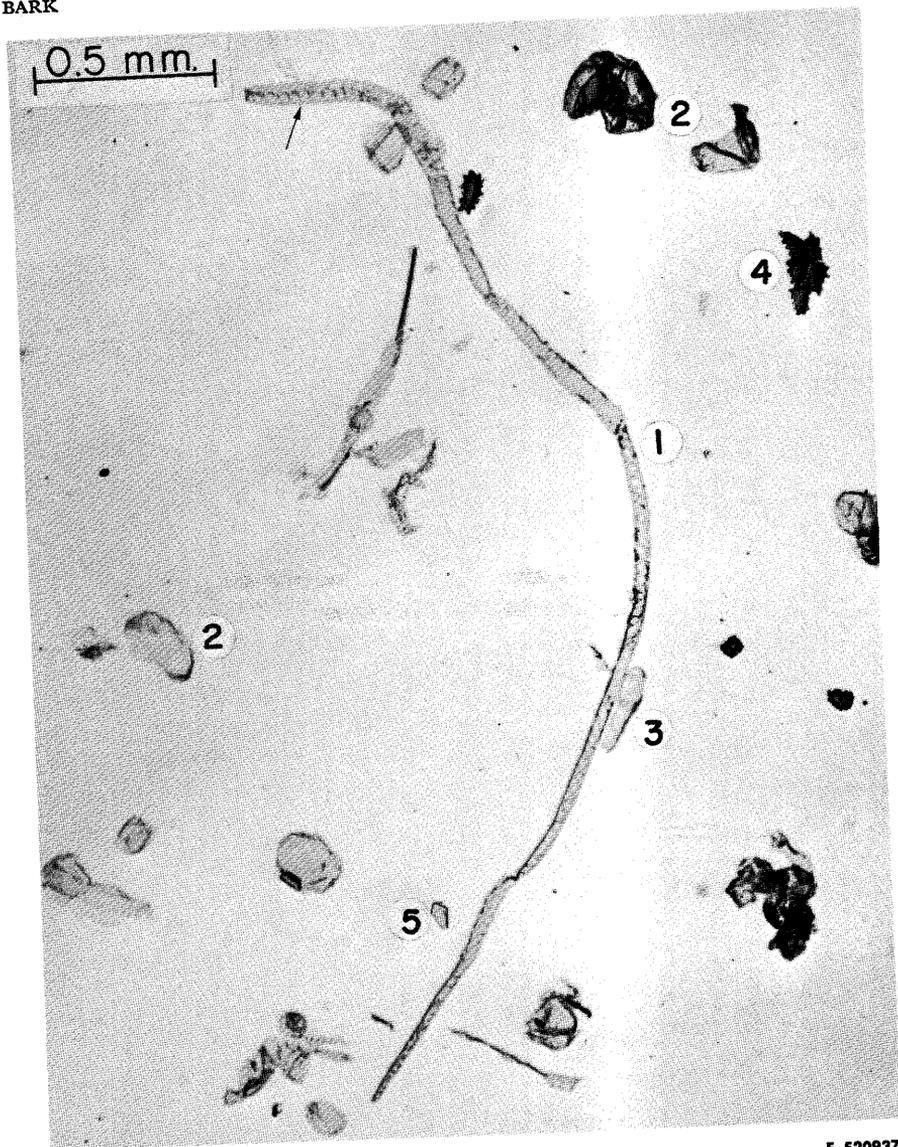
<u>Xylem</u>	<u>Phloem</u>
Tracheids	Sieve cells
Rays	Rays
Ray tracheids	Albuminous cells
Ray parenchyma	Ray parenchyma
Epithelial cells (only at resin canals of fusiform rays)	Epithelial cells (only at resin canals of fusiform rays)
Longitudinal parenchyma (at longitudinal resin canals only)	Dispersed longitudinal parenchyma (longitudinal resin canals normally absent)

Sieve cells.—The only distinctly elongated elements of southern pine bark are the sieve cells (figs. 12-2A, 12-3, 12-4). They are the main food-conducting cells and are vertically oriented. Sieve cells are comparable to xylem tracheids in size, shape, and arrangement, being long and slender with overlapping ends. The thin, nonlignified, cellulosic walls have numerous circular to oval sieve areas (specialized pit fields), which correspond to tracheid pitting and are mainly confined to the radial walls. Walls in the sieve areas are thinner than in the rest of the cell and contain a



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Figure 12-2.—Phloem cells in the inner bark. (A) Radial section of slash pine. 1, ray; 2, longitudinal parenchyma strand; 3, sieve cells; 4, sieve area; 5, crystals. (B) Tangential section of pond pine. 6, fusiform ray; 7, uniseriate rays; 8, albuminous cell; 9, epithelial cell; 10, ray parenchyma; 11, sieve cells; 12, longitudinal parenchyma. Distortion produces areas neither truly radial nor tangential, as evidenced by the discontinuous portion of ray in (A) and oblique view of some rays in (B). (Photos from Howard 1971.)



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Figure 12-3.—Macerated bark from longleaf pine. All other cells are quite small in relation to sieve cells. 1, sieve cell, showing sieve areas (arrow indicates a portion of another sieve cell still adhering at upper left); 2, expanded parenchyma; 3, unexpanded parenchyma; 4, phellem stone cells; 5, phelloderm cell. (Photo from Howard 1971.)

variable number of pores, which are often clustered into several groups. In living tissue, protoplasmic connecting strands pass through the pores to sieve areas of other sieve cells and to ray albuminous cells.

Sieve areas were observed to be of only one structural type, but they varied in size according to cell dimension and position. In a single sample they ranged from 5 to 30 μm . in diameter.

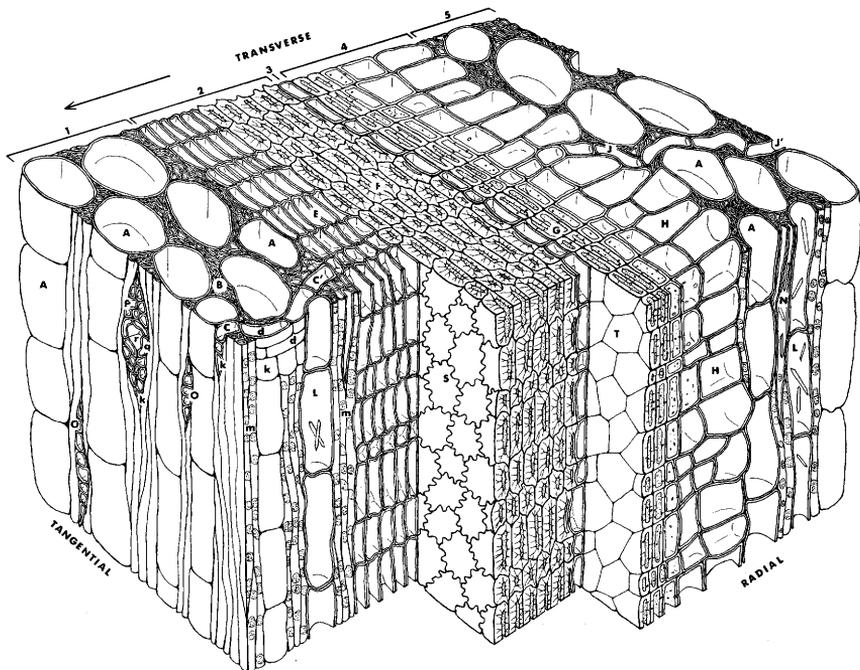


Figure 12-4.—Schematic drawing of southern pine rhytidome tissues. Periderm is comprised of 2, 3, and 4. Arrow points to tree exterior. *Transverse view.* (1) Obliterated phloem. A, expanded parenchyma; B, crushed sieve cells; C-C', uniseriate ray; d, ray parenchyma. (2) Phellem. E, thin-walled cork (slightly distorted); F, stone cells with ramified pit canals. (3) Phellogen (cork cambium). (4) Phelloderm. G, thickened unexpanded phelloderm with simple pits; H, expanded thin-walled phelloderm. (5) Newer layer of obliterated phloem. J-J', inner portion of ray C-C'. *Radial view.* k, albuminous cells of ray; L, longitudinal parenchyma with styloid crystals; m, sieve areas of sieve cells; N, sieve cell containing crystals. *Tangential view.* O, uniseriate rays; P, fusiform ray; q, epithelial cells; r, horizontal resin canal; S, interlocking spicules of stone cells; T, irregular polygonal phelloderm arrangement. (Drawing after Howard 1971.)

The functioning life of sieve cells in southern pines is not precisely known, although for most trees it is presumed to be only 1 year, or possibly 2 years, after formation (Srivastava 1964; Esau 1965, p. 302). A carbohydrate deposit called **callose** lines the pores of sieve areas (Esau 1965, p. 277). With reduced activity of the cell, callose grows to become the massive accumulation known as definitive callose. This marks the end of the functioning life of the sieve cell. Definitive callose gradually disappears (leaving minute open perforations) after death of the cell; only rarely, therefore, are remnants found in outer bark. While still in inner bark, the sieve cells lose turgidity and collapse, and their original radial alignment becomes distorted.

Chang (1954a, p. 224) reported that, in slash pine, sieve cells make up 54.2 percent and parenchyma 37.5 percent of inner bark. Sieve cells prob-

ably occupy less than 30 percent of the volume in rhytidome because of further sieve cell collapse, parenchyma enlargement, and introduction of periderm tissue.

Longitudinal parenchyma.—In southern pine wood, longitudinal parenchyma is found only in association with the vertical resin canals (Howard and Manwiller 1969). In phloem, however, vertical resin canals usually are lacking and the longitudinal parenchyma is dispersed among the sieve cells. Phloem parenchyma cells, like those of wood, have thin primary walls, are somewhat cylindrical, and occur in vertical strands (figs. 12-2, 12-4).

While in some specimens tangential alignment of parenchyma is discernible in undistorted phloem, the parenchyma is usually only one cell wide and somewhat discontinuous. In transverse views of some samples, parenchyma appear scattered. The suggestion that parenchyma arrangement may indicate seasonal growth increments has not been confirmed by growth studies. Tangential arrangement, where present, is soon distorted and eventually obscured; consequently, it is not observed in rhytidome of most specimens.

Starch, tannins, resins, oil globules, crystals, and other substances are stored in phloem parenchyma. Walls of parenchyma cells have primary pit fields (areas of the primary wall with submicroscopic pores) through which they communicate with other parenchyma and with ray cells. Parenchyma cells usually do not appear to be associated with sieve cells (Srivastava 1963; Outer 1967). Some parenchyma cells become meristematic and give rise to phellogen.

Rays.—Phloem rays are continuous with xylem rays and perform similar conductive functions. As in southern pine xylem, rays in phloem are mostly uniseriate, but some fusiform rays containing horizontal resin canals are present (figs. 12-12B, 12-4). All ray cells in phloem have thin, primary, un lignified walls. No ray tracheids are present; instead, erect structures called albuminous cells form the margins of most rays (fig. 12-4k). Their presence is a characteristic of conifer phloem. They may occasionally occur in the middle of a ray and have been reported distributed among the other phloem tissues (Chang 1954a; Srivastava 1963; Esau 1965, p. 288). Albuminous cells are physiologically associated with sieve cells and communicate with them through one-sided sieve areas on the sieve cell wall only. They are thought to regulate sieve cell activities and serve in translocation between sieve cells and ray parenchyma. Albuminous cells die and collapse simultaneously with their associated sieve cells.

Ray parenchyma in phloem is much like that in xylem. Since the sieve cells normally do not have sieve-area contact with ray parenchyma, southern pine phloem has no visible features analogous to crossfield pits.

Epithelial cells line the horizontal resin ducts of fusiform rays and are similar to those of xylem. In older phloem, epithelial cells may sometimes overproliferate and clog resin ducts with tyloids.

Radial alignment of rays becomes distorted at a short distance from the cambium. Long before they enter the rhytidome (fig. 12-5), rays assume an undulating pattern in cross section; consequently, in radial section only discontinuous portions are visible. Slightly enlarged rays are occasionally observed in older phloem; the rays of southern pines do not, however, undergo the extreme dilation found in many other species.

Except for the albuminous cells, rays remain alive throughout inner bark and transport nutrients from the actively conducting zone to living longitudinal parenchyma and the innermost phellogen. The outermost portions of rays die when ultimately sealed off by formation of a new and deeper phellogen.

Crystals.—Abundant crystals can be observed throughout southern pine inner bark and rhytidome (fig. 12-2A). They are composed of calcium oxalate and are deposited as a byproduct of metabolism (Srivastava 1964; Esau 1965, p. 29; Kennedy et al. 1968). Therefore, the quantity of crystals in a particular sample may be somewhat dependent on nutrient availability and tree vigor (Great Britain Forestry Commission 1932). Crystals are found in the lumina of both sieve cells and longitudinal parenchyma. In contrast with those reported in other species, the crystal-bearing cells in

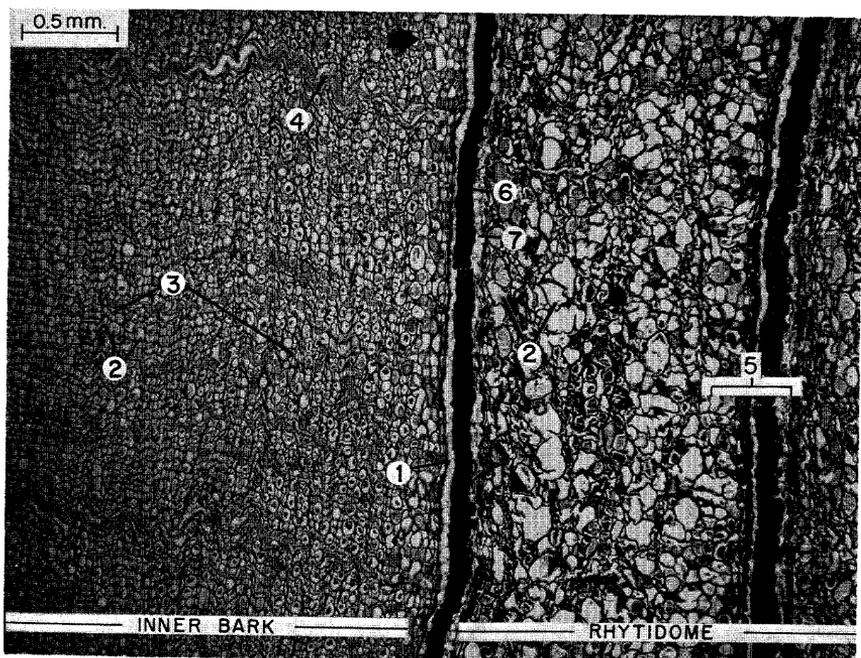


Figure 12-5.—Cross section showing distortion of cell alignment in inner bark and obliteration of rhytidome. The living periderm, with the active phellogen (1) in its center, separates the two zones. Large arrow indicates outward growth. Vascular cambium is just outside the left edge of the photo. 1, active phellogen; 2, parenchyma; 3, sieve cells; 4, undulating ray; 5, dead older periderm; 6, phellem stone cells; 7, thin-walled cork. (Photo from Howard 1971.)

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southern pines do not appear specially modified for this function. The southern pines, and other hard pines, have crystals that are characteristically elongated prisms with chisel-like ends (fig. 12-6), whereas soft pines have crystals with square, rhomboidal ends (Chang 1954b; Srivastava 1963). Howard (1971) found that crystals of all southern pines were similar in shape but varied greatly in size (from 15 to 105 μm . in length), even within the same cell.

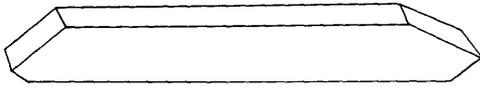


Figure 12-6.—Typical styloid crystal found in sieve cells and longitudinal parenchyma of southern pine bark. (Drawing after Howard 1971.)

RHYTIDOME FORMATION

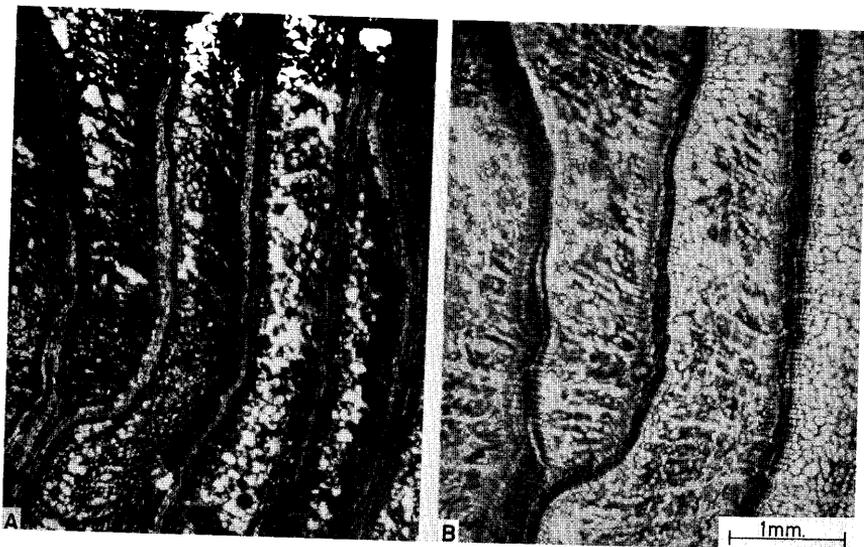
In southern pines the transformation from inner bark to rhytidome involves drastic changes: (1) formation of a new tissue system—the periderm; (2) extreme alteration of cell structures and arrangements; and (3) abundant deposition of substances in the cells.

As sieve cells cease to conduct and begin to collapse, the vertical parenchyma cells enlarge. This process is called **obliteration**. Resultant cell changes are easily visible in older portions of inner bark and are strikingly evident outside of the newest periderm (fig. 12-5). Here the longitudinal parenchyma cells are many times their original diameters and the sieve cells are crushed. In inner bark, longitudinal parenchyma cells are greatly outnumbered by sieve cells and occupy little volume; in rhytidome, however, the enormously enlarged parenchyma cells occupy most of the volume of old phloem tissue. Rhytidome therefore has a very porous structure.

Collapse of sieve cells, parenchyma expansion, and the resultant displacement of old phloem cells alters original radial or tangential alignment and obscures any possible evidence of growth rings in outer bark.

In the trees studied by Howard (1971) obliteration was most evident in samples from near ground level and least pronounced in bark high in the tree. No consistent radial variation was noted. Although some degradation may occur in older rhytidome layers, only where the protective periderms have been ruptured (as in the extreme outer layers or near furrows) is there any noticeable variation from the inner rhytidome layers.

Rhytidome contains an abundance of deposited materials (fig. 12-7). These amorphous deposits—mainly tannins, phlobaphenes, and other phenolic substances—may be found in all cell types and are responsible for the dark reddish-brown color. Although the physiological function of these phenolic compounds is not clear, it has been suggested that they resist fungal attack and act as antioxidants (Kurth 1944). A limited degree of



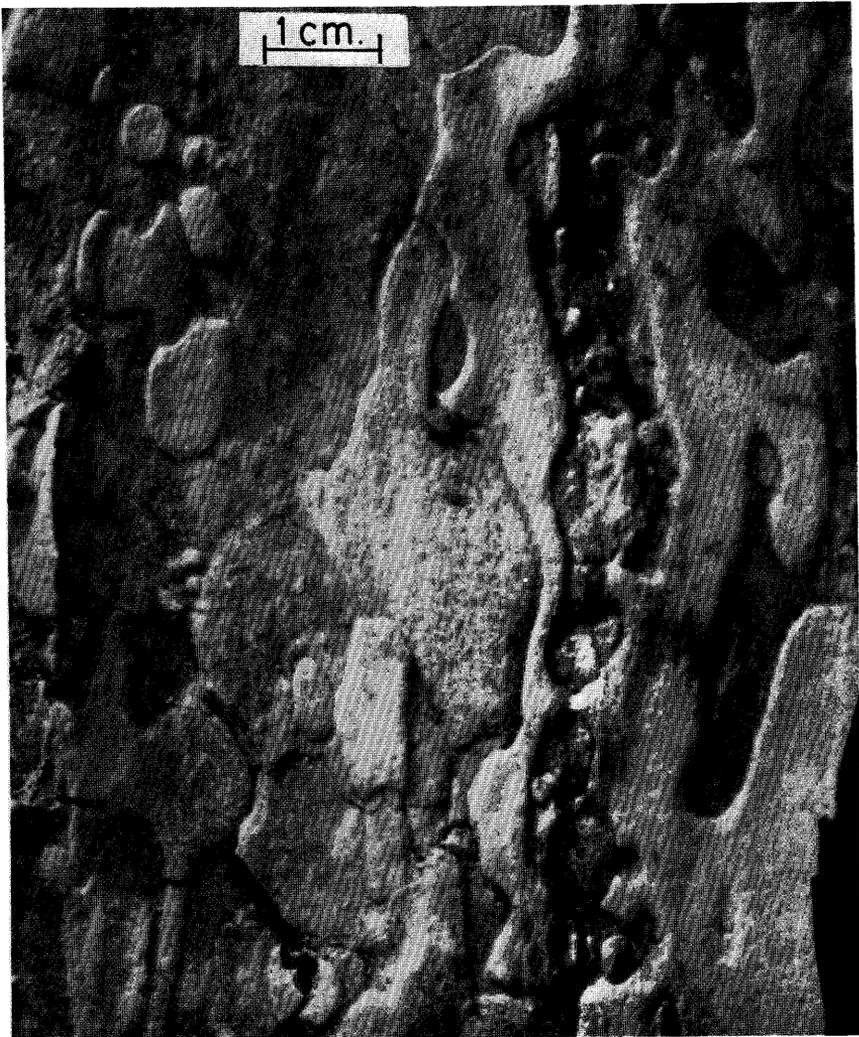
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 Figure 12-7.—Deposits in rhytidome of Ocala sand pine. (A) Untreated cross section. (B) Same section after bleaching to dissolve deposits. Both are at the same magnification; the section expanded during treatment. Radial alignment of periderm cells is easily seen in bleached section. (Photos from Howard 1971.)

lignification is sometimes observed in dead phloem tissues of rhytidome, but in stained sections the coloration of deposits adhering to the inner walls makes the identification uncertain.

PERIDERM

The inner bark is protected from desiccation by the periderms, of which only the innermost is alive. Periderms form in discontinuous, irregularly shaped layers (fig. 12-8) with the edges curving outward to merge with older periderms (fig. 12-1). A periderm is composed of three types of cells—**phellogen**, **phelloderm**, and **phellem**. Phellogen is a layer of meristematic cells which differentiate from unspecialized longitudinal and ray parenchyma cells in older phloem. Phellogen cells divide tangentially to produce radially aligned cells toward both the inside (phelloderm) and the outside (phellem or **cork**). Usually more phellem cells are produced than phelloderm (figs. 12-4, 12-5, 12-9).

Phellogen.—Phellogen may be recognized as the tin-walled row of cells in the midst of the periderm, just to the outside of a two- or three-cell band of thick-walled phelloderm cells (figs. 12-4, 12-5, 12-9). Like the vascular cambium, it is considered one cell wide, but may appear slightly wider if undifferentiated daughter cells are present. Unlike vascular cambium, phellogen has only one type of initial. The cells are flattened radially and are narrowly rectangular in cross and radial sections, but they are irregularly polygonal in tangential view (Srivastava 1964). Except for those



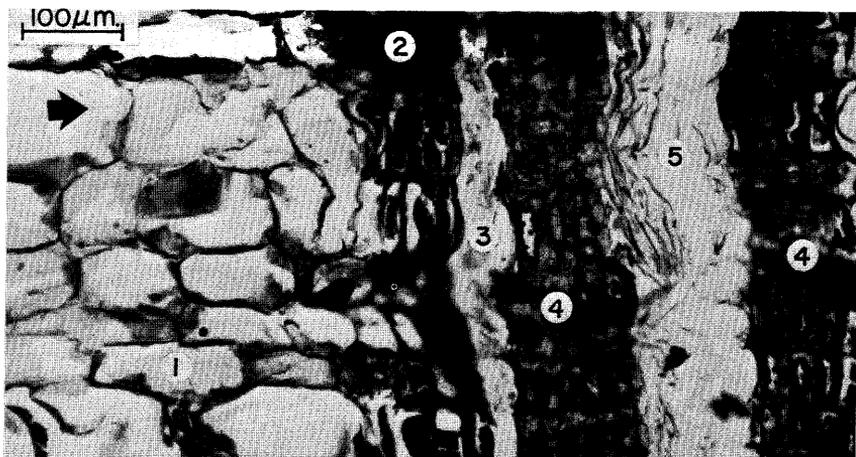
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Figure 12-8.—Interior tangential view of periderms, looking outward from the stem. Inner bark has delaminated, revealing highly irregular periderm shapes, mostly elongated in direction of tree axis. Table-Mountain pine. (Photo from Howard 1971.)

which enlarge or become stone cells, most derivative cells (phelloderm and phellem) retain the original phellogen arrangement and have five to seven sides when viewed tangentially (figs. 12-4, 12-10A).

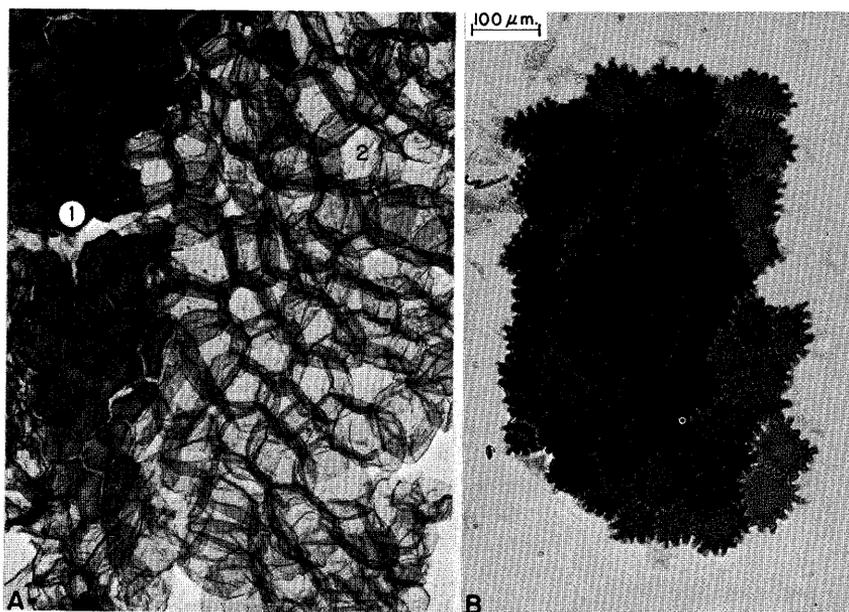
Derivative cells are aligned in radial files but not tangentially or longitudinally (figs. 12-4, 12-11).

Phelloderm.—The function of phelloderm is not entirely understood. In the innermost, or living, periderm these cells are relatively uniform, unenlarged, and unligified. In all older periderms, cell morphology changes across the width of the phelloderm (figs. 12-9, 12-11).



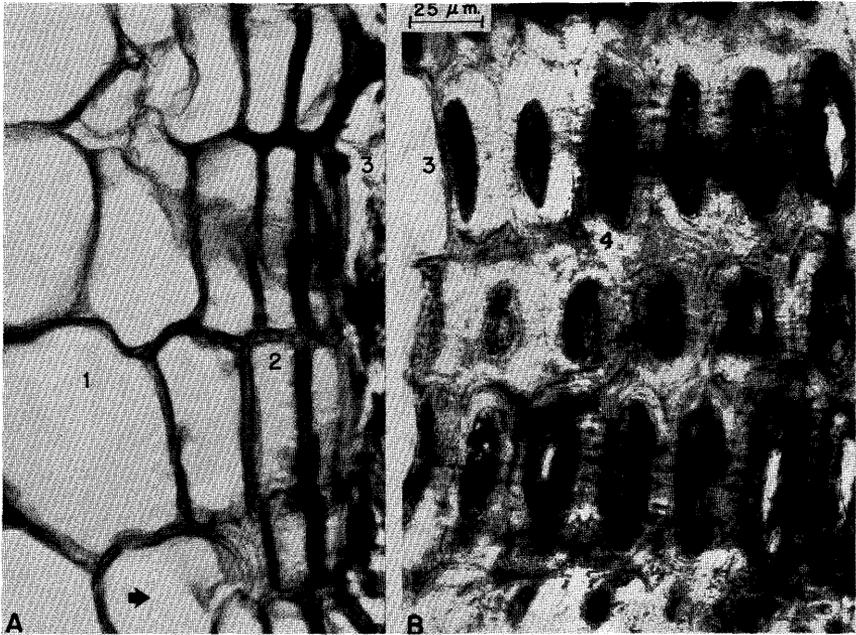
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Figure 12-9.—Radial section of shortleaf pine periderm. 1, radially elongated phelloderm; 2, thickened unexpanded phelloderm, with dark deposits in lumens; 3, phellogen; 4, stone cells; 5, thin-walled cork (distorted here). Periderm cells appear the same in both radial and transverse sections. Arrow points to exterior of tree. Phelloderm develops from the phellogen toward the interior of the tree and phellem toward the exterior. (Photo from Howard 1971.)



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Figure 12-10.—Masses of periderm cells from partially macerated bark. (A) 1, thickened phelloderm cells; 2, thin-walled cork cells. If viewed in an undisturbed section, these cell layers would be separated by the unicellular phellogen layer. Tangential view, slightly oblique. Note angular shape and configuration of cork cells (slash pine). (B) Phellem stone cells. Tangential view showing interlocked arrangement and profuse minute pits (longleaf pine). (Photos from Howard 1971.)



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Figure 12-11.—Periderm, cross-sectional views. Arrow points to exterior of tree. Files of cells are not in precise alignment either longitudinally or tangentially. 1, partially expanded phelloderm; 2, unexpanded phelloderm with simple pits of varying size; 3, phellogen; 4, phellem stone cells with distinct lamellae and numerous pit canals. Lumens are occluded with deposits. Cells which appear smaller were cut near their borders. (A) Pond pine. (B) Longleaf pine. (Photos from Howard 1971.)

The two or three rows of cells nearest the phellogen are similar in shape and size to the mother phellogen but have thickened lignified walls and numerous simple pits (figs. 12-4, 12-10A, 12-11A). With increasing distance inward (within each periderm) the older phelloderm cells are progressively more enlarged, with thinner, radially stretched walls and enlarged pits. The innermost—hence oldest—cells have very thin walls and usually are as large as expanded phloem parenchyma, with which they seem to merge (fig. 12-5).

Radial alignment and, usually, radial elongation distinguish these expanded phelloderm cells from the adjacent old phloem parenchyma cells which tend to be enlarged more in the tangential direction. The distinction is best seen in radial section (fig. 12-4AH).

Radial enlargement of the older phelloderm cells seems in direct contradiction to the tangential stresses and radial compression produced by stem growth, whereas the stretching of the phloem parenchyma cells appears to be a response to these forces.

Howard (1971) found more cell layers of phelloderm than have been previously reported for southern pines. The innermost, expanded, thin-

walled phelloderm layers are easily mistaken for obliterated phloem. There are usually two or three, but occasionally four, layers of thick-walled phelloderm plus a variable number (commonly three to four, but occasionally nine or more) of layers of phelloderm cells in varying stages of enlargement. In some specimens the expanded phelloderm occupied most of the volume between periderms; in these cases, periderms were very closely spaced. The usual descriptions—i.e., that phelloderm is only two to four cells deep—probably stem from recognition of only the thick-walled, unexpanded layers.

Phellem.—Phellem cells are primarily responsible for the protective characteristics of the periderm. All the southern pines have two distinct types of cells in the phellem region: thin-walled cork cells and thick-walled **stone cells**. Bands of both are usually found in the same periderm and either type may be next to the phellogen (figs. 12-4, 12-5); alternating bands occur frequently (fig. 12-9).

Thin-walled cork cells have unpitted cellulose walls overlaid with a lamella of suberin and waxes, which renders them practically impervious to moisture and gases (Sitte 1957; Esau 1965, p. 340). Cell shapes, except for slight crushing, are approximately the same as those of the mother phellogen cells (figs. 12-4, 12-10A). The cork cells are compactly arranged, without intercellular spaces, and may be empty or filled with dark deposits.

Some phellem cells sclerify and become stone cells (figs. 12-3, 12-4, 12-10B, 12-11B, 12-12).² They are arranged in tangential bands of variable width, commonly five to six cells, and form the only heavily lignified tissue of southern pine bark. The stone cells are about the same size as cork cells but have very thick secondary walls with profuse, tiny, ramified pit canals. The walls are composed of a number of concentric lamellae which are distinct in both ordinary and polarized light. The outer tangential wall is usually thicker than the side nearer the phellogen (figs. 12-11B, 12-12A). The inner wall of the last-formed cell layer of a band is especially thin. Cell lumens are narrow and occluded with deposits.

The phellem stone cells are easily identified in tangential sections and macerated tissue (figs. 12-3, 12-4, 12-10B). Distinct, irregular projections form the cell margins and interlock with adjacent cells in a cog-like manner. Tangential walls are comparatively flat.

Unlike the thin-walled cork cells, which gave a positive reaction with Sudan IV (a stain for suberin), Howard (1971) found that the thick-walled phellem stone cells did not stain for suberin in any portion of their walls.

From visual estimates of bark examined in this study, stone cells appear to occupy about 10 percent, or less, of most rhytidome samples.

² Chang (1954ab) called these cells "transformed phelloderm," probably because a few somewhat similar, sclerified cells occasionally can be found in the outermost cell row of phelloderm.

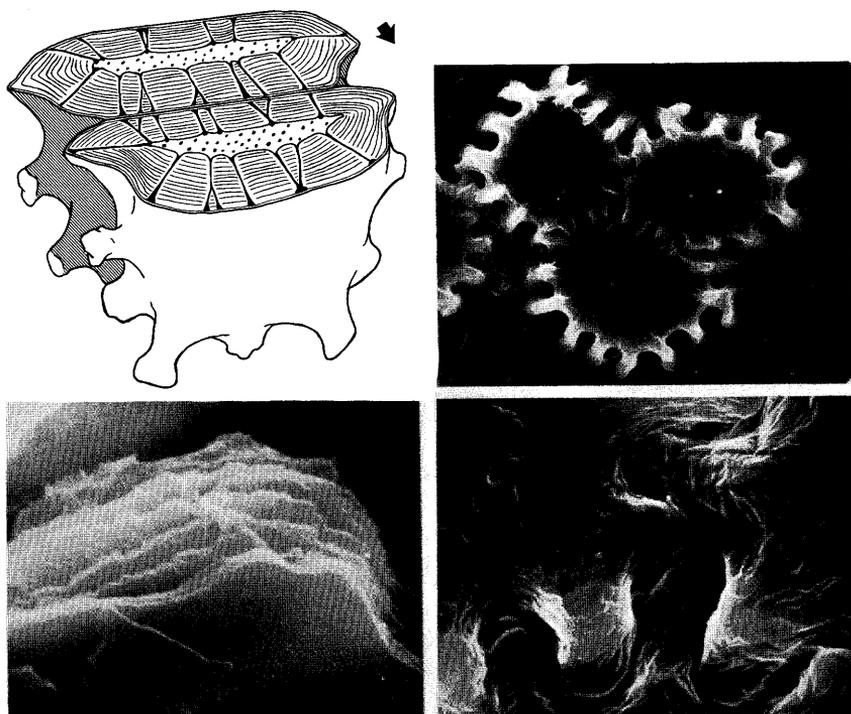


Figure 12-12.—(Top left) Two phellem stone cells of a radial file. Cross-sectional cut reveals distinctly lamellate walls with numerous ramified pit canals. Arrow points toward exterior of tree. (Top right) Interlocked cog-like phellem cells from longleaf pine bark. (400X). (Bottom left) Cross-sectional break of thick-walled phellem cell showing wall layers. Loblolly pine. (5,000X). (Bottom right) Enlargement of central area of photo at top right. Some indications of possible intercellular fibrillar strands exist (2,000X). (Drawing after Howard 1971; photos from Martin and Crist 1970.)

SPECIES COMPARISON

Howard (1971) found no significant differences that would separate individual pine species, although surface characteristics, odor, color, and microstructure did provide some clues to species identity.

External characteristics.—In external appearance, the bark of individual southern pines is highly variable within a species, and samples from trees of different species may be quite similar. Surface coloration varies with exposure conditions, and spacing and depth of fissures are known to be greatly affected by growth rate. Manner and ease of scale exfoliation are related to structure and may have some species significance, but Howard's (1971) sampling was too limited to permit definite determination. The oak-like surface of spruce pine bark has numerous, small, very shallow, transverse cracks (fig. 12-13); in thicker bark of this species, especially where outer scales have been detached, ridges often curve outward at the edges to form concave longitudinal depressions (fig. 12-14). Although

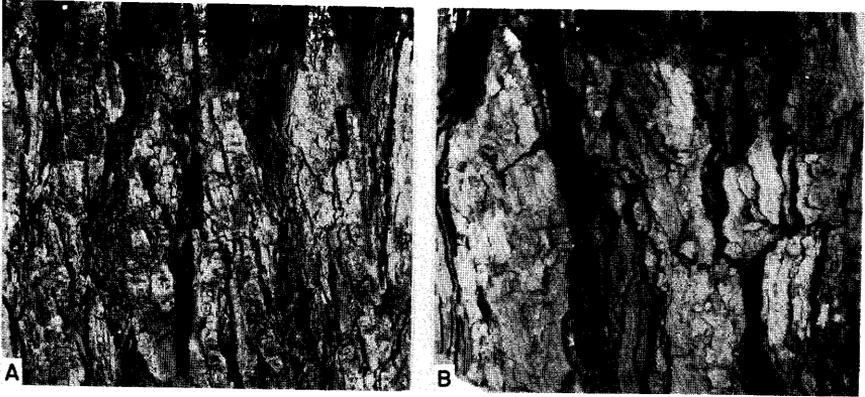


Figure 12-13.—Oak-like appearance and small transverse cracks distinguish mature spruce pine bark (A) from that of the other southern pine species, as typified by loblolly pine bark (B). Samples are from bolts of the same size. (Photos from Howard 1971.)

occasional resin pockets are enclosed in rhytidome layers of several species, only in shortleaf pine do they appear as conspicuous and numerous surface craters or nodules (fig. 12-15).

Odor.—Freshly cut surfaces of some dry samples, notably from the two varieties of slash pine, emit a strong, spicy fragrance reminiscent of cinnamon and cedar. Occasionally samples of other species yield a faint fragrance.

Periderm color.—When viewed with a hand lens, most periderms display two or more lines of varying color, arrangement, and width. These indi-

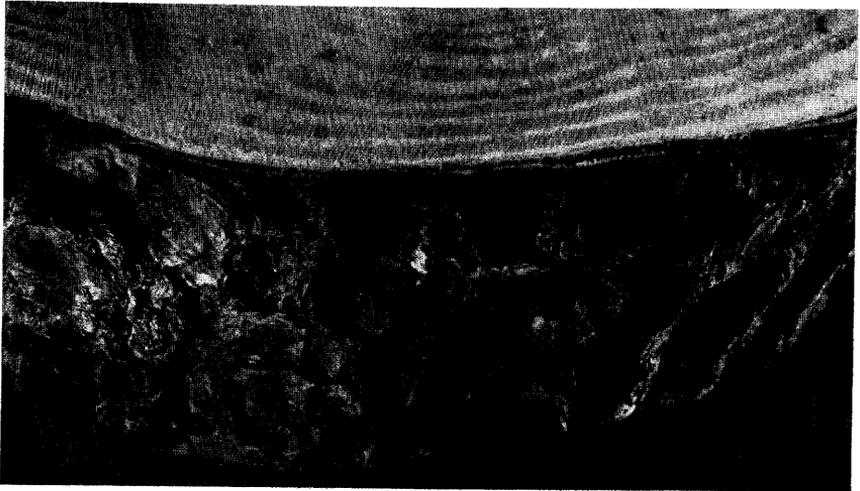
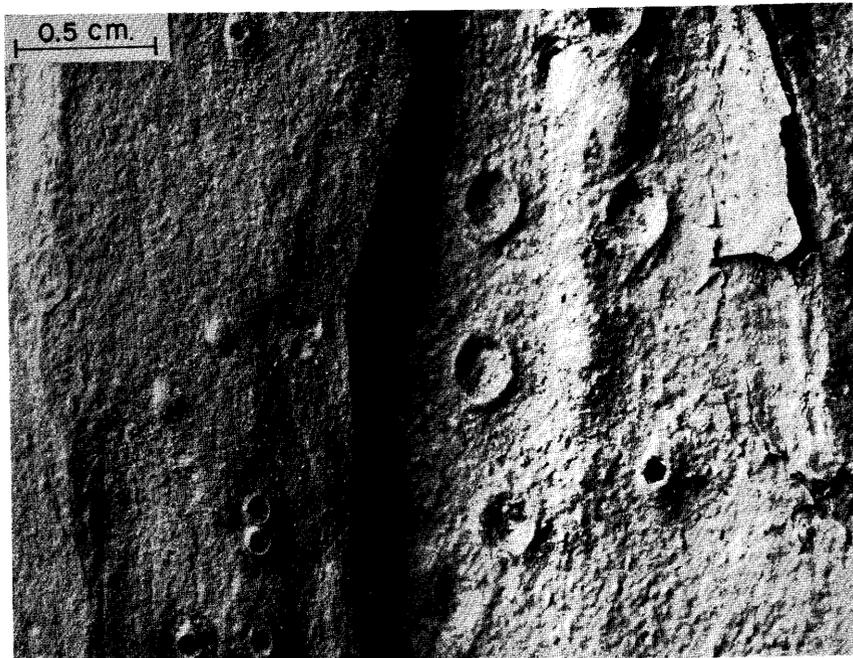


Figure 12-14.—Mature spruce pine bark with edges of some ridges curved outward, forming concave longitudinal depressions. Some outer scales have been detached. (Photo from Howard 1971.)



F-520946

Figure 12-15.—Characteristic resin pockets on surface of shortleaf pine bark, in form of craters and nodules. Samples from two trees show varying size. Craters result when periderm diverges to form behind the resin deposit; periderm formation around the outer portion of the deposit produces a nodule. (Photo from Howard 1971.)



F-520947

Figure 12-16.—Radial section of Ocala sand pine rhytidome. 1, old phloem (relatively unobliterated); 2, radially elongated phelloderm; 3, phellem of alternating thick-walled stone cells and thin-walled cork cells. Arrow points to exterior of tree. (Photo from Howard 1971.)

vidual lines may be dark and dull, ivory white, or dark and shiny. In the samples investigated, wide bands of phellem stone cells resulted in white lines. Samples with dark lines had bands of cells (primarily thin-walled phellem) filled with very dark deposits. Lack of such dark inclusions apparently resulted also in light-colored periderm lines.

Observations of periderm color are best made on freshly cut surfaces, as coloration of older surfaces is often altered by exposure. Four loblolly and four pond pines were examined by Howard (1971) and found to have dark, inconspicuous periderms, as reported by DeVall (1945). Of six Virginia pines, all had light-colored periderm lines, although lines in some samples were very narrow and inconspicuous. The other seven species were variable, some highly so even in adjacent periderms. Although periderm lines were predominantly light in slash pine and mostly dark in other species (e.g., spruce and sand pines), the variation from stem to stem ruled out positive identification of individual trees by this feature alone.

Periderm shape.—Periderm shape, spacing, and length—as viewed in transverse section—vary greatly within a species. Chang (1954b) noted that barks of the soft pines have very short and sharply curved periderms; they may therefore be distinguished from barks of hard pines, which have longer, mostly parallel periderms that gradually overlap. In most sample trees of Howard's (1971) study, the periderms were generally parallel and straight, except where edges curved to join other periderms (fig. 12-1). However, some specimens had very short, distinctly curved periderm patterns.

Microstructure.—All species contain the same periderm cell types, but wide within-species variations occur in periderm arrangement. Several species, however, seem to be consistent in the type of cell forming the outermost band of each periderm.

Except for an occasional incompletely differentiated cell, Howard (1971) observed that stone cell bands consistently formed the outer margin of each spruce pine periderm. In longleaf, sand (both races), slash (both varieties), and Virginia pines, the outer margins were comprised of thin-walled cork cells. The other five species (loblolly, pitch, pond, shortleaf, and Table-Mountain pines) were variable. The value of this feature for separation of species requires further study.

Phloem obliteration was less pronounced in bark from the upper stem than in bark taken near the ground. In some species, particularly spruce pine, Virginia pine, and the two sand pines, old phloem of the rhytidome was much more intact than in other species (fig. 12-16). Bark of these species was more difficult to section, as it was fibrous, brittle, and noticeably harder. Bark from Virginia pine and the two sand pines was extremely thin at upper heights. Although it is not yet verified whether these are consistent species characteristics, it is interesting to note that bark samples from these three species outranked bark of other southern pines in several physical and mechanical properties measured by Martin and Crist (1968) and Martin (1969).

12-2 THICKNESS

The volume and weight of stem bark varies among and within southern pine species. Data on the quantities available per tree, cord, thousand board feet (M b.f.) log scale, and M b.f. lumber scale can be found in section 29-3 under the subsection heading, BARK. (See also equations 29-24 through 29-27, figs. 29-6 and 29-7, tables 29-54 through 29-59, and table 13-4.)

Because mensurationists assess the content of trees and logs by measuring circumferences outside bark with a tape, they need to have an estimate of bark thickness in order to compute solid wood volume; the bark thickness of interest to a mensurationist is the distance from a tape running outside the bark to the woody surface of a stem. A method of accurately measuring this distance from circumferential tape to wood surface—hereafter called gross bark thickness—has been described by Mesavage (1969b).

For those interested in utilization of bark, measurements of the actual bark thickness at numerous sample points afford a more accurate assessment of in-place bark volume; usually this is accomplished by scribing eight or more radial lines on sample disks and measuring the bark thickness outside the vascular cambium at the end of each radial line. This method takes into account the corrugated nature of bark surfaces and the variability in bark thickness around the circumference of a tree; it is hereafter referred to simply as bark thickness.

Regression equations from experimental data indicate a strong relationship between gross bark thickness and diameter, with usually a small constant term and occasionally an age term.

According to Row et al. (1965), mixed southern pine logs from southern Arkansas and northern Louisiana have average gross bark thickness (B, inches) directly proportional to log diameter inside bark (d.i.b., inches) as follows:

$$B = (0.06) (\text{d.i.b.}) \quad (12-1)$$

Based on survey data of pines growing in the Southeastern States, McCormack (1955) reported that for every inch in breast height diameter growth inside bark, the diameter outside bark increases according to the following ratios:

Pine species	Ratio	Number of trees sampled
Loblolly.....	1.10	2,654
Longleaf.....	1.06	1,581
Pitch.....	1.08	93
Pond.....	1.09	258
Sand.....	1.06	57
Shortleaf.....	1.09	1,681
Slash.....	1.07	1,205
Spruce.....	1.06	54
Table-Mountain.....	1.06	16
Virginia.....	1.10	742

Because upper diameters inside bark are inaccessible for measurement in standing trees, Mesavage (1969a) studied diameter relationships in 79 shortleaf, 32 loblolly, 17 longleaf, and 15 slash pines. He concluded that diameter inside bark (d.i.b.) at any tree height could be estimated by the following formula:

$$\text{D.i.b.} = \text{d.o.b.} \left[1 - \left(1 - \frac{d}{D} \right) \left(\frac{1}{2 - \frac{\text{d.o.b.}}{D}} \right) \right] \quad (12-2)$$

In this equation, d.o.b. is diameter outside bark at the height of interest, usually measured with an optical instrument; d and D are breast height diameters, inside and outside bark, respectively.

LOBLOLLY PINE

The gross thickness of bark at breast height on loblolly pines varies according to locality. In the Cumberland Plateau of Tennessee, Burton (1962) measured a total of 326 trees 5 to 25 years old in 35 plots and found the following relationship significant ($r^2 = 0.97$):

$$B = 0.085 + 0.078D \quad (12-3)$$

In the Florida parishes of Louisiana, Minor (1953) measured 2,000 trees and obtained the following relationship ($R^2 = 0.55$; standard error of the estimate = 0.16), which indicates that loblolly pine has thinner bark in Louisiana than on the Cumberland Plateau:

$$B = 0.250 + 0.043D - 0.003A \quad (12-4)$$

Equation 12-4 is shown graphically in figure 12-17.

Renfro (1956) measured loblolly pines 4 to 18 inches in diameter in North Carolina; his equation for gross bark thickness at breast height follows ($R^2 = 0.97$):

$$B = 0.4679 + 0.07714D - 0.01176A \quad (12-5)$$

For loblolly pines in the Southeastern States, McCormack (1955) found gross bark thickness at breast height to be a function only of diameter:

$$B = 0.321 + 0.043D \quad (12-6)$$

In the foregoing equations, B = gross bark thickness at breast height, inches; D = diameter outside bark at breast height, inches; and A = tree age, years.

Ashe (1915, p. 40) listed the following breast-height gross bark thicknesses for loblolly pine in North Carolina:

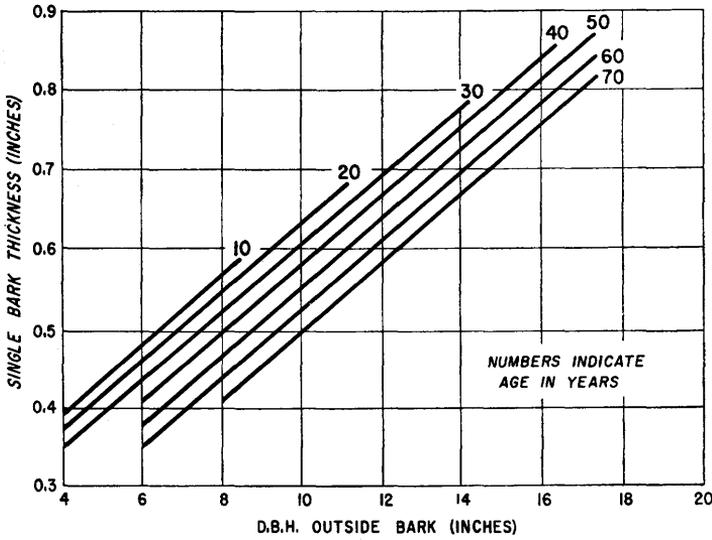


Figure 12-17.—Relation of gross bark thickness at breast height to age and diameter of loblolly pine from the Florida parishes of Louisiana. (Drawing after Minor 1953.)

D.b.h.	Tree height in feet			
	40	70	100	140
<i>Inches</i>	<i>Inches</i>			
4	.6	-----	-----	-----
6	.8	.6	-----	-----
8	.9	.7	-----	-----
10	1.1	.8	.6	-----
12	1.3	.9	.7	-----
14	-----	1.0	.8	-----
16	-----	1.2	.9	-----
18	-----	1.3	1.0	-----
20	-----	-----	1.1	-----
24	-----	-----	1.5	1.0
28	-----	-----	1.7	1.3
32	-----	-----	-----	1.6

According to Renfro (1956) fissures in loblolly pine bark at breast height are about 0.25 inch deep in 4-inch trees and about 0.7 inch deep in 18-inch trees; fissures at stump height are 0.35 to 1.0 inch deep. He also noted that for trees of 4-inch d.b.h., gross bark thickness at stump height was about 0.2 inch greater than that at breast height; in 18-inch trees the difference was about 0.5 inch.

From all of the foregoing, it is evident that gross bark thickness of loblolly pine varies substantially—even between trees of the same diameter. Judson (1964) has provided information on the range of this variability (fig. 12-18); his data are based on breast-height measurements of gross bark thickness of 6,091 trees in Louisiana and Alabama.

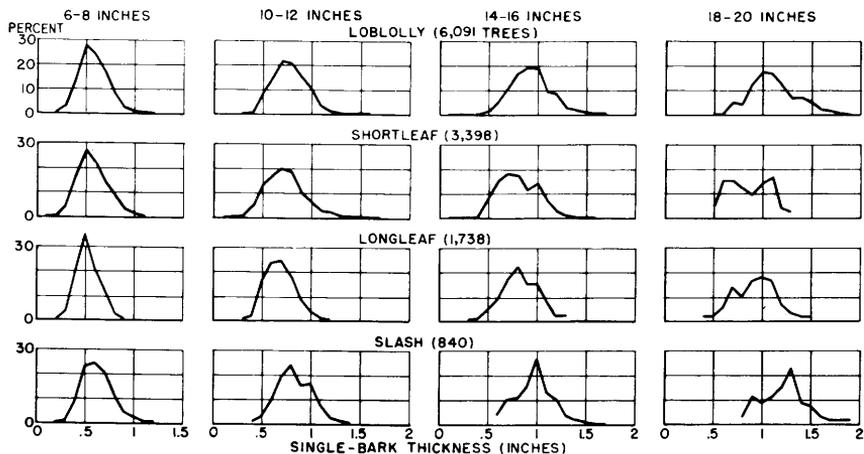


Figure 12-18.—Distribution of southern pine trees by gross bark thickness at 4.5 feet. All trees sampled were from Louisiana and Alabama. (Drawing after Judson 1964.)

LONGLEAF PINE

As with loblolly pine, gross bark thickness at any height is positively correlated with diameter at that height (Wahlenberg 1946, p. 218). MacKinney (1934) measured 426 longleaf pines growing in South Carolina and found that gross bark thickness at breast height (B , inch) was related to d.i.b. as follows ($r^2 = 0.59$; standard error of the estimate = 0.106 inch):

$$B = 0.2322 + 0.0537 \text{ (d.i.b.)} \quad (12-7)$$

The trees on which this equation is based were about 35 years of age and had never been burned.

Judson's (1964) data on 1,738 longleaf pines from Louisiana and Alabama show that gross bark thickness at breast height is about $\frac{1}{2}$ -inch for trees 6 to 8 inches in diameter; trees 18 to 20 inches in diameter have bark nearly an inch thick, but variation among trees is substantial (fig. 12-18).

MacKinney (1934) observed that gross bark thickness at breast height was reduced approximately 0.05 inch by four annual fires, regardless of diameter class; based on measurements of 236 trees, the reduction in gross thickness was about 0.1 inch in all diameter classes as the result of an accidental fire following 14 years of protection. Wahlenberg (1936) found that 10 annual fires reduced gross bark thickness at breast height by about 0.033 inch; his measurements were made on 2- to 8-inch longleaf pine trees in Mississippi.

Ashe (1915, p. 41) related bark thickness of longleaf pines at stump height to breast-height diameter outside bark as follows:

BARK

<u>D.b.h.</u>	<u>Bark thickness at stump</u>
----- Inches -----	
2	0.2
5	.4
10	.6
15	.8
20	1.0
25	1.1

POND PINE

Renfro (1956) related the gross bark thickness at breast height (B, inch) in North Carolina pond pine to breast height diameter outside bark (D, inches) and tree age (A, years) as follows ($R^2 = 0.66$):

$$B = 0.4906 + 0.06817D - 0.00735A \quad (12-8)$$

He also observed that fissures in bark at breast height were about 0.3 inch deep in 4-inch trees and about 0.6 inch deep in 18-inch trees; fissures at stump height were deeper, i.e., 0.4 and 0.7 inch. For trees of 4-inch d.b.h., gross bark thickness at stump height was about 0.15 inch greater than that at breast height; in 18-inch trees the difference was about 0.3 inch.

SHORTLEAF PINE

Judson (1964) summarized data from 3,398 trees sampled in Louisiana and Alabama and showed that gross bark thickness at breast height was about 1/2-inch in trees 6 to 8 inches in diameter and about 3/4-inch in 18- to 20-inch trees; variability was similar to that observed for longleaf pine (fig. 12-18).

SLASH PINE

Miller (1961) studied gross bark thickness of small slash pine trees growing near Savannah, Ga. by sampling 32 trees in each of three diameter classes, i.e., 7-, 9-, and 11-inch diameter breast height outside bark. Eight trees in each class were measured during each of the four seasons of the year. Diameters before and after bark was removed were measured at various heights with a circumferential tape. Of the 96 trees in the experiment, one-fourth were on hill or ridge sites with sandy soil and excessive drainage. These trees had an average gross double bark thickness of 0.95 inch, whereas the other 72 trees—which were cut from minor drainage sites, flat sites with poor internal drainage and seasonal flooding and depressed sites containing some water a large portion of the year—had thinner bark averaging 0.86 inch for gross double bark thickness. Bark thickness variation with diameter was least among ridge trees (table 12-1).

TABLE 12-1.—Gross double bark thickness of Georgia slash pine related to site, d.b.h., and distance up stem (Miller 1961)

Site and d.b.h. (inches)	Distance up stem in feet							
	4.5	10	17 ¹	20	30	40	50	60
	----- Inches -----							
Ridge sites ²								
6	1.17	0.87	0.67	0.61	0.45	0.34		
8	1.29	.99	.79	.73	.58	.47	0.38	
10	1.42	1.12	.92	.85	.70	.59	.51	
12	1.54	1.24	1.04	.98	.82	.72	.63	
14	1.66	1.36	1.16	1.10	.95	.84	.76	
16	1.79	1.49	1.29	1.23	1.07	.96	.88	
Other than ridge sites ³								
6	1.04	.78	.60	.55	.41	.32	.24	
8	1.21	.95	.77	.72	.58	.48	.41	0.35
10	1.38	1.11	.94	.88	.75	.65	.58	.52
12	1.55	1.28	1.10	1.05	.92	.82	.75	.69
14	1.72	1.45	1.27	1.22	1.08	.99	.92	.85
16	1.88	1.62	1.44	1.39	1.25	1.16	1.08	1.02

¹ Top of first 16-foot log.

² Computed from equation 12-9; values for 14- and 16-inch trees are extrapolations.

³ Computed from equation 12-10; values for 14- and 16-inch trees are extrapolations.

In all the trees, gross double bark thickness (i.e., twice single gross bark thickness) was found to be related to diameter breast height outside bark (D, inches) and height above ground (H, feet), as follows. For hill or ridge sites (table 12-1, top):

$$\text{Gross double bark thickness, inch} = 1.363 + 0.062D - 0.868 \log_{10} H$$

$$R^2 = 0.81; \text{ standard error of the estimate} = 0.20 \text{ inch} \quad (12-9)$$

For other than ridge sites (table 12-2, bottom):

$$\text{Gross double bark thickness, inch} = 1.040 + 0.084D - 0.766 \log_{10} H$$

$$R^2 = 0.85; \text{ standard error of the estimate} = 0.16 \text{ inch} \quad (12-10)$$

Judson's (1964) data on 840 slash pines in Louisiana and Alabama showed that they had thicker bark at breast height than the other three major species in this area; trees 6 to 8 inches in diameter had a gross bark thickness of about 0.6 inch, and 18- to 20-inch trees had 1.3-inch-thick bark (fig. 12-18).

SPRUCE PINE

Manwiller³, in a study of 72 spruce pine trees of three age classes and two growth rates drawn from the major commercial range, found that young, slow-growing trees had the thinnest bark. He observed actual bark thickness by scribing eight radius lines on cross sectional disks from various heights and measuring the bark thickness outside the vascular cambium along each radial line. His tree-average values for bark thickness to a 4-inch top, and values at stump height follow:

Tree age class and growth rate (rings per inch)	Tree average	Stump height
	----- Inch -----	
15 years		
More than 6.....	0.16	0.22
Less than 6.....	.19	.27
30 years		
More than 6.....	.18	.25
Less than 6.....	.22	.32
45 years		
More than 6.....	.21	.28
Less than 6.....	.25	.36

Manwiller also found that actual bark thickness (*b*, inch) could be expressed for any height in the tree in terms of diameter inside bark at the height of interest (*d*, inches), and height above ground (*H*, feet), as follows (see also fig. 12-19):

$$b = 0.0891 + 0.0175 d - 0.0000871 dH \quad (12-11)$$

The relationship accounted for 67 percent of the observed variation, standard error of the estimate was 0.045 inch.

VIRGINIA PINE

According to Chamberlain and Meyer (1950), gross bark thickness of Virginia pine pulpwood is equal to 2.7 percent of diameter outside bark.

12-3 MOISTURE CONTENT

The moisture content of southern pine bark varies substantially within and between trees. While evidence is not conclusive, bark moisture content may be greater during August, September, and October than during the rest of the year (fig. 12-20).

³ Manwiller, F. G. Characterization of spruce pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.1 dated May 1, 1972.

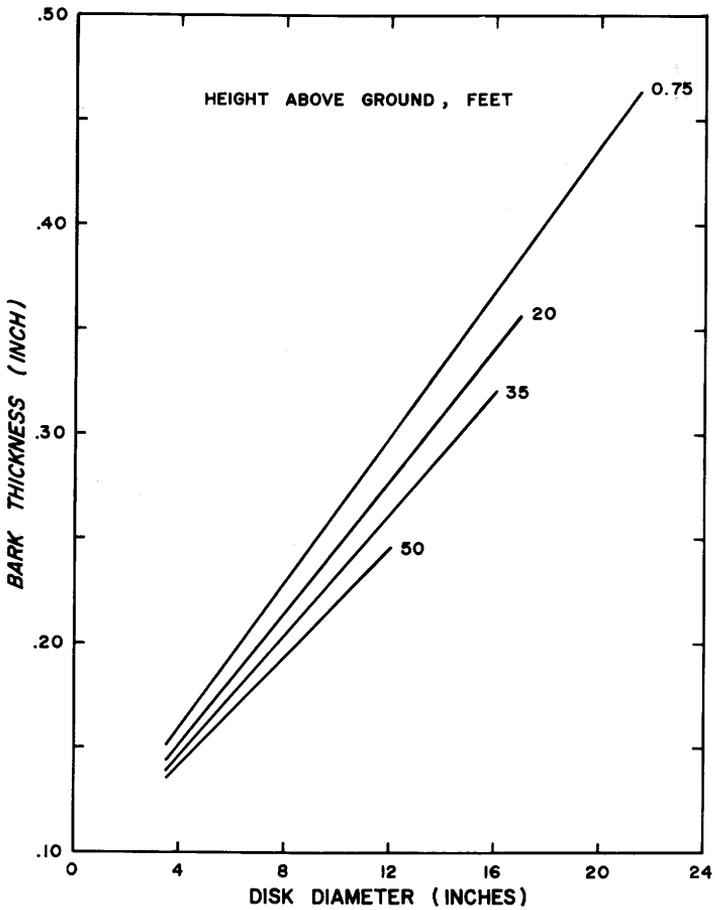


Figure 12-19.—Bark thickness in spruce pine trees as related to diameter inside bark at height of interest and height above ground. (Drawing after Manwiller³.)

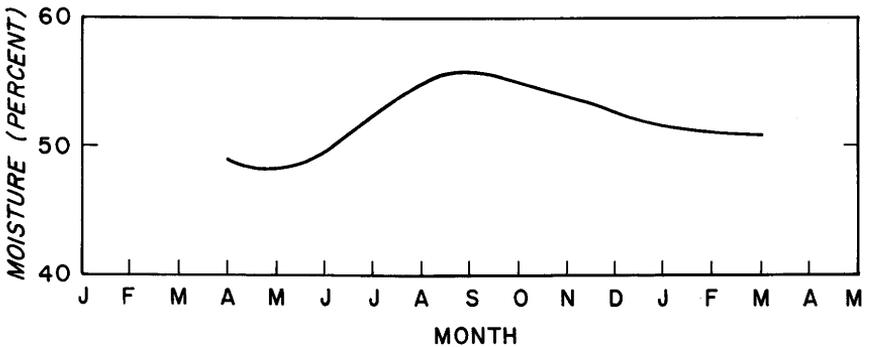


Figure 12-20.—Moisture content (ovendry weight basis) of whole bark from pitch pine related to season during 1 year of observation. (Drawing adapted from Spalt and Reifsnyder 1962, based on data from Stickle⁴.)

INNER BARK

According to Martin (1963a, pp. 89, 92, and 104), the inner bark of the southern pines ranges in moisture content from 150 to 300 percent of the oven-dry weight. In a sample of five loblolly, four longleaf, one shortleaf, and eight slash pines, he found that inner bark moisture content averaged less at 1 foot from ground level (227 percent) than at breast height (237 percent), as follows:

Pine species	Height above ground in feet		
	0	1.0	4.5
	----- Percent -----		
Loblolly.....	256	221	237
Longleaf.....	189	208	222
Shortleaf.....	244	243	264
Slash.....	233	234	223

There are no published data that relate inner bark moisture contents to heights above 4.5 feet.

OUTER BARK

The outer bark of the southern pines has much less water content than the inner bark. Renfro (1956) observed that moisture in the outer bark of pond and loblolly pines was only about 17 percent of the oven-dry weight.

According to Martin (1963a, pp. 89 and 104), moisture contents of outer bark samples from southern pines range from about 18 to about 63 percent of oven-dry weight. He observed that the driest bark was outermost and well above ground level; outer bark at ground level was moistened by wet litter. Martin's average values for outer bark moisture content follow:

Pine species	Trees sampled	Height above ground in feet		
		0	1.0	4.5
		----- Percent -----		
	<i>Number</i>			
Loblolly.....	5	49	29	29
Longleaf.....	4	46	24	21
Shortleaf.....	1	40	30	26
Slash.....	8	59	27	25

Information on variability with height above 4.5 feet has not been published.

WHOLE BARK

Because the innermost periderm delineating inner bark from outer bark is more or less impervious to water movement, the transition in moisture content from inner to outer bark is abrupt (fig. 12-21).

The moisture content of whole bark is dependent on the ratio of outer

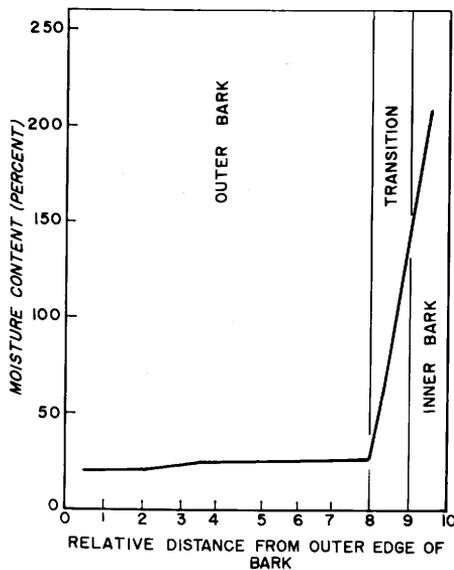


Figure 12-21.—Moisture content (percent of oven-dry weight) in inner, transition, and outer bark of southern pine trees at breast height. Because of difficulty in sampling the transition zone accurately, these zone samples contained some inner and some outer bark. Curve is average of values obtained from three loblolly, two slash, and two longleaf pine trees. (Drawing adapted from Martin 1963a, p. 91.)

bark to total bark volume. This ratio is greatest in butt logs of old trees and least in tops of young trees. Stickel's⁴ data provide ratios of outer bark thickness to total bark thickness one foot above ground level in pitch pine, as follows:

Tree age	Ratio
Years	
5	0.27
10	.67
50	.91

Data pertinent to the major species are scarce. Snow (1949, p. 509) found that shortleaf pine outer bark comprised 76 percent of the total bark weight when freshly cut; in Virginia pine the percentage of outer bark was 79. According to Howard (1971) and Renfro (1956), inner bark of the southern pines averages about 0.06 inch in thickness.

T. C. Carlson and D. J. Henckel (unpublished data on 30 loblolly pine trees in Arkansas) found that moisture content of whole bark was greatest in the upper portions of trees and varied according to tree diameter as follows:

⁴ Stickel, P. W. Preliminary report on the anatomical structure of the bark of six northeastern forest trees. USDA Forest Service, Northeastern Forest Experiment Station, Preliminary Report dated January 28, 1936.

<u>Tree d.b.h. and height in tree</u>	<u>Whole-bark moisture content</u>	<u>Tree d.b.h. and height in tree</u>	<u>Whole-bark moisture content</u>	<u>Tree d.b.h. and height in tree</u>	<u>Whole-bark moisture content</u>
	<i>Percent</i>		<i>Percent</i>		<i>Percent</i>
1 to 5 inches		6 to 10 inches		12 to 20 inches	
Breast height	50	Breast height	55	Breast height	54
Midheight	—	Midheight	109	Midheight	96
At 4-inch top	—	At 4-inch top	151	At 4-inch top	155

They found that whole stem bark (breast height to 4-inch top) in southern pines 6 inches d.b.h. and larger averaged 94 percent moisture content.

This information is in agreement with data from Metz and Wells (1965), who showed that water content in upper stem bark from loblolly pine trees 7 to 21 years old was generally over 100 percent of oven-dry weight.

<u>Location of bark</u>	<u>Percent</u>
Upper one-third of crown	140
Mid one-third of crown	124
Lower one-third of crown	103
Below crown	78

12-4 CHEMICAL CONSTITUENTS

In contrast to the extensive literature on the chemistry of wood, relatively little is published on the chemistry of bark, e.g., the two-volume wood chemistry text of Wise and Jahn (1952) devotes only four pages to bark. Of the 534 citations in the bibliography by Roth et al. (1960) and its supplement (Roth and Weiner 1968) on the structure, extractives, and utilization of bark, only four relate to bark of the southern pines. About one-tenth of the pages in Browning (1963) describe the chemistry of bark, but little of the information is specific to southern pine. In short, knowledge of the chemical constituents of southern pine bark is very limited.

Entomologists studying the life cycles of insects that feed on the living inner bark of southern pines have done substantial research on the seasonal changes in the free amino acid and carbohydrate content of loblolly pine inner bark (Hodges and Lorio 1969; Clark and Mills 1970). For utilization purposes, however, interest centers on the chemical constituents of rhytidome after its removal from mature trees.

Analysis of whole southern pine bark yields four classes of chemicals in addition to ash, namely holocellulose, lignin, phenolic acids, and extractives.

CARBOHYDRATES, LIGNIN, AND PHENOLIC ACIDS⁵

Carbohydrates.—Chang and Mitchell (1955) determined the carbohydrate content of slash pine bark by hydrolysis with 72 percent sulfuric acid. Yields of reducing sugars, measured as glucose, were as follows:

⁵ The text under this heading is taken with some editorial changes from Sproull (1969) by permission of Reavis C. Sproull and the Forest Products Research Society.

<u>Condition of bark</u>	<u>Percent</u>
Unextracted	29.7
Extracted	29.8
Alkali extracted	26.4

Sugars in the hydrolysate of extracted bark were 63 percent glucose, 15 percent xylose, and 7 percent each of galactose, mannose, and arabinose.

Browning and Sell (1957) reported 28 percent total sugar content in ash-free unextracted slash pine bark.

Lignin.—Chang and Mitchell (1955) found that extractive-free, oven-dry slash pine bark contained about 50 percent lignin; their values for lignin and methoxyl content (percent) of slash pine bark follow:

<u>Condition of bark</u>	<u>Lignin</u>	<u>Methoxyl</u>
Extractive free	49.9	6.3
Alkali extracted	26.1	10.2
Unextracted	—	4.0

This lignin fraction was the acid-insoluble residue from bark by the 72 percent sulfuric acid method—probably consisting of bark lignin plus insoluble corky substances; methoxyl yield (TAPPI method TM-60) was based on the oven-dry lignin from extracted bark.

Doughty et al. (1956) used 15 to 30 percent sodium hydroxide to separate alkali soluble fractions and thioglignin from southern pine bark; yields of thioglignin were 25 to 48 percent.

Lewis et al. (1944) and Brauns and Lewis (1944) have presented evidence that there is a stable lignin-carbohydrate linkage in bark that is absent in wood.

Phenolic acids.—The alkali-soluble fractions of southern pine bark are phenolic acids or polyphenols. Hergert et al. (1965) suggests that aerobic aging of moist bark converts some of its carbohydrates and extractives to phenolic acids.

Slash pine bark contains 50 to 55 percent aromatics (Chang 1954a; Chang and Mitchell 1955), of which about two-thirds is estimated to be phenolic acid. These phenolics are structurally similar to phlobaphenes and the water-soluble tannins (Stanley 1969).

Hergert (1960) has reported that slash pine bark yields numerous phenolics as follows:

<u>Compound</u>	<u>Compound</u>
Dihydromyricetin	Leucocyanidin A
Dihydromyricetin glucoside	Leucocyanidin B
Dihydroquercetin	Leucodelphinidin(s)
Dihydroquercetin glucoside	Gallic acid
Dihydrokaempferol	Protocatechuic acid
Pinobanksin	Phloroglucinol
Myricetin	Caffeic acid (<i>trans</i>)
Quercetin	Ferulic acid (<i>trans</i>)
Gallocatechin	Coniferylaldehyde
Catechin	Vanillin

In his study, these compounds were present in highest concentration in the inner bark and in the phellogen. He concluded that genera may be distinguished from each other on the basis of amount and kinds of polyphenols and color bodies in the bark.

Erman and Lyness (1965) described the isolation of a phenolic acid from slash pine and its conversion to a relatively homogenous methylated phenolic acid derivative. Alkaline extraction of the bark with 3 percent NaOH followed by neutralization with dilute acid yielded an amorphous phenolic acid insoluble in water or organic solvents. By treatment with diazomethane the phenolic groups were methylated and the derivative was soluble in organic solvents but insoluble in water. Analysis of the derivative suggests that it is a polymer of substituted catechin-type units having the empirical formula $[C_{15}H_{11}O_4(OCH_3)_3]_{17}$

EXTRACTIVES ⁶

The compounds present in the extractives of southern pine barks exceed in amount and number those found in the wood of the species, but knowledge of them is very incomplete.

Browning and Sell (1957), in successive extractions of slash pine bark, found that benzene removed 4.6 percent of the dry weight, hot water yielded an additional 10.9 percent, and 1 percent NaOH at 90° F. removed another 21 percent of the original dry weight. In a sequence of solvents, Harkin and Rowe (1969) reported solubility percentages for slash pine bark of 3.4 in benzene, 10.6 in 95 percent alcohol, 3.7 in hot water, and 28.9 in 1 percent sodium hydroxide; if treated initially with 1 percent sodium hydroxide, 48.5 percent of slash pine bark was soluble. Water extracts most of the sugars and minerals and some tannins. Alkali removes phenolics and carboxylic acids as described in the foregoing paragraph, *Phenolic acids*.

Southern pine barks, once a factor in the leather tanning industry, are no longer a competitive source of tannin. According to Howes (1953), loblolly pine bark contains about 12 percent tannin, shortleaf 11 to 18 percent, and longleaf 17 to 18 percent. Tannins are condensed (polymerized) polyphenols.

In addition to the phenolic and tannin substances, bark extractives also contain resins, waxes, saponins, starches, simple carbohydrates, alkaloids, and minerals.

Ether extracts from phloem tissue of slash pine saplings and growing tips show a greater variety of fatty acids and related alcohols than does the wood (Hall and Gisvold 1935, 1936). These extracts contain a complex $C_{30}H_{56}O_3$ waxy alcohol, plus *n*-caproic, dodecosanic, palmitic, oleic, and linoleic acids, sitosterol, and sterolin along with fats and sugars.

⁶ The text under this heading is taken with minor editorial changes from Stanley (1969) by permission of Robert G. Stanley and the Forest Products Research Society.

Rowe (1965) characterized the steroids of loblolly pine bark and presented a possible biosynthetic pathway for the steroids from a common terpene precursor. Benzene extract of loblolly pine bark contained 2.8 percent steroids with composition as follows:

Component	Percent
β -sitosterol	68.0
Campesterol	7.0
α -sitosterol	4.0
7-keto- β -sitosterol	3.0
Δ^4 -stigmasten-3-one	1.8
Other	16.2
	100.0

ASH

Bark from 30- to 45-year-old trees of the major species has been shown by Renfro (1956, p. 32), Harkin and Rowe (1969, p. 36), and others to have an ash content of about 0.6 percent of the oven-dry weight (table 26-4), with analysis as shown in table 26-7.

Variation within and between trees is substantial. Data on the ash content of stem-bark from 10 young loblolly pine trees 8 to 46 feet high show that ash content in bark is least in the lower stem and greatest in the upper crown (table 12-2).

TABLE 12-2.—Ash content (by weight) in oven-dry bark of young loblolly pine trees related to position in crown (Metz and Wells 1965)

Tree age	Position of stem-bark relative to crown				
	Upper third	Middle third	Lower third	Below crown	Average
<i>Years</i>	<i>Percent</i>				
7	1.9	1.4	1.4	-----	1.2
7	2.1	1.4	1.6	-----	1.3
7	1.7	1.3	1.3	1.4	1.4
7	.1	.1	.0	.0	.1
7	2.1	1.2	.9	.9	1.3
8	1.5	1.3	1.0	1.2	1.3
8	-----	1.5	1.2	1.2	1.0
13	2.1	1.5	1.3	1.1	1.5
21	.7	.5	.4	.2	.5
21	2.1	1.7	1.2	.9	1.5
Average	1.4	1.2	1.0	.7	

Metz and Wells (1965) found that content of nutrient elements in the bark of these 10 loblolly pines averaged as follows:

<u>Element</u>	<u>Percent of oven-dry weight of bark</u>
Calcium	0.21
Magnesium	.09
Nitrogen	.42
Phosphorus	.06
Potassium	.32

In this determination, the nitrogen content was determined by the Kjeldahl method; the metallic elements were determined from ash. In all 10 trees magnesium content in stem-bark increased with increasing height above ground. Stem-bark contained a lower percentage of all nutrient elements than the needles, but more than stem-wood.

12-5 PHYSICAL AND MECHANICAL PROPERTIES

Bark of the southern pines is variable in density and less strong than southern pine wood; its volumetric shrinkage when dried, is about the same as that for wood. While the specific heats of southern pine wood and bark are roughly comparable, the thermal conductivity of bark is lower and the heat of combustion higher than that of wood.

SPECIFIC GRAVITY

According to Martin (1969), southern pine barks are low or intermediate in density compared to other species, but there is great variability among and within species and within trees. Much of this variation is probably attributable to the degree of expansion of old phloem cells and to varying proportions of phellem stone cells which have thick, heavily lignified walls and narrow lumens.

Variation among species.—Data are insufficient to permit definition of species averages for bark density; the literature does, however, contain some data on all 10 species. In all cases, the data following refer only to the outer bark or rhytidome.

Specific gravity values for four southern pine barks have been given by two sources without indication of variability, as follows (basis of volume and weight when oven-dry) :

<u>Pine species</u>	<u>Specific gravity</u>	<u>Source</u>
Shortleaf.....	0.486	Harkin and Rowe (1969)
Longleaf.....	.526	Harkin and Rowe (1969)
Loblolly.....	.320	Renfro (1956, p. 32)
Pond.....	.330	Renfro (1956, p. 32)

Martin (1969) has provided average values with standard deviations for outer bark of all 10 species; his data are ranged from low to high gravity and indicate that pond and pitch pines have bark specific gravities

of about 0.36, while gravities of both Virginia and sand pine barks exceed 0.7 (table 12-3).

From samples of outer bark of spruce pines taken at all heights from 72 trees 15 to 45 years old, Manwiller³ observed that the overall average was 0.38 with standard deviation of 0.03. Manwiller's data were based on green volume and oven-dry weight.

TABLE 12-3.—*Specific gravity of outer bark from the southern pines*¹
(Martin 1969)

Pine species	Trees	Samples	Average	Standard deviation
	- - - - Number - - - -			
Pond.....	6	132	0.361	0.070
Pitch.....	3	75	.362	.069
Shortleaf.....	3	126	.473	.106
Slash.....	9	297	.474	.085
Loblolly.....	7	264	.477	.105
Table-Mountain....	2	48	.560	.103
Spruce.....	8	72	.622	.116
Longleaf.....	11	351	.640	.097
Virginia.....	3	84	.721	.102
Sand.....	3	126	.754	.078

¹ Based on oven-dry volume and weight.

Variation among trees.—In Manwiller's³ observations of 72 spruce pines, tree-average values for bark specific gravity (basis of green volume and oven-dry weight) were lowest in the youngest, most vigorously growing trees, as follows:

Tree age class and growth rate (rings per inch)	Specific gravity
15 years	
Less than 6	0.36
More than 6	.38
30 years	
Less than 6	.38
More than 6	.40
40 years	
Less than 6	.38
More than 6	.40

The tree-average value for whole bark specific gravity (basis of green volume and oven-dry weight) of spruce pine has been expressed by Manwiller³ in terms of tree age (A, years) and growth rate (R, rings per inch measured at stump height), as follows:

$$\text{Specific gravity} = 0.3308 + 0.00436R + 0.000635A \quad (12-12)$$

Equation 12-12 accounted for 21.9 percent of the observed variation with standard error of the estimate of 0.029.

Renfro (1956, p. 33) observed that specific gravity of breast-height bark in pond pines was positively correlated with tree age; this trend was not, however, evident in loblolly pines. His values were based on oven-dry volume and weight as follows:

<u>Tree age</u>	<u>Pond pine</u>	<u>Loblolly pine</u>
<i>Years</i>		
20	0.30	0.33
40	.34	.31
60	.35	.33

T. C. Carlson and D. J. Henckel (unpublished data on 30 loblolly pine trees in Arkansas) observed that tree-average values for whole bark specific gravity (basis of green volume and oven-dry weight) were about 16 percent higher for trees 12 to 20 inches d.b.h. than for trees 6 to 10 inches d.b.h.; the overall average they observed for all trees was 0.27.

Variation within trees.—In Martin's (1969) studies of southern pine outer bark (55 trees, including samples from all 10 species), he observed a significant positive linear correlation between height of sample above ground level (feet) and specific gravity (based on volume and weight when oven-dry); his equation took the form:

$$\text{Specific gravity} = a + b (\text{height}) \quad (12-13)$$

Intercepts (a), coefficients (b), and coefficients of determination (r^2) were as follows (each based on 48 to 351 samples):

<u>Pine species</u>	<u>a</u>	<u>b</u>	<u>r^2</u>
Loblolly	0.36803	0.00446	0.45
Longleaf	.54273	.00374	.42
Pitch	.31808	.00229	.11
Pond	.32890	.00218	.12
Sand	.68463	.00262	.30
Shortleaf	.43704	.00133	.05
Slash	.38701	.00390	.49
Spruce	.51323	.00539	.57
Table-Mountain	.41818	.00756	.50
Virginia	.65145	.00311	.14

Martin, in determining the foregoing relationships, measured bark specific gravity on the basis of volume and weight when oven-dry. In two other studies, however, in which specific gravity was computed on the basis of green volume and oven-dry weight, height in the tree accounted for little of the observed variation in specific gravity. In Manwiller's³ study of spruce pine the correlation was positive and significant but r^2 was only 0.085; in 30 loblolly pine trees in Arkansas, T. C. Carlson and D. J. Henckel

(unpublished data) failed to find a significant relationship between bark specific gravity and height.

Bulk density.—Williams and Hopkins (1969, pp. 82 and 83) reported that a cubic foot of green southern pine bark weighed 26 pounds when loosely piled; when at 39-percent moisture content and coarsely pulverized, bark from sawmills weighed 20 pounds per cubic foot.

STRENGTH

Martin and Crist (1968) used modifications of standard test procedures and smaller than standard specimens to evaluate the mechanical properties of bark from five southern pine species, i.e., the four major species and Virginia pine. Specimens were tested dry at the equilibrium moisture content they attained during a month or more of storage in the laboratory.

Crushing strength.—Strength of pine bark under compressive load was positively correlated with specific gravity; it was greatest when loaded radially and least when loaded tangentially (fig. 12-22). The equations took the following form with intercepts (a), coefficients (b), and coefficients of determination (r^2) as tabulated:

Crushing strength, kg./cm.² = a + b (specific gravity based on (12-14)
ovendry volume and weight)

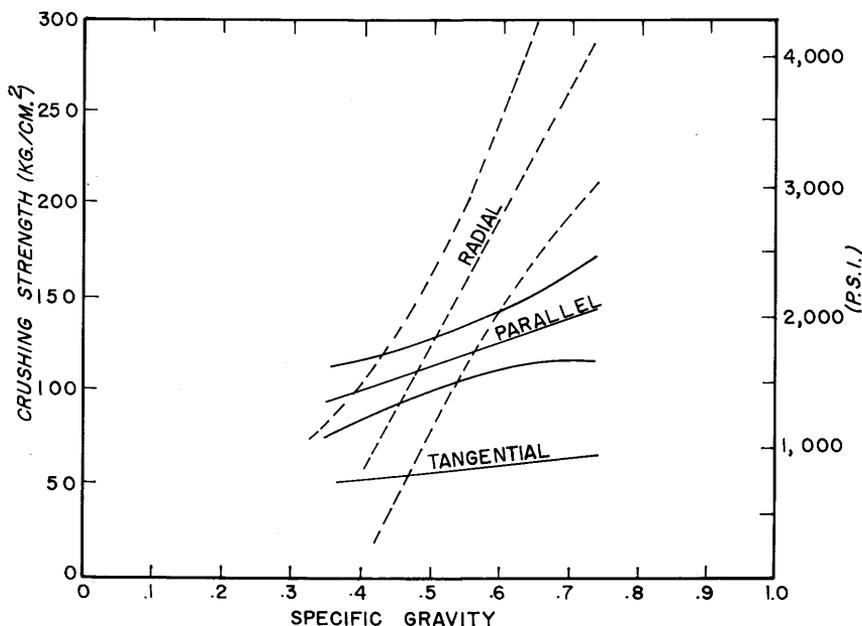


Figure 12-22.—Crushing strength of dry pine bark loaded longitudinally (parallel to the grain) and in the radial and tangential directions; 95-percent confidence limits are indicated for parallel and radial directions. Of the seven pine species tested to obtain these data, five were southern pines. (Drawing after Martin and Crist 1968.)

Loading direction	a	b	r ²
Longitudinal	52.4	126.1	0.28
Radial	-223.9	703.8	.80
Tangential	39.2	36.4	.10

The high correlation between radial crushing strength and specific gravity is likely explained by bark anatomy. Bark with phloem cells having relatively little expansion and relatively thick cell walls tends to be dense; also, dense bark may contain a fairly high proportion of stone cells and thickened phelloderm. Periderms with sharply curved edges, and with stone cells in these curves, should be relatively resistant to radial compression. In longitudinal and tangential compression, southern pine bark should tend to separate along the periderms (Howard 1971).

Hardness.—Because of small sample size, Martin and Crist (1968) used an 0.222-inch ball (instead of the standard 0.444 inch) to measure hardness. They found that the force to impress the ball to half its depth (H, kg.) was positively correlated with specific gravity (G) based on oven-dry volume and weight; the following equation accounted for 60 percent of the observed variation:

$$H = -26.6 + 144.5G \quad (12-15)$$

For comparability with standard tests, the data were converted to results expected with an 0.444-inch ball (fig. 12-23).

Shear strength.—Under shear stress, southern pine bark tends to separate along the periderms. Martin and Crist (1968) found that shear strength

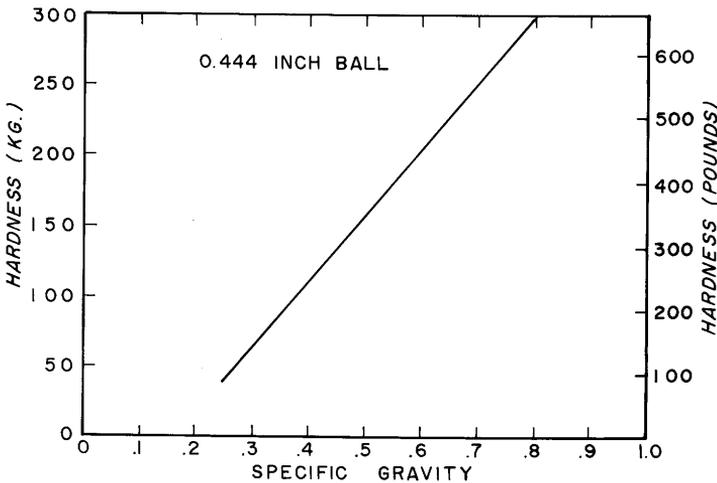


Figure 12-23.—Hardness of dry bark related to specific gravity. Data from seven pine species (including five southern pines) and 12 hardwood species were pooled to compute this relationship. (Drawing after Martin and Crist 1968.)

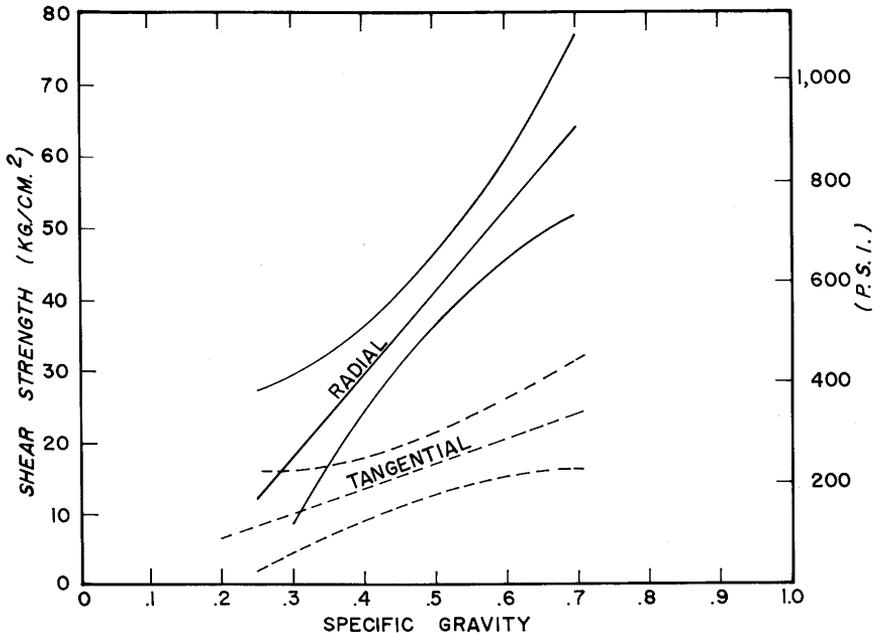


Figure 12-24.—Shear strength of dry pine bark in the tangential and radial planes as related to specific gravity; 95-percent confidence limits are indicated. Of the seven pine species tested to obtain these data, five were southern pines. (Drawing after Martin and Crist 1968.)

had a positive linear correlation with specific gravity (G , basis of oven-dry volume and weight) and that shear strength in the radial plane was greater and more closely correlated with specific gravity ($r^2 = 0.75$) than that in the tangential plane ($r^2 = 0.41$) as shown by figure 12-24 and the following equations:

$$\text{Shear strength in radial plane} = -14.9 + 113.5G \quad (12-16)$$

$$\text{Shear strength in tangential plane} = -0.329 + 34.6G \quad (12-17)$$

In the foregoing equations, shear strength is given in kg./cm.^2 .

Modulus of rupture.—In bending, bark is weakened by shear failures along the periderms; beams of bark therefore tend to separate into layers when stressed. Modulus of rupture is positively correlated with specific gravity (G) based on oven-dry weight and volume as follows:

$$\text{Modulus of rupture, kg./cm.}^2 = 59.6 + 143.5G \quad (12-18)$$

The relationship (fig. 12-25) accounted for 16-percent of the variation observed by Martin and Crist (1968).

Tensile strength.—The southern pines have no fibers in their bark; therefore, any tendency for them to have greater strength in the longitudinal direction than in the radial or tangential directions must come from sieve

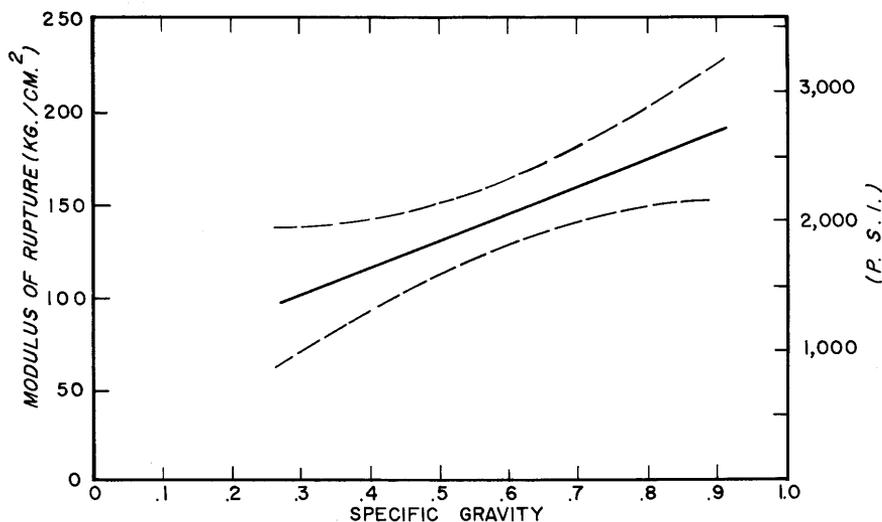


Figure 12-25.—Modulus of rupture of dry bark in static bending as related to specific gravity. Dashed lines indicate 95-percent confidence limits. Data from seven pine species (including five southern pines) and 12 hardwood species were pooled to compute this relationship. (Drawing after Martin and Crist 1968.)

and parenchyma cells. These cells are thin walled, however, and contribute little to the strength of bark stressed in tension. Howard (1971) observed that southern pine barks showing little obliteration, i.e., little collapse of the sieve cells and little expansion of the parenchyma cells, were hard and fibrous and had little tendency to powder; obliteration-resistant barks should therefore have greater tensile strength than obliterated barks.

Martin and Crist (1968) found that specific gravity (G) based on oven-dry volume and weight accounted for 44 percent of the variation ob-

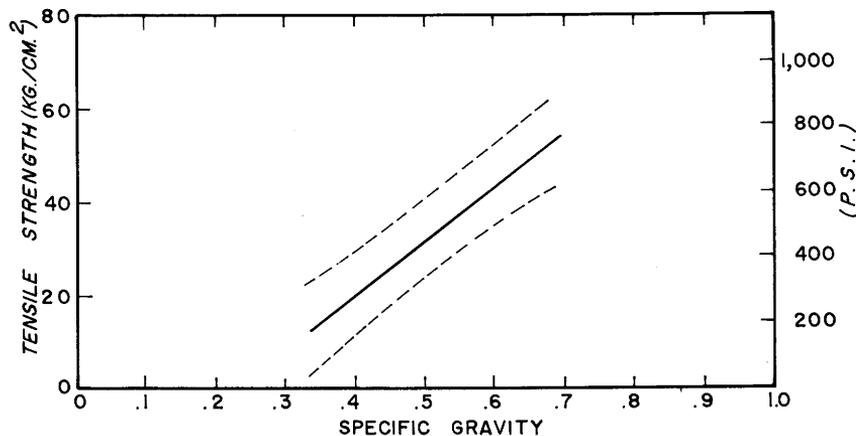


Figure 12-26.—Tension strength at failure of dry pine bark tested parallel to the grain. Dashed lines indicate 95-percent confidence limits. Of the seven pine species tested to obtain these data, five were southern pines. (Drawing after Martin and Crist 1968.)

served in the tensile strength parallel to the grain of dry pine bark, as follows (fig. 12-26):

$$\text{Tensile strength, kg./cm.}^2 = -24.8 + 113.0G \quad (12-19)$$

Toughness.—Martin and Crist (1968) observed that pine barks were less tough than the hardwood barks they tested; toughness was not correlated with bark specific gravity. Toughness of dry bark from three of the southern pines was as follows; the values were not significantly different:

Pine species	Number of replications	Toughness Kg. cm./cc.
Shortleaf	3	0.350
Longleaf	6	.261
Virginia	2	.657

SHRINKAGE AND EQUILIBRIUM MOISTURE CONTENT

Martin (1968) has given limited information on volumetric expansion, and Martin and Crist (1968) have published data on dimensional expansion of bark when moistened from oven-dry condition to fiber saturation, as follows:

Pine species	Volumetric <i>Percent of wet volume</i>	Longitudinal	Radial	Tangential
Shortleaf.....	10.9-15.7	2.8-6.2	6.8-10.1	4.4-10.3
Longleaf.....	—	3.0-3.4	6.3- 8.7	3.6- 4.4

Longitudinal shrinkage of bark, while generally less than transverse shrinkage, is substantially greater than that observed in normal wood of the same species. Howard (1971) suggests that the rather inflexible bands of stone cells aligned tangentially in periderms somewhat inhibit shrinkage of southern pine bark in the longitudinal and tangential directions, but not in the radial direction.

In the absence of more complete information, Martin (1968) assumes that bark does not change volume at moisture contents above fiber saturation point, and that shrinkage between fiber saturation point and the oven-dry condition is linear. On this basis, he advanced the following formulas for computing the volume (V_M) of a piece of bark at any moisture content, given the wet volume (V_W), or the oven-dry volume (V_o):

$$V_M = (0.8647 + 0.00534M)V_W \quad (12-20)$$

$$V_M = (1 + 0.00618M)V_o \quad (12-21)$$

where M is the moisture content as a percentage of oven-dry weight. He proposes 25.3 percent as the fiber saturation point for bark. These formulas are not specific to southern pine, but are based on pooled data from numerous species.

Martin (1967) also published data on the equilibrium moisture content of bark from loblolly, longleaf, shortleaf, and slash pine bark during adsorp-

tion and desorption at 25° C. and various relative humidities; average equilibrium moisture contents for the four species were as follows:

<u>Relative humidity</u>	<u>Adsorption</u>	<u>Desorption</u>
----- Percent -----		
19.0	4.6	7.0
43.0	8.1	10.9
75.5	14.2	18.1
86.0	17.1	20.8
93.0	22.1	24.9

SPECIFIC HEAT

In a study of 72 spruce pine trees from the major commercial range of the species, Koch (1969) determined the specific heat of oven-dry bark in the temperature range 60 to 140° C.

$$\begin{aligned} \text{Specific heat of tree bark} &= 0.3322 && (12-22) \\ &- .0002582 \text{ (temperature in } ^\circ\text{C.)} \\ &+ .000005137 \text{ (temperature squared)} \end{aligned}$$

Equation 12-22 accounted for 95 percent of the variation with standard error of the estimate of 0.006171° C. (fig. 12-27). The data showed that bark from fast-grown trees had a higher specific heat than that from slow-grown trees; variation between age classes of trees was also significant (table 12-4, fig. 12-27).

TABLE 12-4.—*Specific heat of oven-dry spruce pine bark representative of entire trees* (Koch 1969)

Stratification of trees	Specific heat at		
	60° C.	100° C.	140° C.
15-year-old trees			
Slow-grown.....	0.3307	0.3541	0.3948
Fast-grown.....	.3361	.3602	.3957
30-year-old trees			
Slow-grown.....	.3369	.3566	.3963
Fast-grown.....	.3359	.3586	.3958
45-year-old trees			
Slow-grown.....	.3352	.3556	.3958
Fast-grown.....	.3366	.3615	.4022

In Koch's (1969) study, three disks were taken from each tree (near ground level, at a 4-inch top, and halfway between) to permit study of within-tree variation and variation with geographic location. To show all relationships, disk bark data were studied by stepwise regression. Factors evaluated were temperature, temperature squared, age of disk, specific gravity of disk bark, height in tree, and latitude and longitude. All of

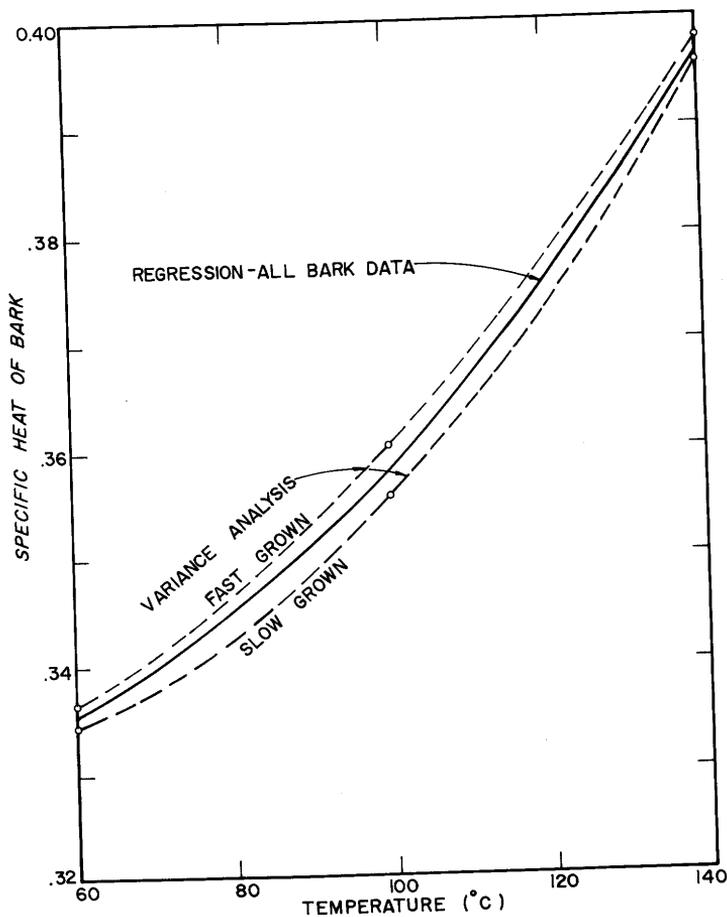


Figure 12-27.—Specific heat of oven-dry spruce pine bark (entire tree average) related to temperature; regression curve based on 1,080 observations. The dashed lines connect category averages and illustrate the temperature \times growth interaction. (Drawing after Koch 1969.)

these except diameter, longitude, and bark specific gravity proved significant. The equation accounted for 90 percent of the variation with standard error of the estimate of 0.008455° C. The equation for oven-dry bark follows:

$$\begin{aligned}
 \text{Specific heat of disk bark} &= 0.4292 && (12-23) \\
 &- .0004518 \text{ (temperature, } ^{\circ}\text{C.)} \\
 &+ .0000779 \text{ (height, feet)} \\
 &- .0001022 \text{ (age of disk, years)} \\
 &- .0026718 \text{ (latitude, degrees)} \\
 &+ .000005957 \text{ (temperature squared)} \\
 &+ .0062364 \text{ (growth rate, inches of} \\
 &\quad \text{diameter per year)}
 \end{aligned}$$

A few values for specific heat of southern pine bark are available for comparison with Koch's (1969) data for spruce pine:

Reference	Pine species	Specific heat at 60° C.
Reifsnyder et al. (1967)	Longleaf	0.303
Reifsnyder et al. (1967)	Shortleaf	.322
Martin (1963b)	Loblolly	.329 (at 56° C.)
Koch (1969)	Spruce	.335 (for bark representative of entire trees)

Although the wood of spruce pine trees evidently has lower specific heat than wood of some other species (see fig. 9-15), these data suggest that spruce pine bark may be comparatively high in specific heat. The major difference between the specific heat of spruce pine bark and wood was found to be in the temperature relationship. The bark curve was a function of temperature and temperature squared and was concave upward, while the curve for wood was a straight line.

Otherwise, the mean values for wood and bark representative of entire spruce pine trees were quite similar (Koch 1969):

Temperature	Specific heat	
	Wood	Bark
°C.		
60	0.325	0.335
100	.366	.358
140	.405	.397

For spruce pine disk bark in the range from 60 to 140° C., relationships developed by Koch (1969) indicated that bark of maximum specific heat was from the tops of fast-grown trees in the southern part of the major range. With all other factors fixed, specific heat of bark was negatively correlated with number of annual rings at the point of sampling. It is probable that the observed variability in specific heat with position, location, and growth rate reflects a positive correlation between specific heat and the ratio of inner bark to rhytidome.

Specific heat of wet bark.—For bark at 22° C. and in the range from 0- to 27-percent moisture content, Koljo (1950) observed a simple additive relation (estimated from his graph):

$$c_{pu}(1+u) = u + 0.320 \quad (12-24)$$

where:

c_{pu} = specific heat of moist bark

u = moisture content expressed as a fraction of dry weight

then:

$$c_{pu} = \frac{u + 0.320}{1 + u}$$

In other words, at 22° C. the specific heat of oven-dry bark was 0.320 and the specific heat of moist bark was 0.382 at 10-percent moisture and 0.433 at 20-percent moisture.

In 19 tests on six species (some of which were southern pine), Martin (1963b) measured the elevation of specific heat of bark at fiber saturation point. For saturated bark ($u = 0.27$), he obtained an elevation of specific heat of 0.083 calorie per gram dry bark per degree C. (observed in bark at 56° C.).

With some simplifying assumptions, Martin concludes that the specific heat of moist bark (expressed in terms of the bark-water mixture) is:

$$c_{pu} = \frac{u + c_p}{u + 1} + \frac{\Delta c}{u + 1} \quad (12-25)$$

where:

c_{pu} = specific heat of bark-water mixture

c_p = specific heat of oven-dry bark at the temperature in question

u = moisture content expressed as a fraction of the weight of dry bark

Δc = elevation of specific heat at the temperature in question. In

calories per gram dry bark per degree C., $\Delta c = \left(\frac{u}{0.27}\right)(0.083)$;

at moisture contents of 27 percent and higher, $\Delta c = 0.083$.

If it is assumed that:

$$u = 0.25$$

$$c_p = 0.329 \text{ for oven-dry bark at } 56^\circ \text{ C.}$$

$$\Delta c = (0.083) \left(\frac{0.25}{0.27}\right) \text{ calorie per gram of oven-dry bark per degree C. at}$$

25-percent moisture content.

Then, from Martin's formula, the specific heat of moist bark equals:

$$\begin{aligned} c_p &= \frac{0.25 + 0.329}{0.25 + 1} + \frac{(0.083) \left(\frac{0.25}{0.27}\right)}{0.25 + 1} \\ &= 0.4632 + 0.0615 \\ &= 0.525 \end{aligned}$$

At 56° C. then, 0.525 calorie is required to raise 1 g. of moist bark (25-percent moisture content) 1° C. This is 13.4 percent greater than the relative portions of bark and water would suggest (0.463). Martin's conclusions on the elevation of specific heat caused by addition of water to bark were based on data from several species; it is likely, however, that the concept is applicable also to southern pine bark.

HEAT TRANSMISSIVITY

Thermal conductivity and diffusivity, together with the units in which they are measured, are defined in section 9-4.

Thermal conductivity.—In tests of 10 species including three southern pines, Martin (1963b) found that desiccated bark has a thermal conductivity about 20 percent less than wood of the same density. In southern pine bark conductivity is greatest in the longitudinal direction and least in the radial direction, as follows (Martin 1970):

Pine species	Ratio of tangential/radial conductivity	Ratio of longitudinal/tangential conductivity
Loblolly.....	1.156	1.102
Longleaf.....	—	1.072
Shortleaf.....	1.139	1.085

The ratio greater than unity for tangential/radial conductivity contrasts with that for wood, where radial conductivity is the greater of the two. In wood, the rays are intact and possibly serve as radial conductors, whereas those in bark are discontinuous because of obliteration.

Transverse (combination of radial and tangential) thermal conductivity values for a number of barks—including three southern pine species—have been expressed by Martin (1963b) in terms of a regression equation requiring the measurement of specific gravity and moisture content, as follows:

$$k = \left[5.026S + (13.241)(S) \left(\frac{\text{percent moisture content}}{100} \right) - 0.202 \right] 10^{-4} \quad (12-26)$$

where

k = thermal conductivity, cal. per cm., sec., °C.

S = specific gravity based on oven-dry weight and volume at test.

To convert k to B.t.u. inch per sq. ft., hr., °F., divide by 0.0003445.

Martin (1970) has also provided a method of computing the conductivity for each of the three directions, given k as stated above; because the directional differences in southern pine are so small, the formulae are not reproduced here.

Using equation 12-26, Martin (1963b) computed the thermal conductivity of shortleaf and loblolly pine barks to be about $(1.80)(10^{-4})$ cal. per cm., sec., °C. This is equivalent to 0.52 B.t.u. inch per sq. ft., hr., °F., and is somewhat less than the value for wood (fig. 9-18). The low conductivity of bark is probably attributable to the expanded parenchyma in phloem plus multiple zones of both expanded phelloderm and thin-walled cork cells.

The thermal conductivity of solid southern pine bark is about 50 percent higher than that of commonly used insulating materials (Martin 1963b).

Thermal diffusivity.—Martin (1963b) computed values for thermal dif-

fusivity of barks in the specific gravity range from 0.20 to 0.80, at moisture contents from 0 to 100 percent of oven-dry weight, and at temperatures from 0 to 100° C. His values ranged from $(10.6)(10^{-4})$ to $(18.3)(10^{-4})$ cm.²/sec.

As an average value of thermal diffusivity for bark, he concluded that $(13)(10^{-4})$ cm.²/sec. was best. This is equivalent to 0.00020 in.²/sec. and is slightly lower than the values shown for wood in figure 9-20.

HEAT OF COMBUSTION

Southern pine bark has a heat of combustion of about 8,900 B.t.u. per oven-dry pound—a value somewhat higher than that of southern pine wood (about 8,600 B.t.u. per oven-dry pound). As shown in table 9-8 and figure 9-21, southern pine bark sampled near ground level has a higher heat of combustion than bark taken from upper stem portions.

12-6 USES IN AGRICULTURE AND LANDSCAPING

Southern pine bark, as well as sawdust and planer shavings, is useful as ground cover, mulch, and soil amendment for growing plants, and as bedding for animals, especially poultry. As ground cover or mulch, bark suppresses weeds, conserves moisture, insulates the soil, and improves appearances. When decayed, it provides humus which replenishes soil organic matter, improving tilth and moisture-holding capacity, and slowly releasing nutrients for plant use. For animal bedding, its advantages are absorbency and resistance to compaction.

In productive soils, organic colloids act as cement to bind fine mineral particles together into larger aggregates, improving soil porosity. Soil micro-organisms break down raw organic materials and—as they die and decompose—release nutrients, including fixed nitrogen, in forms available to plants. Because these and other soil processes continually deplete soil organic materials, organic amendments are applied where crop or other residues are inadequate.

The composition of organic materials greatly affects their usefulness to plants. Although not the primary source of minerals, the amount and character of minerals they contain can be important. Potassium and phosphorus are major plant nutrients, and are generally desirable; excesses of salts may be detrimental. Lignin is a major constituent of humus. Carbohydrates provide food for micro-organisms; since their metabolism requires nitrogen, excessive amounts of carbohydrate may deplete nitrogen available to plants unless accompanied by a nitrogenous fertilizer.

Since soil acidity affects plants and the efficiency of fertilizers, the pH of organic additives is often important. Most crop and ornamental plants, as well as trees, prefer neutral or slightly acid soils; a few require acid or highly acid soil. Only for such special applications are highly acid additives preferred over materials whose pH approaches neutral.

BARK AND SAWDUST pH

The pH of southern pine wood is about 4.7 to 5.0 (McCool 1948; Stamm 1961). Treatment of wood prior to evaluation, and method of evaluation affect values observed, as indicated by the following data (unpublished) from C. Y. Hse of the Southern Forest Experiment Station, USDA Forest Service, for freshly cut loblolly and longleaf pine wood.

	Slope intercept method of Stamm (1961)	NaCl solution method of McNamara et al. (1970)
	----- pH -----	
Ovendried at 212 to 240° F.....	4.7	4.4
Freeze dried.....	5.6	4.9
Extracted and then freeze dried.....	5.8	4.9

Martin and Gray (1971) evaluated barks from all the southern pine species except Table-Mountain pine, and found them to be somewhat more acidic than wood; the observed range in pH was from about 3.1 to 3.8 with average of 3.4 to 3.5.

NITROGEN DEPLETION

Finely divided southern pine wood added to soil rapidly decomposes; because of its higher lignin content, bark decomposes less rapidly than wood in soil. Since the micro-organisms that cause the decomposition require nitrogen, this necessary nutrient is temporarily robbed from the plant. The problem can be met in several ways—by prior use of the wood or bark as mulch or as animal bedding, by addition of nitrogen through ammoniation or addition of fertilizer, or by prior composting. Another approach is treatment of the wood or bark to render it resistant to decay before its application as a soil amendment.

PEATMOSS IN RELATION TO PINE BARK AND SAWDUST

According to Guthrie (1969), total annual sales of peat (usually sold as "peatmoss") in the United States increased from 600,000 tons in 1958 to 900,000 tons in 1966; virtually all of this tonnage was used in horticultural or agricultural applications. If southern pine bark is to penetrate the market for soil amendments, it must successfully compete against peat in both price and function.

Composition of southern pine bark and sawdust is compared below with that of peat; data on peat are approximated from Feustel and Byars (1930), Anderson et al. (1951), and Basham and Thompson (1967).

Content	Sawdust	Bark	Peat
	----- Percent -----		
Mineral content.....	<0.5	0.6	4.3
Organic content			
Carbohydrate.....	66-69	30.0	70.0
Lignin.....	27-30	50.0	18.0
Other (including waxes and tannins).....	<1.0	19.0	8.0
Mineral plus organic content.....	100.0	100.0	100.0
Water soluble.....	2-8	<15.0	5.0
Nitrogen.....	0.1-0.3	0.4	0.8

Of the three, bark has the highest lignin content and the lowest carbohydrate content. The total carbohydrate content of peat (70 percent) is probably comprised of about 4/7 cellulose and hemicellulose and 3/7 other carbohydrates soluble in sulfuric acid or 2 percent hydrochloric acid (Feustel and Byars 1930; Anderson et al. 1951). Peat is more acid than wood, with a pH of about 3.8.

Bulk densities of peatmoss and shredded pine bark are almost identical (Joiner and Conover 1969); both are light in weight, and neither changes much in bulk density on exposure. Bulk density is important since it affects weight of potted products and this, in turn, affects handling and transportation costs. Both amendments produce about the same percentage drainable pore space when mixed in equal volumes with sand—a factor important to soil aeration and drainage.

Bark and peat are also very similar in cation exchange capacity (CEC), i.e., the ability to retain nutrients against leaching.

Organic amendments used in container growing—where water loss is rapid—should hold four to five times their weight in water. Both bark and peatmoss meet this requirement.

The carbon/nitrogen (C/N) ratio should be relatively low, or additional nitrogen must be added to offset that temporarily lost to protoplasm of micro-organisms using the organic matter as a carbon source. These micro-organisms have a C/N ratio of about 10/1. Optimum decomposition in soil usually results when the ratio of carbon to nitrogen is about 20/1 (Bollen and Glennie 1963). A shortage of nitrogen can limit the rate of decomposition of organic matter. Peat-sand combinations, which may have a C/N ratio of 50 or 60 to 1, decompose slowly; additional nitrogen is not usually necessary. The C/N ratios of bark-sand combinations are higher, and additional nitrogen is generally required; the added nitrogen becomes available to plants following decomposition of the bark. Soils mixed with sawdust require greater additions of nitrogen than those mixed with bark.

The relationships governing nitrogen requirement and rate of decomposition are complex; generally the nitrogen requirement increases with increased rate of decomposition. Decomposition rate is dependent on the

organic material (lignin decomposes more slowly than cellulose, for example), soil pH, soil aeration, and soil moisture and temperature. Readers desiring additional information will find Russell (1961, pp. 240-250) and Alexander (1967, chapter 9) useful.

Joiner and Conover (1969) conclude that physically bark compares closely with peatmoss. The major disadvantage of bark is its high C/N ratio and more rapid rate of decomposition. On the plus side, southern pine bark never has a high level of soluble salts—a problem with some peatmoss.

POTTING AND ROOTING MEDIUMS AND SOIL AMENDMENTS

Generally, soil amendments should have high water-holding capacity and CEC, low soluble salt level and C/N ratio, slow decomposition rate, and uniform particle size (Joiner and Conover 1969).

Potting medium.—Joiner and Conover (1967) grew *Pittosporum* (*Pittosporum tobira*) in cans to compare southern pine bark and peatmoss for mixture with sand in growing mediums. Tested were peat-sand, shredded bark-sand, and extracted shredded bark-sand in 1:1 by volume mixtures; also tested were shredded bark-sand in 1:2 and bark-sand in 2:1 mixtures.

In the experiment, rooted cuttings were planted in March—one per 6-inch can. Growth index, measured as (height in centimeters + width in centimeters)/2, was taken in July and October of the year planted and April of the following year. Nitrogen was applied before planting and N, P, and K after planting. Plants were watered as needed.

Their results were as follows:

Medium	CEC	Maximum water content by volume	Growth index after 1 year
	<i>Milliequivalents per pot</i>	<i>Percent</i>	
Peat-sand, 1:1	222	40.8	53.5
Bark-sand, 1:1	227	35.1	51.1
Treated bark-sand, 1:1	230	37.3	50.9
Bark-sand, 1:2	166	34.4	50.6
Bark-sand, 2:1	162	37.8	50.1

They concluded that shredded southern pine bark was as satisfactory as peat for the organic component in container-growing of *Pittosporum*. Pre-plant N, to compensate for initial microbial activity in decomposition where 50 percent or less of bark or peat was used, proved valuable only within the first 4 months of the experiment and thereafter had no effect. Where a higher amount of bark was used, addition of preplant N produced valuable effects throughout the experiment. With the mediums used, 750 pounds per acre per year of N was adequate for excellent plant growth and quality.

Pokorny (1966) evaluated milled southern pine bark aged 2 years from

removal as an organic substitute for peatmoss by planting 1-year-old woody plants of five species in 1-gallon cans. The pH of the mixtures in all cans was adjusted and maintained at 5.5 with limestone, and all received the same water and fertilizer treatments. After 1 year (November to November), a growth index—(increase in height, centimeters + increase in spread, centimeters)/2—was used to compare relative growth (table 12-5). Mediums using pine bark were slightly less acid, and weighed only slightly more than peatmoss mixtures.

Medium	pH	Weight per 183 cu. in. at field capacity of moisture
Peat mixtures		
Peat-sand, 1:1-----	4.47	6.7
Peat-perlite, 1:1-----	4.58	3.7
Peat-clay-sand, 1:1:1-----	4.97	7.2
Bark mixtures		
Bark-sand, 1:1-----	5.15	6.8
Bark-perlite, 1:1-----	5.23	3.8
Bark-clay-sand, 1:1:1-----	5.63	7.9

Pokorny (1966) concluded that milled southern pine bark could probably replace peat for container-grown nursery stock.

TABLE 12-5.—Growth index of five woody ornamental plant species grown in various mediums¹ (Pokorny 1966)

Medium tested	<i>Pyra- cantha</i>	<i>Gardenia radicans</i>	<i>Ilex crenata rotundifolia</i>	<i>Ilex cornuta burfordi</i>	<i>Azalea obtusum Hinodogiri</i>	Mean ²
Peat mixtures						
Peat-sand, 1:1-----	14.8	4.7	7.8	8.2	6.2	8.3
Peat-perlite, 1:1-----	17.2	5.6	8.9	7.0	6.4	9.0
Peat-clay-sand, 1:1:1-----	15.4	6.4	7.6	5.9	3.7	7.8
Bark mixtures						
Bark-sand, 1:1-----	14.5	6.9	7.8	5.8	6.5	8.3
Bark-perlite, 1:1-----	13.2	6.9	7.6	8.9	5.7	8.5
Bark-clay-sand, 1:1:1-----	16.6	8.3	6.6	7.7	6.1	9.0

¹ Data based on 10 replications per treatment.

² Mean index score: Peat used as organic amendment—8.38. Milled pine bark used as organic amendment—8.59.

In similar tests (Pokorny and Guigino 1967), clonal plantlets of African violet (*Saintpaulia ionantha* Wendl.) and rooted cuttings of a red-leafed coleus (*Coleus blumei* Benth.) were potted in 3½-inch clay flowerpots with a variety of mixtures of peatmoss, sand, perlite, clay, and milled pine bark. Also evaluated was milled pine bark not mixed with other material. All mixtures were adjusted to a pH of 6.5, then fertilized and watered equally.

Pokorny and Guigino concluded that milled southern pine bark may be substituted for peatmoss as an organic amendment in potting mixes for African violets and coleus pot plants. In artificial mixes, milled pine bark was best combined with fine sand; when soil was included in the mix, no particular combination of ingredients was best for the two plants tested. Generally, both African violets and coleus grew satisfactorily in 100 percent milled southern pine bark.

Rooting medium.—An ideal rooting medium should be free of harmful infections and insects or be sterilizable to eliminate these hazards, be free of toxic materials that inhibit rooting, hold and apply water needed for rooting, be sufficiently porous to permit aeration and runoff of excessive water, and be light in weight.

Pokorny and Perkins (1967) have demonstrated that southern pine bark is a good rooting medium for most ornamental woody plants. In their experiment, loblolly and shortleaf pine bark with some wood attached was processed through a hammermill to an average particle size of about 1 mm. square. The milled bark—alone and in half-and-half mixtures with sand or perlite—was compared to half-and-half mixtures of peat with sand or perlite, and with sand alone.

For 13 of the 20 plant species tested, rooting response did not differ significantly among the six different mediums. Cuttings of six species rooted significantly better in mediums containing milled pine bark or peat than in 100 percent sand. Only with gray lavender cotton (*Santolina chamaecyparissus*) was root initiation and development best in 100 percent sand.

The weights, and unmodified pH of the six mediums should be of interest to the horticulturist. Data of Pokorny and Perkins (1967), listed in order by pH, follow:

Medium	Air-dry density	Density at field capacity of moisture	pH
	— Pounds per cubic foot —		
Peat-sand, 1:1.....	47.0	60.8	4.47
Peat-perlite, 1:1.....	9.7	24.9	4.58
100-percent bark.....	19.1	27.6	4.90
Bark-sand, 1:1.....	47.3	60.8	5.15
Bark-perlite, 1:1.....	13.6	22.9	5.23
100-percent sand.....	64.5	76.7	6.62

Bark has found considerable acceptance as a medium on which to grow

orchids (Davidson 1961; Lunt et al. 1961; Sheehan 1961); the published data do not, however, include descriptions of southern pine bark used for this purpose.

Soil amendments.—Particles of wood or bark are incorporated (mixed) in soils to provide a source of soil humus; such amendments are of especial value in the improvement of the physical properties of heavy clay soils. They also improve moisture-holding capacity of sands. Yields of certain crops on some soils can be substantially increased by amendments of southern pine wood or bark if the nitrogen level and pH of the amended soil is controlled in a manner appropriate for the crop. Wood and bark differ in their rate of decomposition in soil, and therefore in the amount and timing of nitrogen supplement required for optimum plant growth.

To evaluate toxicity, Allison (1965) germinated and grew garden peas in mixtures of soil with 1 to 8 percent (by oven-dry weight) of southern pine sawdust and bark. Nitrogen was added as urea, and soil pH adjusted to approximately 6.5 by addition of calcium carbonate. Neither bark nor wood of any of the four southern pine species evaluated had any toxic effect on the plants.

Allison (1965) also studied the decomposition of southern pine sawdust and bark in soils; the wood and bark had carbon/nitrogen ratios in the range from 346/1 to 1,313/1, as follows:

Pine species and source	Carbon	Nitrogen	C/N ratio
	----- Percent -----		
Loblolly (South Carolina)			
Wood.....	48.7	0.068	716
Bark.....	50.9	.082	621
Longleaf (Louisiana)			
Wood.....	49.9	.038	1,313
Bark.....	50.2	.092	546
Shortleaf (Maryland)			
Wood.....	45.0	.130	346
Bark.....	51.3	.128	401
Slash (Florida)			
Wood.....	49.2	.050	984
Bark.....	52.1	.056	930

It is likely that these differences in C/N ratios are not attributable to species, but are a result of great variability within species.

The wood or bark particles were ground to pass through a six-mesh sieve, and 1 percent by weight was added to a sandy loam surface soil with 0.057 percent N, 0.84 percent C, and an initial pH of 5.4. As the C/N ratio of the soil was about 15/1, and the amount of wood or bark added was small, C/N conditions for decomposition were near optimum in the mixtures.

Decomposition of the wood and bark in the soil mixtures was determined by measuring the release of carbon dioxide in 60 days, and expressed as a percentage of total carbon. In mixtures with no nitrogen

added, 19 percent of the bark carbon was released as CO₂ (data for all species pooled). Addition of supplemental nitrogen to the mixtures did not greatly alter decomposition rates, probably because C/N ratios in the unfertilized mixtures were already favorable. After 60 days, pH averaged about 5.8—not substantially different from the original value of 5.4.

After 365 days the slash pine wood had 22 to 28 percent of its carbon oxidized, whereas only 9 to 12 percent of the bark carbon was oxidized. Longleaf pine wood after 580 days had 37 to 45 percent of its carbon oxidized; in the same period longleaf bark carbon was only 17 to 21 percent oxidized.

It is evident that direct addition of the required amounts of nitrogen to southern pine bark or wood would be expensive on a per acre basis. Assuming that total carbon decomposition requires 6 years, that required nitrogen to give a C/N ratio of about 20/1 amounts to 50 pounds per oven-dry ton of bark or sawdust, that nitrogen cost is \$0.10 per pound, and that a 2-inch-thick layer of sawdust or bark (weighing 12 pounds per cubic foot, oven-dry) is worked into the top 6 inches of soil—then the total nitrogen cost would be \$215 per acre, or about \$36 per acre per year for 6 years. If the C/N ratio in the unmixed soil is favorable to decomposition, lower applications of nitrogen may be appropriate.

Bark and other organic materials can be converted to soil amendments which do not deplete nitrogen by providing favorable and partially controlled conditions for decay in **compost** piles.

Field (1958) and Ivory and Field (1959) described a procedure for annually composting about 12,500 tons of bark from western conifers, primarily true firs. Addition of bacteria or other organic waste proved unnecessary; composting time averages about 6 months (range 3 to 12 months). To initiate the process, small amounts of nitrogenous material in water solution (e.g., ammonium sulfate, ammonium nitrate, or urea) are applied to the bark immediately after it is removed from the log and pulverized. The bark is then placed in windrows 5 feet high, 20 feet wide, and 150 feet long. Temperature within the pile is a good index of bacterial activity, with 139° F. considered optimum. Maximum interior temperature recorded was 178° F.; at temperatures less than 130° F., bacterial activity diminishes. After 2 to 3 months—when pile temperature diminishes—nitrogen is again added, causing temperature to again rise. Moisture content in the pile is maintained at 30 to 80 percent of the oven-dry weight. The composting reaction is aerobic and is accelerated by frequent turning of material in each pile. Carbon/nitrogen ratio in the completed compost is about 40:1.

Harkin and Rowe (1969), in their review of uses for bark, note that pure strains of micro-organisms are occasionally used for preparing compost, e.g., *Coprinus ephemerus* (Wilde 1958, 1960), but generally no special inoculum is used (Farber and Hind 1959; Ivory and Field 1959; Bolterslev 1968; Yerkes and Markstrom 1968).

Composting can be accelerated by adding nitrogen and other mineral nutrients as chemical fertilizers or as nitrogenous materials such as whey (Midgely 1963), brewery waste, sterilized sewage sludge, fish waste, or manure. If sewage sludge is added to the compost, it must be sterilized first, since some pathogenic bacteria harmful to plants or animals present in the raw sludge may withstand windrow composting conditions (Reeves 1965). Moreover, although the nitrogen content of sewage is quite high, most of it is bound up in a form unavailable to plants (Harkin and Rowe 1969). The sludge also tends to have an obnoxious odor when wet. Composting with added nutrients has four important advantages. The nitrogen depletion problem is solved; the product can often be marketed as a combined soil conditioner and fertilizer; any possible toxicity is removed in the composting process; and the composting process is greatly accelerated (Harkin and Rowe 1969).

Readers wishing further information on composting will find numerous articles in the journal, *Compost Science*.

Bark and sawdust contain many chemical groups that will combine with ammonia. Processes for **ammoniation** of woody residues have been described by Davey (1953), Wilde (1958), Davey and Wilde (1960), and Bollen and Glennie (1961a). Simple equipment to accomplish treatment of sawdust with anhydrous ammonia is described by Krause (1962).

In the process described by Davey (1953), fresh sawdust is treated with anhydrous ammonia at the rate of 15 pounds of nitrogen per cubic yard. Five pounds of 50 percent potassium sulfate is added per cubic yard, and the sawdust is allowed to stand for 10 days. Neutralization then is accomplished by the addition of 2 pounds of 85 percent phosphoric acid per cubic yard (acid is diluted with 8 gallons of water to facilitate uniform distribution). After another 10 days, the material is inoculated with the wood-destroying fungi, *Coprinus ephemerus*. The compost mixture is then allowed to ferment for about 3 months with occasional reworking and watering. The final product has microaggregate structure and strongly resembles a rich, mulch-like soil in appearance.

Burton (1959) proposed that bark be first used as a **trickling filter** for secondary treatment of sewage effluent, and then as a soil conditioner. One objection to this process might be that harmful bacteria could be passed on from the sewage with the bark (Reeves 1965).

Carrier for fertilizer.—When bark is steamed and plant nutrients such as nitrates, phosphates, ammonia, and urea added, some reactions occur that enable the material to be used as fertilizer (Sproull and Cone 1959; Sproull et al. 1965; Sproull and Pierce 1963). Products made from mixed southern pine barks by this process have been field-tested on potatoes, corn, tomatoes, squash, cantaloupes, beans, peppers, cabbages, onions, azaleas, camellias, roses, chrysanthemums, pansies, grass turf, and ilex. The yields of fruit, foliage, and flowers have been reported excellent by Sproull and Pierce (1963) and Sproull (1969).

A relatively stable soil conditioner that is resistant to decay can be made by treating sawdust with dilute sulfuric acid at temperatures near the charring point; this conditioner can then be used as a carrier for nitrogen and other fertilizers (Farber and Hind 1959).

MULCH

Mulch is material applied to the surface of a soil to prevent erosion, soil compaction or crusting, evaporation of soil moisture, emergence of weeds, and extreme fluctuations in soil temperature. A good mulch is attractive in appearance, helps the soil absorb moisture, and prevents mud and surface organisms from splashing onto plants during a rain or periods of overhead irrigation.

In dry cool air, an organic material placed on the surface of soil should decompose more slowly than if mixed with the soil; Allison (1965) observed, however, that in an air at 100-percent relative humidity shortleaf pine sawdust on top of the ground decomposed at about the same rate as that mixed in the soil. He also observed that shortleaf pine wood that barely passed through a six-mesh sieve decomposed about as rapidly as wood of finer grind. Because of its higher lignin content, southern pine bark decomposes more slowly than southern pine wood when used as a mulch.

Because wood and bark use nitrogen as they decompose, some nitrogen should be added to such mulches to prevent them from robbing plants of available soil nitrogen. Dewerth (1969) stated that organic sources of nitrogen for this purpose are much safer to use than inorganic sources which may cause buildup of undesirable soluble salts; when required, he suggested addition of $\frac{1}{2}$ -pound of actual nitrogen per 10 cu. ft. of material.

Southern pine residues of several types are used as mulch. **Sawdust** is an excellent mulch for nursery sales yards if available aged; fresh material needs supplemental nitrogen. Bollen and Glennie (1961b) found that sawdust from resaws, because of its small particle size, tended to pack tightly and retard aeration and moisture penetration. **Shavings** last longer and do not mat as badly as sawdust, but will blow away easily during strong winds; as with fresh sawdust, supplemental nitrogen is required. **Chips** of wood make a good, long-lasting, coarse mulch less apt to be wind blown than sawdust or shavings. Southern pine **bark** has an attractive brown color, does not mat or blow away easily, and is long lasting. To be most acceptable to users, bark mulch should be free of light-colored pieces of wood and cambium so that it is uniform in color, and free of both chunks and dusty fines. Particles measuring $\frac{1}{4}$ - to $\frac{5}{8}$ -inch appear to be acceptable. Mulches should not be slimy or moldy.

Information on growth of plants mulched with southern pine wood and bark is meager; data from work with other species is available, however. Roberts and Mellenthin (1959) found that sawdust and bark were superior to other mulches for **blueberries**; sawdust and bark mulches 4 to 6 inches

thick—with or without nitrogen supplement—were particularly beneficial for blueberries and **strawberries**. For crops requiring more nitrogen, they recommended first-year application of 100 pounds of nitrogen per acre inch of sawdust (i.e., nitrogen in the amount of 0.3 percent of sawdust weight); for the following 2 or 3 years, about half this amount was suggested for application annually.

Pratt and Comstock (1958) showed that sawdust mulches 1 inch deep more than doubled yields of various vegetables and were better than black polyethelene film.

In one of the few publications describing work with southern pine, White et al. (1959) showed good growth response in **tomatoes** and **beans**; to obtain increased yields in mulched **corn**, however, nitrogen application was required. When the sawdust was incorporated in the soil, they found no growth benefits for any of the plants. Sproull (1969) found that tomato plants mulched with southern pine bark yielded 20 to 57 percent more than unmulched plants, and the quality of the tomatoes was improved.

Other references that describe the use of sawdust and bark mulches for a variety of fruits, vegetables, and flowers include:

Savage and Darrow (1942)	Allison and Anderson (1951)
Collison (1944)	McIntyre (1951)
Latimer and Percival (1944)	Bollen (1953)
Baker (1947)	Dunn (1956)
Latimer (1947)	Bollen and Lu (1957)
Turk and Partridge (1947)	Bollen and Glennie (1961b, 1963)
Roberts and Stephenson (1949)	Allison (1965)
Shutak et al. (1949)	

GROUND COVER FOR LANDSCAPING EFFECTS

Decorative ground cover made from fairly large bark chunks, while not widely manufactured from southern pine bark prior to 1970, may become a factor in the market as use for this purpose increases (Wall Street Journal 1970). Southern pine bark in large sizes has an attractive color, is rustic in appearance, deteriorates slowly, and is not blown by winds.

Chunk sizes marketed are ¼- to ¾-inch, ¾-inch to 1½ inches, 1½ to 3 inches, and over 3 inches. The smaller sizes are used for walkway and yard cover, while the larger sizes are used to achieve decorative landscape effects. Based on experience with bark of western conifers, only logs with bark thickness of an inch or more will yield particles of sufficient size for decorative ground cover.

POULTRY LITTER

For many years, dry planer shavings have been the primary source of litter in sheds where broiler chickens are reared. Weldon (1969) observed that a good poultry litter must be absorptive and must release absorbed moisture readily to the atmosphere; it must not be excessively dusty, or it

will cause respiratory disorders in the young birds; it must be light in weight and resist compaction; finally, a good litter must be readily available at low cost. His data indicate that air-dried, pulverized bark resists compaction and caking better than shavings, and he observed that screened bark was less dusty than planer shavings. Bulk densities of the two materials are similar, and bark is ordinarily available at lower cost than planer shavings. In Weldon's evaluation of moisture content of litter in poultry houses, he observed that bark had a higher initial moisture content (31 to 125 percent) than shavings (13 percent), but that after 9 weeks in use bark moisture content (37 to 40 percent) was only slightly greater than that of shavings (31 percent).

Thornberry⁷ and his associates evaluated many thousands of chickens reared on southern pine bark processed to a particle size of 1 inch or less in diameter; their data compared average body weight, incidence of breast blisters, mortality, percentage of rejected birds (condemnations), and feed conversion efficiency of birds reared on planer shavings versus birds reared on southern pine bark. He concluded that, if reduced to particles less than 1 inch in diameter, southern pine bark was equal to—and perhaps superior to—planer shavings as a poultry litter.

12-7 INDUSTRIAL UTILIZATION

At the time this text was written, southern pine bark was largely unutilized by industry except as boiler fuel. It is likely, however, that new uses—in addition to those related to agriculture—will be developed. Some of the possibilities for industrial use of bark are outlined in the following paragraphs.

FUEL

Section 12-5 contains a discussion of heat of combustion of bark, and chapter 26 is devoted to the burning of southern pine bark and wood.

CHARCOAL

The manufacture of charcoal from particulate residues, including bark, is described in Section 28-4.

OIL INDUSTRY USES

While only a limited quantity, if any, southern pine bark is at present utilized by the oil industry, it is possible that some uses can be developed. For example, bark tannins from western hemlock (*Tsuga heterophylla*

⁷ Thornberry, F. Research shows processed pine bark is good litter. Paper presented at the Annual Meeting of the Mid-South Section of the Forest Products Research Society, Lufkin, Tex., October 6-7, 1969.

(Raf.) Sarg.) find a large market as clay deflocculants that control the viscosity and gel strength of drilling muds (Hergert et al. 1965). Also, bark fibers can be added to drilling muds to reduce circulation losses. Miller and Van Beckum's (1960) review of the uses and sources of bark products for oil well drilling should be helpful to those considering this market for pine bark.

Weldon (1970) has demonstrated that southern pine bark can be used to scavenge oil spills from the surface of salt water. Best results were obtained by depositing loose bark particles, measuring 1 to 2 mm. in size, directly on the oil slick; the bark took up the oil in a matter of seconds but absorbed little water. When the oily bark was skimmed from the surface, the water was left free of oil.

CHEMICAL UTILIZATION

The chemical constituents of bark are briefly described in section 12-4. While the literature contains many publications on bark chemistry, information specific to southern pines is meager. Development of major chemical uses for southern pine bark will likely be delayed until a better understanding of its chemical components is achieved.

FIBER PRODUCTS AND PARTICLEBOARD

Southern pine bark contains few long cells useful for developing strength in fiber products (fig. 12-3). When pulverized, a substantial fraction of the total volume is very fine material. It is likely that these fines could be utilized as an extender for resins used in the manufacture of molded products (Lehmann 1968).

Paper.—Martin and Brown (1952), in sulfate pulping tests of shortleaf pine chips without bark, bark alone, and wood-bark mixtures containing up to 21 percent bark by weight, found that considerable percentages of bark could be used. Sulfate pulps made completely from shortleaf pine bark were, however, unsuitable for paper products. In the production of kraft-type bleaching sulfate and sulfate semichemical pulps, the inclusion of bark increased the yield of pulp per cord, but increased consumption of chemicals during cooking and decreased brightness of the pulp.

Keller (1950) compared neutral sulfite semichemical pulps made from bark-free slash pine chips with pulps made from chips containing up to 25-percent bark. Pulp yields were about 76 to 80 percent for the wood, but only 35 percent for the mixture of bark and wood. During impregnation, the bark-wood mixtures absorbed up to twice as much sodium sulfite from the cooking liquor as the wood alone. Strength of standard test sheets made from the bark-wood mixture was less than that of sheets made from slash pine wood alone.

Fiberboards.—Although it is probably possible to incorporate some percentage of southern pine bark in insulation board, the literature contains

no description of board properties resulting. In hardboards, inclusion of southern pine bark should improve resistance to water but would likely reduce strength. Again, no data specific to southern pine bark are published.

Information on fiberboards incorporating bark of species other than southern pine is available, however (Anderson and Runckel 1950, 1956, 1957abc, 1958; Anderson and Helge 1959; Semana and Anderson 1968).

Particleboard.—From a preliminary study by Jaworsky et al.⁸, it appears possible to use the fibrous fraction of southern pine bark as an extender for pine shavings in the manufacture of particleboard. The bark is difficult to process, and recovery of usable fibers may be as low as one-third of the oven-dry weight. Test results on boards with 25-, 50-, 75-, and 100-percent southern pine bark content indicated that commercially acceptable boards might be made with bark extensions no greater than about 25 percent; above this degree of extension, nearly all physical and mechanical properties of the particleboard dropped below acceptable levels.

Southern pine bark has also been tested as an extender for medium-density boards made from southern red oak (*Quercus falcata* Michx.) and mockernut hickory (*Carya tomentosa* Nutt.) fibers disk-refined from chips. The level of most board properties was inversely correlated with the bark content; about 25-percent bark content was the maximum that could be tolerated in boards designed to meet the commercial standard for medium-density particleboard.⁸

⁸ Jaworsky, J. M., Bryant, B. S., and Tracy, J. M. Plan to develop an analysis of the problem of combining disk-refined, low-grade southern hardwoods and southern pine bark into a board competitive with southern pine particleboard. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report, FS-SO-3201-2.29, dated November 30, 1971.

12-8 LITERATURE CITED

- Alexander, M.
1967. Introduction to soil microbiology. 472 pp. N.Y.: John Wiley and Sons, Inc.
- Allison, F. E.
1965. Decomposition of wood and bark sawdusts in soil, nitrogen requirements and effects on plants. USDA Agr. Res. Serv. Tech. Bull. 1332, 58 pp.
- Allison, F. E., and Anderson, M. S.
1951. The use of sawdust for mulches and soil improvement. USDA Circ. 891, 19 pp.
- Anderson, A. B.
1956. The utilization of bark in the wallboard industry. Norsk Skogindustri 10: 475-479.
- Anderson, A. B.
1957a. The influence of some Scandinavian barks on hardboard properties. Norsk Skogindustri 11: 175-179.
- Anderson, A. B.
1957b. The chemistry of hardboards containing bark. Norsk Skogindustri 11: 386-389.

- Anderson, A. B.
1958. The influence of bark in wood as raw material for insulation and hardboard. *In* Fibreboard and particle board, Vol. II, Pap. 4.2, 16 pp. Food and Agr. Organ. UN.
- Anderson, A. B., and Helge, K.
1957. The utilization of unbarked residues in hardboard. *Norsk Skogindustri* 11: 327-330.
- Anderson, A. B., and Helge, K.
1959. Utilization in Norway—bark in hardboard. *Forest Prod. J.* 9(4): 31A-35A.
- Anderson, A. B., and Runckel, W. J.
1950. Utilization of Douglas-fir bark in hardboard. *Proc., Nat. Ann. Meet. Forest Prod. Res. Soc., Vol. 4*, pp. 301-309.
- Anderson, M. S., Blake, S. F., and Mehring, A. L.
1951. Peat and muck in agriculture. *USDA Circ.* 888, 31 pp.
- Ashe, W. W.
1915. Loblolly or North Carolina Pine. *N.C. Geol. and Econ. Surv. Bull.* 24, 176 pp.
- Baker, C. E.
1947. Sawdust as an orchard mulch. *Hoosier Hort.* 29: 67-69.
- Basham, B. M., and Thompson, W. S.
1967. An economic study of the production and use of sawdust and bark as mulches and soil amendments for horticultural and agricultural purposes. *Miss. Forest Prod. Util. Lab. Inform. Ser.* 6, 26 pp. State College.
- Bollen, W. B.
1953. Mulches and soil conditioners. *J. Agr. Food Chem.* 1: 379-381.
- Bollen, W. B., and Glennie, D. W.
1961a. Processing wood wastes to increase crop yields. *Compost Sci.* 2(3): 38-43.
- Bollen, W. B., and Glennie, D. W.
1961b. Sawdust, bark and other wood wastes for soil conditioning and mulching. *Forest Prod. J.* 11: 38-46.
- Bollen, W. B., and Glennie, D. W.
1963. Fortified bark for mulching and soil conditioning. *Forest Prod. J.* 13: 209-215.
- Bollen, W. B., and Lu, K. C.
1957. Effect of Douglas-fir sawdust mulches and incorporations on soil microbial activities and plant growth. *Soil Sci. Soc. Amer. Proc.* 21: 35-41.
- Bollerslev, K.
1968. Bark processing problems. *Forest Prod. J.* 18(6): 19-20.
- Brauns, F. E., and Lewis, H. F.
1944. The nature of the lignin in redwood bark. *Pap. Trade J.* 119(22): 34-38.
- Browning, B. L., editor.
1963. The chemistry of wood. 689 pp. N.Y.: Interscience Pub.
- Browning, B. L., and Sell, L. O.
1957. The analysis of some fractions of slash pine bark. *TAPPI* 40: 362-365.
- Burton, R. E.
1959. Making fertilizer-soil conditioner from bark as a trickling-filter media. *Forest Prod. J.* 9(4): 19A-22A.
- Burton, J. D.
1962. Bark thickness in Tennessee loblolly plantations. *USDA Forest Serv. S. Forest Exp. Sta. S. Forest. Note* 142.
- Chamberlain, E. B., and Meyer, H. A.
1950. Bark volume in cordwood. *TAPPI* 33: 554-555.
- Chang, Y-P.
1954a. Anatomy of common North American pulpwood barks. *TAPPI Monogr. Ser.* 14, 249 pp.
- Chang, Y-P.
1954b. Bark structure of North American conifers. *USDA Tech. Bull.* 1095, 86 pp.
- Chang, Y-P., and Mitchell, R. L.
1955. Chemical composition of common North American pulpwood barks. *TAPPI* 38: 315-320.
- Clark, E. W., and Mills, C. L.
1970. Qualitative seasonal changes in the free amino acids and carbohydrates of loblolly pine inner bark. *Wood Sci.* 3: 90-93.

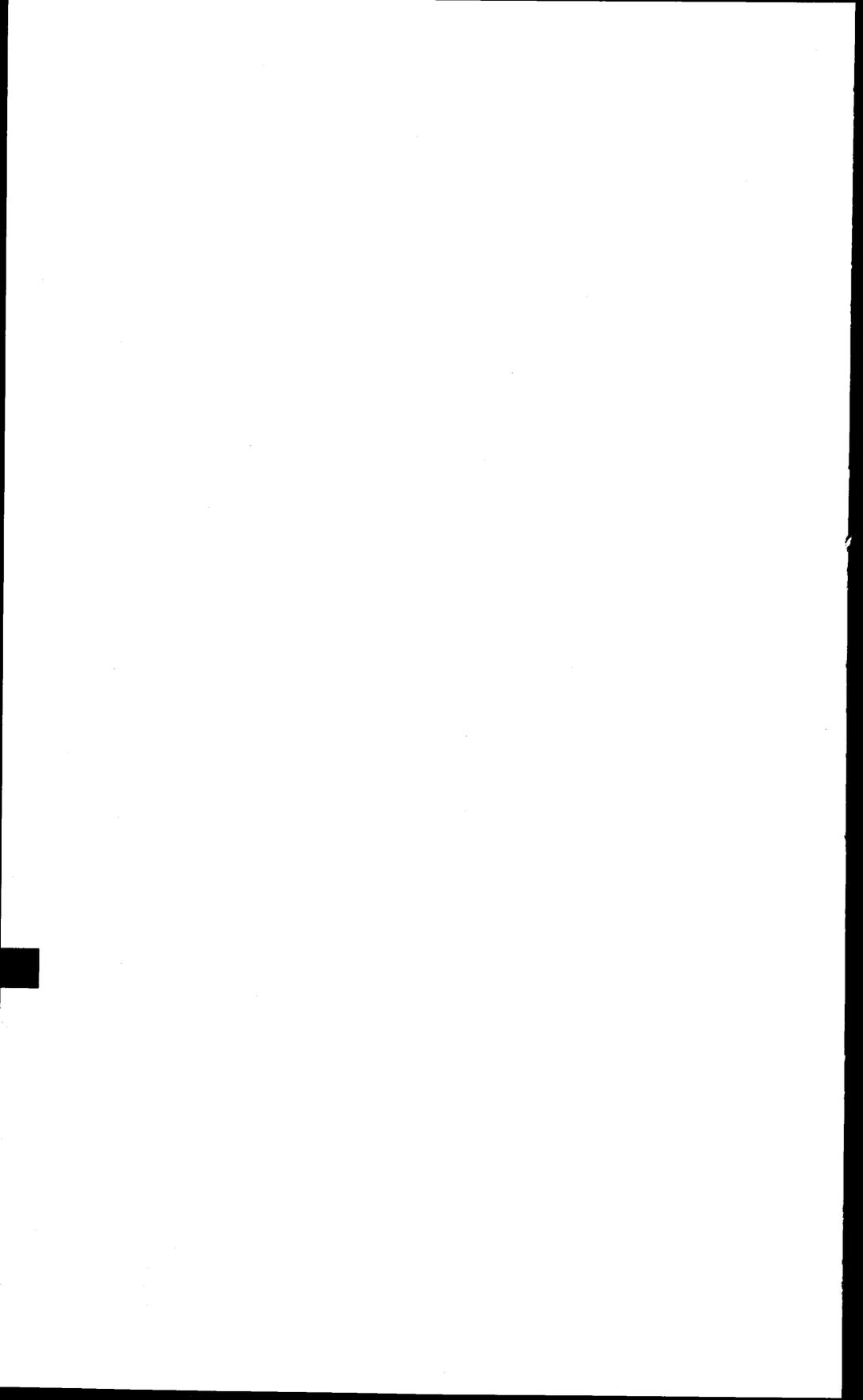
- Collison, R. C.
1944. Sawdust makes an excellent mulch. Usually available, it is easy to handle, is relatively cheap, and has no harmful effect on the soil. N.Y. State Agr. Exp. Sta. Farm Res. 10(3): 10.
- Davey, C. B.
1953. Sawdust composts: their preparation and effect on plant growth. Soil Sci. Soc. Amer. Proc. 17: 59-60.
- Davey, C. B., and Wilde, S. A.
1960. Sawdust composts and method of preparing same. (U.S. Pat. No. 2,946,675.) U.S. Pat. Office, Wash., D.C.
- Davidson, O. W.
1961. Principles of orchid nutrition. Amer. Orchid Soc. Bull. 30(4): 277-285.
- DeVall, W. B.
1945. A bark character for the identification of certain Florida pines. Proc. Fla. Acad. Sci. 7(2-3): 101-103.
- Dewerth, A. F.
1969. Suitable mulches for salesyard and landscape use. In Wood residue utilization, pp. 47-56. Third Tex. Ind. Seminar. Tex. Forest Prod. Lab., Lufkin.
- Doughty, J. B., Taylor, F. W., and Henerney, W. T.
1956. Alkali and thio lignins from pine bark. Forest Prod. J. 6: 476-478.
- Dunn, S.
1956. The influence of waste bark on plant growth. N.H. Agr. Exp. Sta. Bull. 435, 19 pp. Durham.
- Erman, W. F., and Lyness, W. I.
1965. The isolation, purification, and structure determination of a phenolic acid fraction from slash pine bark. TAPPI 48: 249-256.
- Esau, K.
1965. Plant anatomy. Ed. 2, 767 p. N.Y.: John Wiley and Sons, Inc.
- Farber, E., and Hind, R. R.
1959. Process for converting sawdust into fertilizer. Forest Prod. J. 9: 340-344.
- Feustel, I. C., and Byers, H. G.
1930. The physical and chemical characteristics of certain American peat profiles. USDA Tech. Bull. 214, 27 pp.
- Field, P.
1958. Residues from the sawmill —making smoke or profit? Forest Prod. J. 8(11): 27A-30A.
- Great Britain Forestry Commission.
1932. Studies on tree roots. Great Brit. Forest. Comm. Bull. 13, 90 p.
- Guthrie, N.
1969. Marketing of new products from wood residue. In Wood utilization, pp. 10-14. Proc., Ann. Meet. Mid-South Sect. Forest Prod. Res. Soc. Lufkin, Tex.
- Hall, J. A., and Gisvold, O.
1935. Chemistry of slash-pine (*Pinus caribaea*, Morelet). I. Fatty constituents of the phloem. J. Biol. Chem. 109: 585-595.
- Hall, J. A., and Gisvold, O.
1936. Chemistry of slash-pine (*Pinus caribaea*, Morelet). II. Fats, waxes, and resins of the growing tips. J. Biol. Chem. 113: 487-496.
- Harkin, J. M., and Rowe, J. W.
1969. Bark and its possible uses. USDA Forest Serv. Res. Note FPL-091, 42 pp. Forest Prod. Lab., Madison, Wis.
- Hergert, H. L.
1960. Chemical composition of tannins and polyphenols from conifer wood and bark. Forest Prod. J. 10: 610-617.
- Hergert, H. L., Van Blaricom, L. E., Steinberg, J. C., and Gray, K. R.
1965. Isolation and properties of dispersants from western hemlock bark. Forest Prod. J. 15: 485-491.
- Hodges, J. D., and Lorio, P. L.
1969. Carbohydrate and nitrogen fractions of the inner bark of loblolly pines under moisture stress. Can. J. Bot. 47: 1651-1657.
- Howard, E. T.
1971. Bark structure of the southern pines. Wood Sci. 3: 134-148.
- Howard, E. T., and Manwiller, F. G.
1969. Anatomical characteristics of southern pine stemwood. Wood Sci. 2: 77-86.

- Howes, F. N.
1953. Vegetable tanning material. 325 pp. London: Butterworth and Co.
- Huber, B.
1958. Anatomical and physiological investigations on food translocation in trees. *In* The physiology of forest trees, pp. 367-379. (K. V. Thimann, ed.) N.Y.: Ronald Press.
- Ivory, E. P., and Field, P.
1959. Utilizing bark at a medium-sized mill—processing and merchandising bark products. *Forest Prod. J.* 9(4): 28A-30A.
- Joiner, J. N., and Conover, C. A.
1967. Comparative properties of shredded pine bark and peat as soil amendments for container-grown *Pitosporum* at different nutrient levels. *Amer. Soc. Hort. Sci.* 90: 447-453.
- Joiner, J. A., and Conover, C. A.
1969. Southern pine bark market in horticulture analyzed. *Forest Ind.* 96(5): 37.
- Judson, G. M.
1964. Inexpensive and accurate form-class estimates. USDA Forest Serv. Res. Pap. SO-11, 6 pp. South. Forest Exp. Sta., New Orleans, La.
- Keller, E. L.
1950. Effect of bark in the neutral sulphite semichemical pulping of aspen, hickory, and slash pine. *TAPPI* 33: 556-560.
- Kennedy, R. W., Sastry, C. B. R., and Barton, G. M.
1968. Crystals in the wood of the genus *Abies* indigenous to Canada and the United States. *Can. J. Bot.* 46: 1221-1228.
- Koch, P.
1969. Specific heat of oven-dry spruce pine wood and bark. *Wood Sci.* 1: 203-214.
- Koljo, B.
1950. [Notes on thermal phenomena in timber and trees.] *Forstwiss. Centralbl.* 69: 538-551.
- Krause, H. H.
1962. Assembly for the preparation of sawdust and peat composts. *J. Forest.* 60: 563-565.
- Kurth, E. F.
1944. The extraneous components of wood. *In* Wood chemistry, pp. 385-445. L. E. Wise, ed. N.Y.: Reinhold Publ. Corp.
- Latimer, L. P.
1947. Comparative value of sawdust, hay, and seaweed as mulch for apple trees. *Proc. Amer. Soc. Hort. Sci.* 50: 23-30.
- Latimer, L. P., and Percival, G. P.
1944. Sawdust, seaweed and meadow hay as mulch for McIntosh apple trees. *Proc. Amer. Soc. Hort. Sci.* 44: 49-52.
- Lehmann, W. F.
1968. Molding compounds from Douglas-fir bark. *Forest Prod. J.* 18(12): 47-53.
- Lewis, H. F., Brauns, F. E., Buchanan, M. A., and Kurth, E. F.
1944. Chemical composition of redwood bark. *Ind. and Eng. Chem.* 36: 759-764.
- Lunt, O. R., Clark, B., and Kofranek, A. M.
1961. Exploratory nutritional studies on cymbidiums using two textures of fir bark. *Amer. Orchid Soc. Bull.* 30: 297-302.
- McCool, M. M.
1948. Studies on pH values of sawdusts and soil-sawdust mixtures. *Boyce Thompson Inst. Contrib.* 15: 279-282.
- McCormack, J. F.
1955. An allowance for bark increment in computing tree diameter growth for southeastern species. *USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap.* 60, 6 pp.
- McIntyre, A. C.
1951. Wood chips and farming. *In* Chipped wood production and uses, pp. 7-13. Northeast. Wood Util. Council. Bull. 33.
- MacKinney, A. L.
1934. Some factors affecting the bark thickness of second-growth longleaf pine. *J. Forest* 32: 470-474.
- McNamara, W. S., Sullivan, C. E., and Higgins, J. C.
1970. pH measurements on northeastern woods. *Wood Sci.* 3: 48-51.
- Martin, J. S., and Brown, K. J.
1952. Effect of bark on yield and quality of sulphate pulp from southern pine. *TAPPI* 35: 7-10.

- Martin, R. E.
1963a. Thermal and other properties of bark and their relation to fire injury of tree stems. Ph.D. Thesis, Univ. Mich., Ann Arbor. 267 p.
- Martin, R. E.
1963b. Thermal properties of bark. *Forest Prod. J.* 13: 419-426.
- Martin, R. E.
1967. Interim equilibrium moisture content values of bark. *Forest Prod. J.* 17(4): 30-31.
- Martin, R. E.
1968. Interim volumetric expansion values for bark. *Forest Prod. J.* 18(4): 52.
- Martin, R. E.
1969. Characterization of southern pine barks. *Forest Prod. J.* 19(8): 23-30.
- Martin, R. E.
1970. Directional thermal conductivity ratios of bark. *Holzforschung* 24: 26-30.
- Martin, R. E., and Crist, J. B.
1968. Selected physical-mechanical properties of eastern tree barks. *Forest Prod. J.* 18(11): 54-60.
- Martin, R. E., and Crist, J. B.
1970. Elements of bark structure and terminology. *Wood & Fiber* 2: 269-279.
- Martin, R. E., and Gray, G. R.
1971. pH of southern pine barks. *Forest Prod. J.* 21(3): 49-52.
- Mesavage, C.
1969a. Converting dendrometer estimates of outside-bark stem diameters to wood diameters on major southern pines. USDA Forest Serv. Res. Note SO-93, 4 pp. S. Forest Exp. Sta., New Orleans, La.
- Mesavage, C.
1969b. Measuring bark thickness. *J. Forest.* 67: 753-754.
- Metz, L. J., and Wells, C. G.
1965. Weight and nutrient content of the aboveground parts of some loblolly pines. USDA Forest Serv. Res. Pap. SE-17, 20 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Midgley, A. R.
1963. Whey and wood bark make fertile compost. *Compost Sci* 4(1): 29-31.
- Miller, R. W., and Van Beckum, W. G.
1960. Bark and fiber products for oil well drilling. *Forest Prod. J.* 10: 193-195.
- Miller, S. R.
1961. Variation in bark thickness of slash pine by site, tree size, and distance-up-stem. Union Bag-Camp Pap. Corp. Woodland Res. Note 10, 3 p. Savannah, Ga.
- Minor, C. O.
1953. Loblolly pine bark thickness. La. State Univ. LSU Forest. Note 1, 2 pp.
- Outer, R. W. den.
1967. Histological investigations of the secondary phloem of gymnosperms. 119 p. Wageningen, The Netherlands: H. Veenman & Zonen N. V.
- Pokorny, F. A.
1966. Pine bark as an organic amendment in production of container plants. *Ga. Agr. Res.* 7(4): 8-9.
- Pokorny, F. A., and Gugino, F. A.
1967. Comparison of potting media for herbaceous pot plants. *Ga. Agr. Res.* 9(2): 3-4.
- Pokorny, F. A., and Perkins, H. F.
1967. Utilization of milled pine bark for propagating woody ornamental plants. *Forest Prod. J.* 17(8): 43-48.
- Pratt, A. J., and Comstock, S.
1958. Mulches or cultivation for vegetable crops? *Farm Res.* 24(1): 4-5.
- Reeves, J. B.
1965. Studies of sewage sludge and sawdust compost. *Compost Sci.* 6(2): 12.
- Reifsnnyder, W. E., Herrington, L. P., and Spalt, K. W.
1967. Thermophysical properties of bark of shortleaf, longleaf, and red pine. *Yale Univ. Sch. Forest. Bull.* 70, 41 pp.
- Renfro, J. F.
1956. Bark and cambium characteristics of pond pine (*Pinus serotina* Michx.) and loblolly pine (*Pinus taeda* L.) with special reference to fire hardiness. M. F. Thesis. N.C. State Coll., Raleigh. 46 p.

- Roberts, A. N., and Mellenthin, W. M.
1959. Effects of sawdust mulches. II. Horticultural crops. Oreg. Agr. Exp. Sta. Tech. Bull. 50, 34 pp.
- Roberts, A. N., and Stephenson, R. E.
1949. Sawdust and other wood wastes as mulches for horticultural crops. Ore. State Hort. Soc. Proc. (1948) 63: 29-34.
- Roth, L., Saeger, G., Lynch, F. J., and Weiner, J.
1960. Structure, extractives, and utilization of bark. Bibliogr. Ser. 191, 446 pp. Inst. of Pap. Chem., Appleton, Wis.
- Roth, L., and Weiner, J.
1968. Structure, extractives, and utilization of bark. Supplement I. Bibliogr. Ser. 191, 184 pp. Inst. Pap. Chem., Appleton, Wis.
- Row, C., Fasick, C., and Guttenberg, S.
1965. Improving sawmill profits through operations research. USDA Forest Serv. Res. Pap. SO-20, 26 pp. South. Forest Exp. Sta., New Orleans, La.
- Rowe, J. W.
1965. The sterols of pine bark. *Phytochemistry* 4: 1-10.
- Russell, E. W.
1961. Soil conditions and plant growth. 688 pp. London: Longmans, Green and Co. Ltd.
- Savage, E. F., and Darrow, G. M.
1942. Growth response of blueberries under clean cultivation and various kinds of mulch materials. Proc. Amer. Soc. Hort. Sci. 40: 338-340.
- Semana, J. A., and Anderson, A. B.
1968. Hardboard from Benquet pine bark-wood compositions. *Forest Prod. J.* 18(7): 28-32.
- Sheehan, T. J.
1960. Effects of nutrition and potting media on growth and flowering of certain epiphytic orchids. World Orchid Conf. Proc. 3: 211-218.
- Shutak, V., Christopher, E. P. and McElroy, L.
1949. The effect of soil management on the yield of cultivated blueberries. Proc. Amer. Soc. Hort. Sci. 53: 253-258.
- Sitte, P.
1957. Der Feinbau der Kork-Zellwände, pp. 421-432. In *Die Chem. der Pflanzenzellwand* (E. Treiber, ed.), 511 pp. Berlin: Springer-Verlag.
- Snow, E. A.
1949. Pine bark as a source of tannin. J. Amer. Leather Chem. Assoc. 44: 504-511.
- Sproull, R. C.
1969. Fiber, chemical, and agricultural products from southern pine bark. *Forest Prod. J.* 19(10): 38-44.
- Sproull, R. C., and Cone, D. C., Jr.
1959. Process for producing nitrogenated and phosphorylated fertilizer, mulch and soil conditioner. (U.S. Pat. No. 2,881,066.) U.S. Pat. Office, Wash., D.C.
- Sproull, R. C., and Pierce, G. A.
1963. Bark utilization. I. Soil amendment. TAPPI 46(8): 175A-178A.
- Sproull, R. C., Pierce, G. A., and Tokarz, R. M.
1965. Method making fertilizer, mulch, and soil conditioner. (U.S. Pat. No. 3,218,149.) U.S. Pat. Office, Wash., D.C.
- Srivastava, L. M.
1963. Secondary phloem in the pinaceae. 142 pp. Berkeley: Unic. Calif. Press.
- Srivastava, L. M.
1964. Anatomy, chemistry and physiology of bark. In *International review of forestry research*. Vol. 1, pp. 203-277. J. A. Romberger and P. Mikola, eds. N.Y.: Academic Press.
- Stamm, A. J.
1961. A comparison of three methods for determining the pH of wood and paper. *Forest Prod. J.* 11: 310-312.
- Stanley, R. G.
1969. Extractives of wood, bark and needles of the southern pines—a review. *Forest Prod. J.* 19(11): 50-56.
- Turk, L. M., and Partridge, N. L.
1947. Effect of various mulching materials on orchard soils. *Soil Sci.* 64: 111-125.

- Wahlenberg, W. G.
1936. Effect of annual burning on thickness of bark in second growth longleaf pine stands at McNeill, Mississippi. *J. Forest.* 34: 79-81.
- Wahlenberg, W. G.
1946. Longleaf pine. 429 pp. Wash., D.C.: Charles Lathrop Pack Forest Found. in coop. with USDA Forest Serv.
- Wall Street Journal.
1970. Masonite marketing lawn-care products made from tree bark. *Wall St. J.*, May 14, p. 13.
- Weldon, D.
1970. Scavenging oil with southern pine bark. *Tex. Forest Serv. Forest Prod. Lab. Publ.* 106, 3 pp. Lufkin.
- Weldon, D.
1969. Pine bark as poultry litter. *In Wood utilization*, pp. 42-46. *Proc., Annu. Meet. Mid-South Sect. Forest Prod. Res. Soc.*
- White, A. W., Giddens, J. E., and Morris, H. D.
1959. The effect of sawdust on crop growth and physical and biological properties of Cecil soil. *Soil Sci. Soc. Amer. Proc.* 23: 365-368.
- Wilde, S. A.
1958. Marketable sawdust composts: Their preparation and fertilizing value. *Forest Prod. J.* 8: 323-326.
- Wilde, S. A.
1960. Marketable sawdust composts. *Compost Sci.* 1(2): 38-42.
- Williams, D. L., and Hopkins, W. C.
1969. Converting factors for southern pine products. *La. Agr. Exp. Sta. Bull.* 626 rev., 89 p.
- Wise, L. E., and Jahn, E. C., editors.
1952. *Wood chemistry*. Vol. 1, ed. 2, 688 pp. N.Y.: Reinhold Publishing Corporation.
- Yerkes, V. P., and Markstrom, D. C.
1968. Composting ponderosa pine bark—effects of nitrogen additions and aeration. *USDA Forest Serv. Res. Note RM-126*, 4 pp. Rocky Mt. Forest & Range Exp. Sta., Fort Collins, Colo.



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Roots

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Roots

13-1 PHYSIOLOGY

The physiology and growth of pine roots have been studied in considerable detail by specialists in forest regeneration and culture; since their findings have little direct bearing on possible use for roots, they are not abstracted in this text. The interested reader will find useful reviews in Mirov (1967, pp. 363-370), Fayle (1968), Köstler et al. (1968), and Sutton (1969).

As an additional aid to researchers, some citations specific to the physiology and growth of southern pine roots are tabulated as follows:

<u>Subject and reference</u>	<u>Pine species</u>
Mycorrhizae	
Pessin (1928)	Longleaf
Kozlowski (1949)	Loblolly
Addoms (1950)	Loblolly
Kramer and Hodgson (1954)	Loblolly
Wenger (1955)	Loblolly
Marx (1967)	Loblolly, shortleaf
Natural root grafts	
Miller and Woods (1965)	Loblolly
Schultz and Woods (1967)	Loblolly
Suberization	
Barney (1947)	Loblolly
Kramer and Bullock (1966)	Loblolly
Periodicity of root growth	
Turner (1936)	Loblolly, shortleaf
Reed (1939)	Loblolly, shortleaf
Efficiency and carbohydrate content	
Gilmore (1962)	Loblolly
Allen (1967)	Loblolly, shortleaf, slash
Temperature and root growth	
Kramer (1942)	Loblolly
Kozlowski (1943)	Loblolly
Barney (1947, 1951)	Loblolly
Greene (1953)	Loblolly
Soil moisture and root growth	
Kramer (1946)	Shortleaf
Kozlowski (1964)	Loblolly, shortleaf
Kramer and Bullock (1966)	Loblolly

<u>Subject and reference</u>	<u>Pine species</u>
Growth regulators	
Maki and Marshall (1945)	Loblolly
Marth et al. (1956)	Loblolly, Virginia
Gilmore (1965)	Loblolly
Light and root growth	
Wakeley (1935, 1954)	Southern pines
Huberman (1940ab)	Longleaf, shortleaf, slash
Barney (1947, 1951)	Loblolly
Racial variation in root form	
Snyder (1961)	Longleaf
Root pruning prior to transplant	
Huberman (1940ab)	Longleaf, shortleaf, slash
Shoulders (1959, 1963)	Loblolly, longleaf, slash
Wakeley (1965)	Longleaf, slash
Root deformation related to planting method	
Gruschow (1959)	Loblolly
Bilan (1960)	Loblolly
Ursic (1963)	Loblolly
Little and Somes (1964)	Loblolly, pitch, shortleaf
Root growth initiation after planting	
Woods (1959)	Longleaf, sand, slash
Root development in seedlings	
Heyward (1933)	Longleaf
Lenhart (1934)	Longleaf
McQuilken (1935)	Pitch, shortleaf
Pessin (1935, 1938, 1939)	Longleaf
Turner (1936)	Loblolly, shortleaf
Reed (1939)	Loblolly, shortleaf
Huberman (1940ab)	Southern pine
Duncan (1941, p. 155)	Loblolly
Kozlowski and Scholtes (1948)	Loblolly
Wenger (1952)	Loblolly
Bilan (1960)	Loblolly
Little and Somes (1964)	Loblolly, shortleaf, pitch
Stransky and Wilson (1967)	Loblolly, shortleaf
Jorgensen (1968)	Loblolly, longleaf, slash
Kaufman (1968)	Slash
Root weight	
Monk (1966)	Loblolly
Box (1967)	Loblolly
White and Pritchett (1970)	Slash

13-2 ROOT FORM

Information on the form of mature root systems of southern pine trees is meager, but much has been published on root development in very young trees of the major species plus pitch pine; patterns evident in young trees should be indicators of mature patterns.

Root form is affected by soil type and moisture content, soil temperature, competition, depth of litter, exposure to prevailing winds, tree age, and, in plantations, by method of planting.

Little and Somes (1964) described normal root systems of loblolly, pitch, and shortleaf pine seedlings started in place from seeds; taproots usually penetrated vertically, and laterals grew away from taproots almost at right angles and on all sides.

They observed, however, that seedlings planted in slits usually had one-plane root systems, and those poorly placed in slits had taproots initially bent into J-, L-, or U-shape. In these cases, new growth on the taproot bent abruptly to again grow vertically downward; alternatively, another root was developed to replace the original taproot. Seedlings well planted in slits had less distorted roots, but did not have the symmetrical root systems typical of seedlings carefully planted in round holes. In planted seedlings, especially those placed in poor slits, intertwined roots were found near the soil surface.

Other researchers have observed similar patterns and found that the single-plane root system typical of slit-planted pines may persist for several years (Gruschow 1959; Bilan 1960; Ursic 1963). Wakeley (1954) noted, however, that apprehension over ill effects of slit planting of southern pines is unwarranted in view of the evident vigor of thousands of acres of pulpwood-size planted pines.

LOBLOLLY PINE

Much of the published work on root patterns concerns loblolly pine.

Thirty- to 100-day-old seedlings.—Jorgensen (1968) studied the effect of soil type (sand, loam, clay) on seedling root form in loblolly pines direct seeded on scalped sites kept free of grass by herbicides. Thirty days after emergence, taproots of seedlings averaged 2.8 inches in sand and clay and 4.6 inches in loam (table 13-1; fig. 13-1). At 60 days there were no differences among soils, but by 100 days taproots in clay averaged 10.2 inches, those in sand 7.7 inches, and those from loam were intermediate.

Total root length and numbers of lateral roots were strongly influenced by soil. The average 30-day-old plant from the sand had 3.2 inches of total root, less than half the 7.9 inches in the clay or 8.4 inches in the loam. Plants from the sand had few laterals, in contrast to an average of 6.8 for seedlings grown in loam or clay. By 60 days all root lengths nearly doubled, as did the number of roots on plants in the clay and loam. Seedlings from the sand now averaged 5.9 laterals per plant. Site influence continued at 100 days, with roots from the sand little more than half the length of those from the loam or clay.

Two-year-old seedlings.—Bilan (1960), in a study of the effects of root development in modified environments—i.e., naturally sodded ground, a 2-inch mulch of pine needles (unshaded and 50-percent shaded), bare ground (unshaded and 50-percent shaded), and bare sand—examined the

TABLE 13-1.—*Tap and total root length, and number of lateral roots on loblolly pine seedlings 30, 60, and 100 days old, by soil type*¹ (Jorgensen 1968)

Age (days) and soil	Taproot length	Total root length	Lateral roots
	--- Inches ---		Number
30 days			
Sand.....	2.8	3.2	0.8
Loam.....	4.6	8.4	6.2
Clay.....	2.9	7.9	7.5
60 days			
Sand.....	6.3	10.6	5.9
Loam.....	5.8	13.8	13.0
Clay.....	5.6	15.3	12.7
100 days			
Sand.....	7.7	13.0	10.7
Loam.....	9.3	20.6	17.4
Clay.....	10.2	21.5	20.0

¹ Direct seeded near Alexandria, La.; 1964.

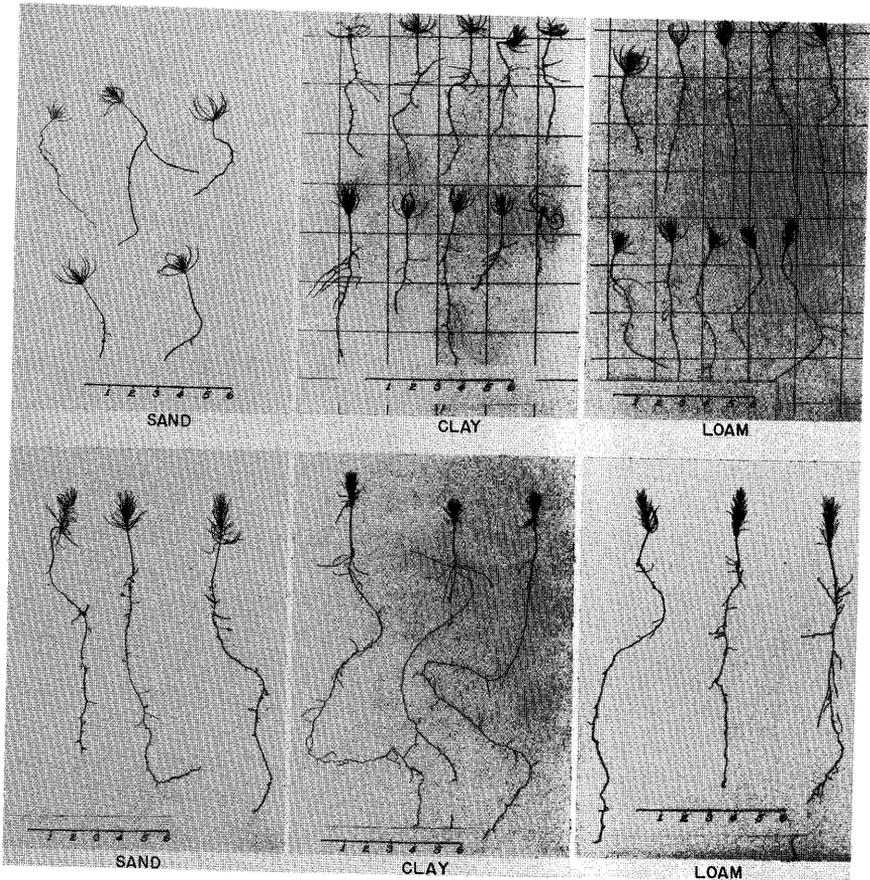
roots of loblolly pine seedlings that had been bar-planted at age 1 on 2-foot spacing in east Texas during February of 1957 and then allowed to grow an additional year before excavation (fig. 13-2). His conclusions follow.

On plots protected by mulch, shade, or sod, more than half the root growth was in the uppermost 3 inches of soil (fig. 13-3), and over 70 percent of the root weight was in the top 6-inch layer. On an oventry basis, the root systems weighed about as much as stems and needles combined; root weight was generally less than 1/2-pound per seedling (fig. 13-4).

Scalping sites before seedlings were planted increased total dry weight of roots by more than four times, increased temperature at the soil surface, and caused a general downward shift of the entire root system (figs. 13-3, 13-4).

Mulching of scalped soil favored root development very close to the soil surface, probably by improving the moisture conditions and by mitigating the temperature extremes. About 70 percent of oventry root weight on mulched plots was in the uppermost 3 inches of soil (fig. 13-3). Mulching increased length of lateral roots (fig. 13-3) but decreased root branching and lignification.

Six-year-old plantation-grown trees.—Box (1967), in a study of 6-year-old, plantation-grown, loblolly pines growing in southeast Louisiana, found that 83 percent of total root weight was in the upper 18 inches of soil; total root systems, including fine roots, weighed about one-third as much



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Figure 13-1.—Direct-seeded loblolly pines in sand, clay, and loam at 30 days (top row) and 100 days (bottom row). Scales show inches. (Photos from Jorgensen 1968.)

as the combined above-ground tree parts (ovendry basis). If roots one-half inch in diameter and smaller were excluded, however, the remaining root system had about one-fifth the dry weight of above-ground tree parts.

Nine-year-old trees.—Zahner (1956) noted that response of loblolly roots to heavy thinnings is comparable to that of crowns and stems. Immediately after thinning a 9-year-old plantation from 1,100 trees per acre to 100, there were well developed roots 3 feet from trees but none at 6 feet. Roots were fully occupying less than 10 percent of the soil within 12 feet of the tree.

Two growing seasons after thinning, he found that crowns and roots had each grown to occupy 30 percent of the area. Roots were well developed at a 6-foot distance from stems 2½ years after thinning, but were not detected at 9 feet; he thought it probable that roots nearest the surface developed most rapidly.

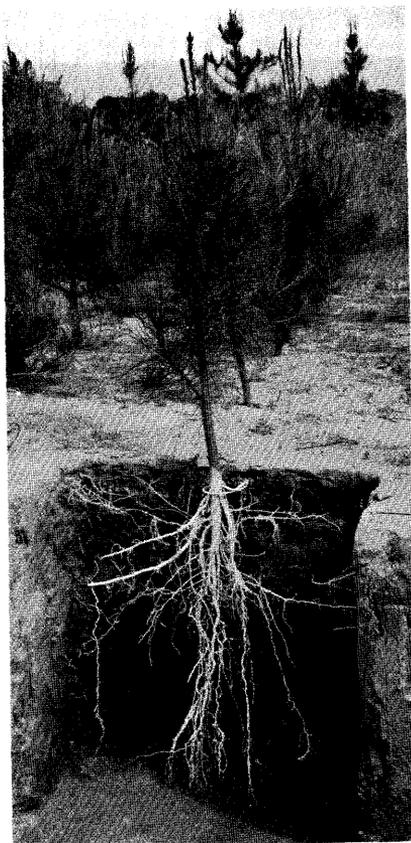


Figure 13-2.—Roots of 2-year-old loblolly pine exposed in a central 6- by 24-inch excavation made parallel to planting slit and about 2 feet deep. (Photo from Bilan 1960.)

Twenty- to 35-year-old trees.—In a study of root distribution in North Carolina Piedmont soils, Coile (1937) found that the number of roots in the A_1 horizon (loam within 1 inch of soil surface) increased rapidly with age until stands were 20 to 30 years old; after 30 years the increase was much slower. The development of roots in the A_2 horizon (loam 1 to 5 inches below soil surface) followed the same trend as in the A_1 , although the numbers were smaller. In the B and C horizons (clay 5 to 21 and 21 to 37 inches below soil surface), the number of roots remained constant after about 20 years.

Korstian and Coile (1938) made vertical trenches around 1-milacre (0.001 acre) plots in a 31-year-old loblolly pine stand with 340 trees per acre (average 9 inches d.b.h.) to determine the number of roots, by size class, per square foot of trench wall; plots were in Alamance stony soil in the Duke Forest, N.C. They found that feeder roots less than 0.1 inch

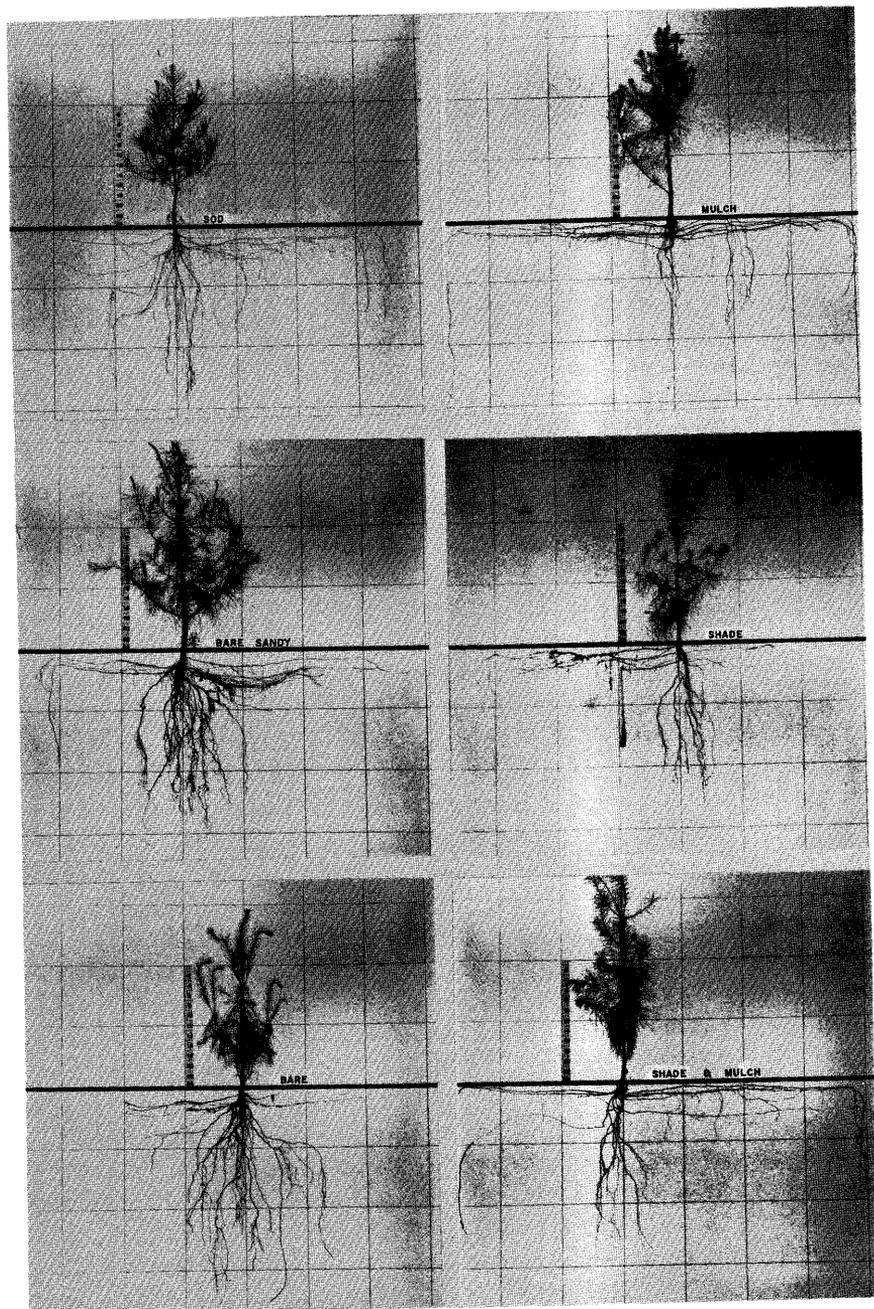


Figure 13-3.—Entire root systems of 2-year-old loblolly pines grown in a variety of shade, soil, and mulch conditions. Background is ruled in 12-inch squares. Extreme ends of lateral roots were turned down to facilitate photography; in the field these roots grew parallel to the soil surface. (Photos from Bilan 1960.)

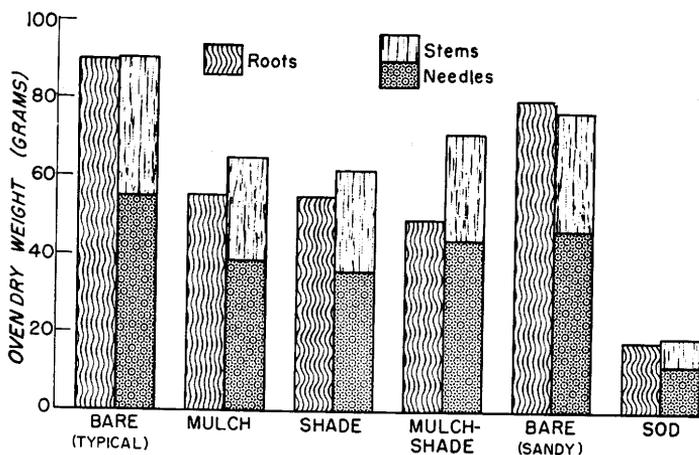


Figure 13-4.—Average weight per seedling of roots, stems, and needles of 2-year-old loblolly pines from a plantation site in east Texas. (Drawing after Bilan 1960.)

in diameter were concentrated in the 6-inch-deep A horizon; practically no lateral roots were found below the B horizon (6- to 21-inch depth). Distribution of roots by diameter class was as follows:

Soil horizon	Smaller than	0.11 to	Larger than
	0.1 inch	0.30 inch	0.3 inch
	----- <i>Number per square foot</i> -----		
A ₁ -----	105-111	10-12	0.8-1.4
A ₂ -----	49-55	8-11	0.8-2.5
B ₁ -----	4-11	1-2	0.1
B ₂ -----	5-8	2	0
C ₁ -----	0.2-0.6	0.2-0.8	0

Roots over 1 inch in diameter were most frequent in the A₂ horizon (2- to 6-inch depth) where they occurred with a frequency of one root every 3 sq. ft. of trench wall.

Mature trees.—Roots of large loblolly pines spread laterally further than their crowns; this is one reason why there is often little young pine in openings, even in fairly light stands of timber (Wahlenberg 1960, p. 54).

Copeland (1952), in excavations made while studying littleleaf disease in mature loblolly pines, found that the greatest mean root diameter was at a depth of 8 to 10 inches; for mature shortleaf the largest roots were only 4 to 5 inches from the soil surface.

Ashe (1915) observed that taproots of loblolly pines are much smaller and shorter than those of shortleaf and longleaf pines, and that the general form of pine roots is greatly modified by soil conditions and tree age. He found that the taproot of loblolly pine seldom penetrates more than 4 or 5 feet and is often forked and blunted; he described them as often becoming flattened or curved at the tip where they penetrate to hardpan and heavy clay (fig. 13-5 top right).

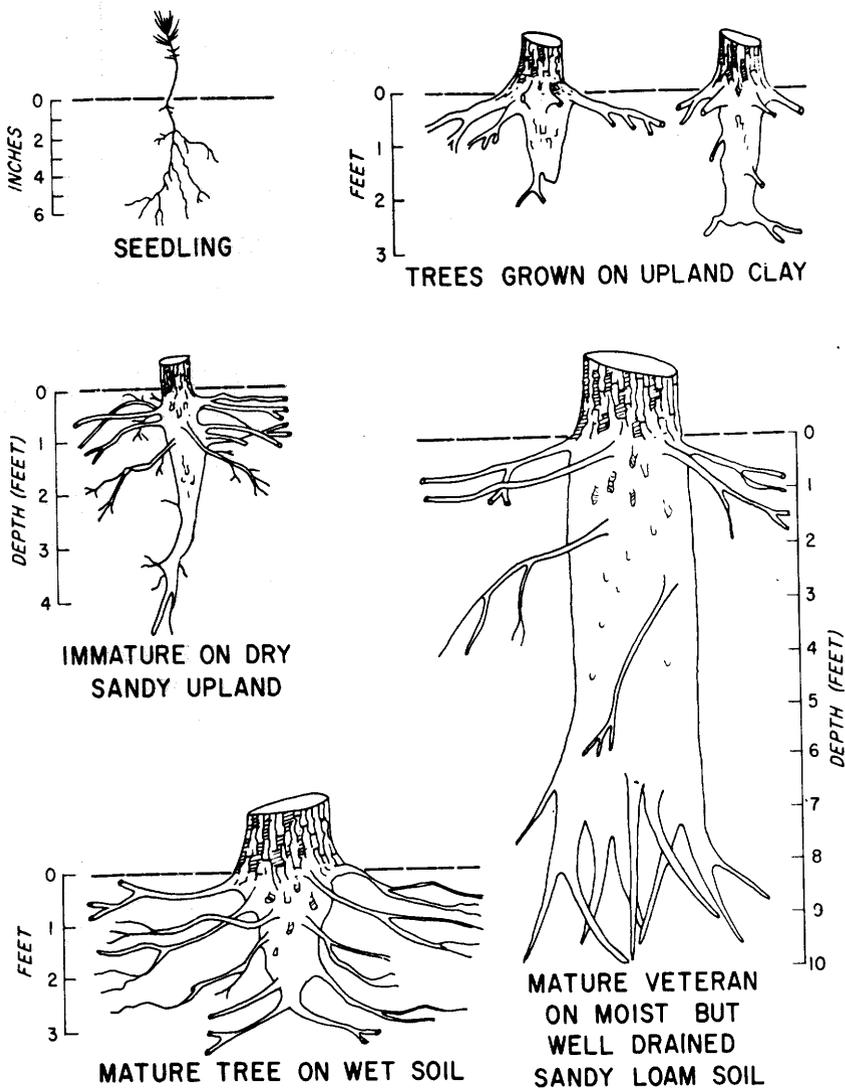


Figure 13-5.—Root systems of loblolly pine are influenced by site and tree age. The deep-seated feeding roots on the veteran pine at right extended to the water table. The seedling is 2 years old. (Drawing after Wahlenberg 1960, based on Ashe 1915.)

Ashe also observed that on loose, moist, or sandy soils many of the oblique and central roots penetrate deeply; in these systems some lateral roots also lie near the surface. On dry sandy upland soils the taproot of young loblolly pines may penetrate 3 to 5 feet (fig. 13-5 left center); on moist but well-drained sandy loam soil, numerous small central roots may descend vertically 10 feet to the water table (fig. 13-5 right center).

On very wet soils, where the water table is near the surface during the

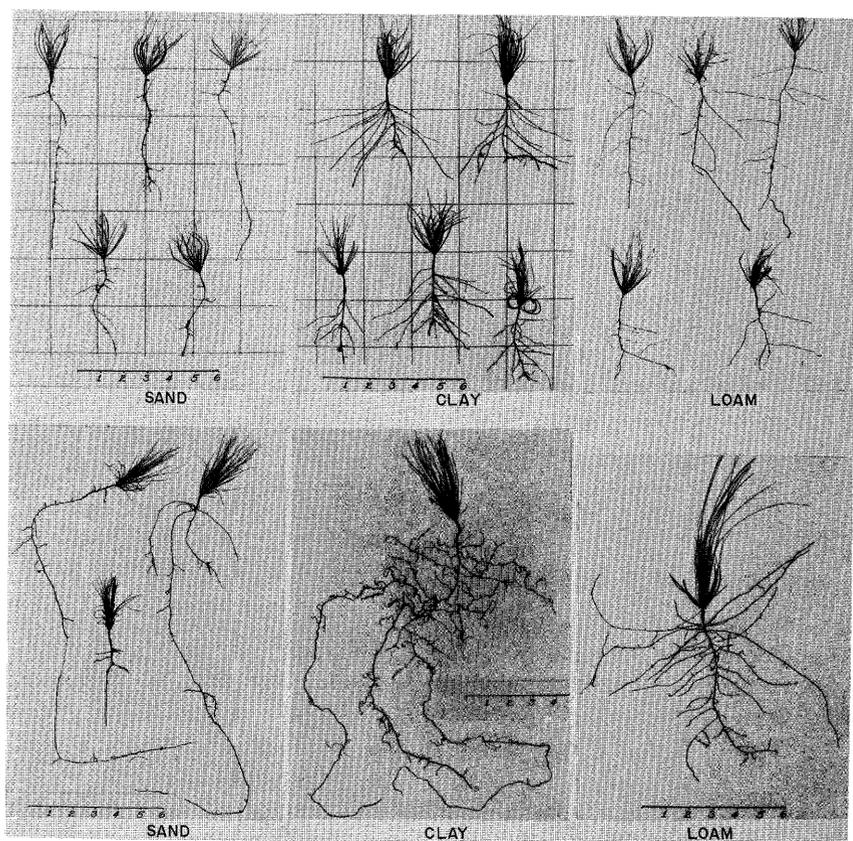
growing season, Ashe found no well-developed taproot in old trees; instead, a great number of spreading roots develop (fig. 13-5 bottom left).

These observations of Ashe have been supported by those of others. Broadfoot (1951) noted that when either the water table or hardpan confines the roots to the surface layers of soil, growth is retarded. Zon (1905) found that in marshy locations, lateral roots are prominent.

Dry weight of root systems.—There are no published data on the weight of root systems of mature loblolly pines. Monk (1966) provided information on oven-dry weights of root systems (including fine roots) of trees 5.2 inches in diameter and smaller. From his data he developed a linear regression equation relating root weight to tree diameter at breast height outside bark, as follows (see fig. 14-6).

$$\text{Dry root weight in grams} = 1573 (\text{d.b.h. in inches}) - 190 \quad (13-1)$$

For trees 3 to 5 inches in diameter, the ratio of total root weight to weight



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 Figure 13-6.—Direct-seeded longleaf pine seedlings grown in 1964 on sand, clay, and loam soils. (Top row) Seedlings when 30 days old. (Bottom row) 100 days old. Scales show inches. (Photos from Jorgensen 1968.)

of above-ground tree parts ranged from 0.20 to 0.35 with average of 0.28; for smaller trees the ratios were higher.

LONGLEAF PINE

Of the southern pines, longleaf has the largest and longest taproot; prominence of the taproot is evident at all ages.

Seedlings to 5 months of age.—Jorgensen (1968) studied the effect of soil type (sand, loam, clay) on seedling root form in longleaf pine direct seeded on scalped field sites kept free of grass by herbicides. Seed was sown in the spring of 1963 on the sand and clay soils and again the following spring on the same soils plus a loam. Jorgensen's observations are summarized as follows.

The seedlings developed rapidly on all sites in 1964 (table 13-2, fig. 13-6). When seedlings were 30 days old, taproots from the sand and loam averaged 5.4 inches long; those in the clay were about 2 inches shorter. Taproots grew regularly until at 100 days the average length was 11.5 inches. Plants lifted from the sand had taproots 2.2 inches longer than those from the clay; those from the loam were 1.8 inches shorter than those from the clay.

In 1963, taproots of 30-day-old seedlings grown on sand were about an inch shorter, and those from the clay an inch longer, than were

TABLE 13-2.—*Tap and total root length, and number of lateral roots on longleaf pine seedlings 30, 60, 100, and 150 days old, by soil and year*¹ (Jorgensen 1968)

Age (days) and soil	Taproot length		Total root length		Lateral roots	
	1963	1964	1963	1964	1963	1964
	----- Inches -----				-- Number --	
30 days						
Sand.....	4.6	5.5	9.3	9.7	6.4	7.2
Loam.....		5.4		15.6		12.2
Clay.....	4.3	3.5	10.2	23.2	7.5	15.8
60 days						
Sand.....	6.7	10.6	13.2	19.4	8.6	10.4
Loam.....		6.8		28.2		16.6
Clay.....	6.7	6.8	21.1	41.1	18.8	27.5
100 days						
Sand.....	16.6	13.6	31.7	28.7	18.8	18.7
Loam.....		9.6		53.3		36.3
Clay.....	15.6	11.4	44.3	45.9	43.6	41.3
150 days						
Sand.....	23.4		54.0		38.0	
Loam.....						
Clay.....	19.3		76.4		62.7	

¹ Direct-seeded near Alexandria, La.

obtained the following year. By the 100-day lifting, these taproots averaged 3.6 inches longer than those from comparable seedlings lifted a year later. Seedlings 150 days old in the sand and clay had taproots approximately 2 and 1.5 feet long, respectively.

Number of lateral roots and total length varied greatly with soil in 1964. Thirty-day-old plants from the clay had 23.2 inches of root, more than twice that possessed by seedlings from the sand. Those from the loam were intermediate. Lateral roots were fairly numerous, but plants from sand had less than half the number of those from clay.

In 1963 the 30- and 60-day plants had fewer and shorter roots than did seedlings the following year, although the root development patterns, with respect to soil, were similar.

In both years, 100-day-old seedlings on the loam and clay soils had about 4 feet of root system, one-third more than that of stock from the sand. Number of lateral roots was also greatest on the loam and clay.

The last 1963 excavation, at 150 days, showed continued root growth, but seedlings in the sand were still about a third smaller, in total length and number of lateral roots, than those from clay.

Older seedlings less than 3 feet tall.—Heyward (1933) examined long-leaf pine seedlings less than 3 feet tall growing on three sites (old field abandoned 12 years, pine-turkey oak (*Quercus laevis* Walt.) stand, poorly drained area adjacent to swamp) in the Choctawhatchee National Forest of the Florida panhandle. The old-field and pine-turkey oak sites were on deep, well-drained sand. The poorly drained site had sand 12 to 14 inches deep underlain by a sandy clay; the water table was 28 inches below the surface.

He found that the root systems consisted of a prominent taproot, 9 to 11 laterals more than 2 feet in length growing horizontally from the taproot—mostly within 2 feet of the soil surface, a varying number of shorter laterals—mostly branching from the taproot at depths greater than 2 feet, and vertical **sinker** roots which branched from the laterals (fig. 13-7).

In well-drained sandy soil the taproots varied from 3 feet to more than 9 feet in length, and averaged about 5 feet. On the poorly drained site the taproots measured only about 2 feet in length (23 to 29 inches). Typically, the taproot took a straight downward course (fig. 13-7).

Lateral roots extended horizontally at more or less constant depth; the roots of almost all trees examined were distributed through the soil almost as if they were following a system of rectangular coordinates in the vertical plane (fig. 13-7).

In plan view (fig. 13-8) the lateral roots frequently changed direction while remaining at constant soil depth. Of 179 lateral roots excavated, nearly 90 percent occurred in the first foot of soil (fig. 13-7). The number of laterals was surprisingly constant (mostly 9 to 13).

Heyward found that seedlings from the old-field site had shorter

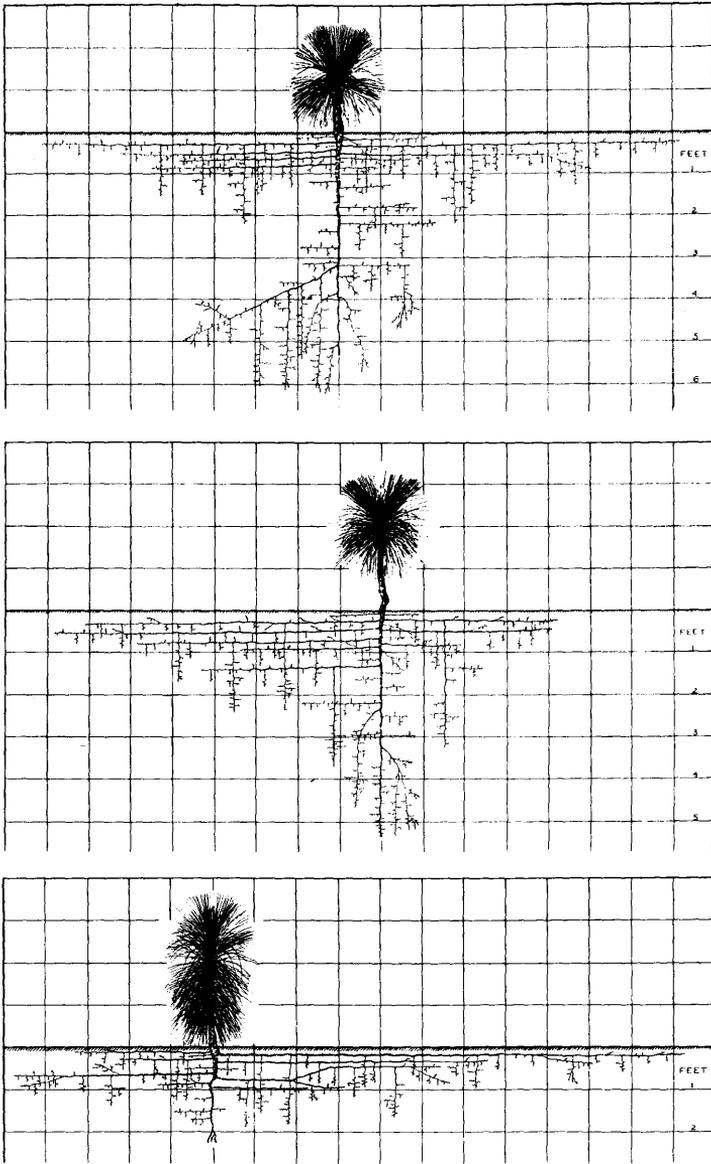


Figure 13-7.—Seedling root systems typical of longleaf pines excavated from the deep sands of the Choctawhatchee National Forest, Fla.; drawn against a 1-foot grid. (Top) From old-field site. (Center) From longleaf pine-turkey oak site. (Bottom) From poorly drained area adjacent to swamp. Roots penetrated to least depth in poorly drained site where water table was 28 inches below soil surface. On all sites roots tended to be either horizontal or vertical rather than oblique. (Drawing after Heyward 1933.)

laterals than those from the other two areas. Each of the three seedlings excavated from the poorly drained site had at least two lateral roots 7 feet or more in length.

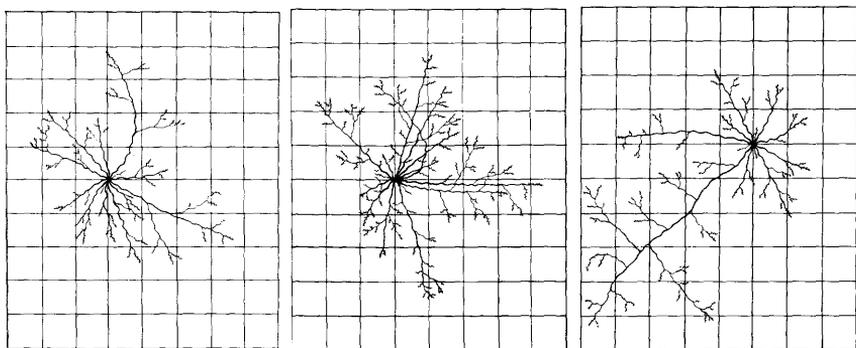


Figure 13-8.—Longleaf pine seedling root distribution in plan view on three sites; drawn against 1-foot grid. (Left) Old field. (Center) Longleaf pine-turkey oak site. (Right) Poorly drained area adjacent to swamp. (Drawing after Heyward 1933.)

Twelve-year-old seedlings in sandy loam.—Data on root forms of 12-year-old longleaf pine grown in the sandy loams of southeast Louisiana and south Mississippi were reported by Pessin (1939). He found that under natural conditions, most root systems of longleaf pine grow symmetrically, but that asymmetrical growth is not uncommon, owing to presence in the soil of old root holes and charcoal pockets as well as to differences in the texture of the soil (fig. 13-9). He also found that most lateral roots of longleaf pine seedlings were in the upper foot of soil.

Twenty-four-year-old plantations pines.—Root extension, that is, the straight line distance from the tree to the point at which a root extremity is observed, has been measured by detecting in tree stems radioactive elements introduced into the soil at various radii and depths.

By this method, Ferrill and Woods (1966) examined root extension in a 24-year-old longleaf pine plantation in the North Carolina sandhills

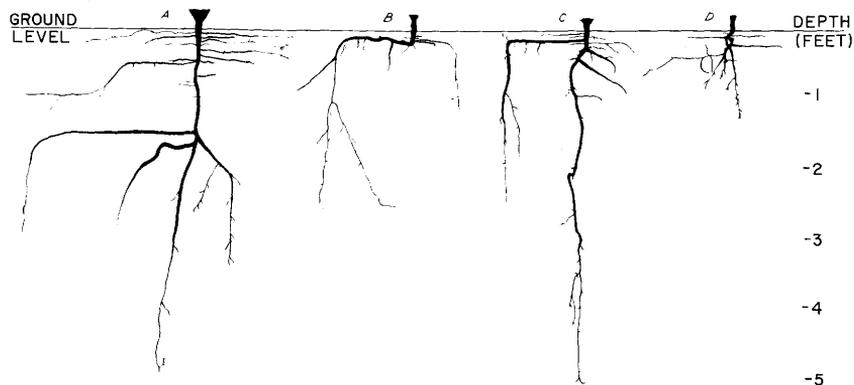


Figure 13-9.—Root systems of 12-year-old longleaf pine seedlings grown in fine sandy loam. (A) Uncommon development of branches at lower depths. (B) Asymmetrical growth attributed to unfavorable site. (C) Two large branches developed from short taproot. (D) An abnormal root system in which a branch root and the taproot have grown together forming a loop. (Drawings after Pessin 1939.)

and found that all trees above 3 inches in diameter absorbed sufficient radioactive material (I^{131}) to be detected at the stem if the I^{131} was applied within 10 feet of the stem. Beyond 22 feet for surface applications, and 33 feet for 1- and 3-foot depths, no I^{131} was detected in any trees. Ferrill and Woods concluded that the shorter distance of extension for surface roots may mean that root competition is greater in upper layers of soil where roots are much more abundant. With lower concentration of roots at the 1-foot and 3-foot depths, roots may extend further from the stem. The plantation studied had coarse to medium sand surface soils, and sandy-clay subsurface soils; drainage was good. Trees were on a 6- by 6-foot spacing and had never been thinned.

Thirty- to 60-year-old pines.—Trees in ages from 30 to 60 years are of particular interest to the utilizer of longleaf pines from managed stands. Information on the root systems of trees in these age classes is meager.

Hough et al. (1965), however, have provided an equation that permits estimation of lateral root extension according to tree age. In their study of a natural stand of longleaf pine and turkey oak in the sandhills of North Carolina, I^{131} was applied to the soil at selected spots, absorbed by roots, translocated to tree stems through vascular elements, and detected in stems by a gamma radiation counter. Radioactivity was detected in pine stems as far as 55.1 feet away from the application point; all pines monitored within a radius of 17 feet from application point showed radioactivity. Factors most closely related to distance of root extension were elevation and tree age, as follows:

$$\begin{aligned} \text{Root extension, feet} = & 1.2643 & (13-2) \\ & +10.3445 \text{ (elevation)} \\ & + 0.9274 \text{ (tree age)} \end{aligned}$$

where elevation was the vertical distance (feet) of the soil surface at the stump above (+) or below (−) the point of application; and age (years) was the number of rings that could be counted at the stump rather than true total age. The equation accounted for 62 percent of the variation observed in root extension.

Root form is strongly influenced by soil structure. Figure 13-10 illustrates an extreme example of the interruption and deformation of taproot growth caused by an impermeable hardpan underlying a more permeable soil.

Old-growth trees.—Heyward (1933) excavated the roots of a 250-year-old longleaf pine growing in deep, well-drained sands of the Choctawhatchee National Forest, Fla.; the tree was 54 feet high, and 17 inches in diameter $4\frac{1}{2}$ feet above the ground. The massive taproot was 14 feet 2 inches long. The diameter of this root $5\frac{1}{2}$ feet below the surface was 17 inches, or the same diameter as the stem $4\frac{1}{2}$ feet above the surface. At a depth of 13 feet 4 inches, it divided into two stout branch roots each 3 inches in diameter (fig. 13-11).



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Figure 13-10.—Root of a 4-inch, 30-year-old longleaf pine arrested in its downward course through fine sand by a hardpan $1\frac{1}{2}$ feet below the surface. Windthrow exposed the root. (Photo from Wahlenberg 1946, p. 400.)

He found 10 laterals, seven of which were examined for a distance of 12 feet from the taproot; all lay within 10 inches of the surface and tapered from 4 to 7 inches in diameter 2 feet from the taproot to approximately 1 inch in diameter 12 to 15 feet from the taproot. Beyond this distance, taper was slight.

One 6-inch lateral was excavated and found to lie at an average depth of 10 inches, where it grew to a length of $71\frac{1}{2}$ feet and then descended vertically to a depth of $3\frac{1}{2}$ feet below the surface, where it ended. The end of this root was 51 feet in a straight line from the taproot.

In the 250-year-old tree examined by Heyward, four vertical roots distinct from the taproot were found. They originated from lateral roots as far as 5 feet from the taproot and penetrated vertically to a rounded lower end $\frac{1}{4}$ - to $\frac{1}{2}$ -inch in diameter. Each of these verticals had two or three horizontal branch roots.

T. A. Liefeld excavated and mapped a mature longleaf pine growing in northern Florida on a semihardpan phase of Blanton fine sand; the



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Figure 13-11.—(Left) Mature longleaf pine from the longleaf pine-turkey oak type of western Florida. (Right) The massive taproot of a 250-year-old longleaf pine of this type measured 14 feet 2 inches in length. (Left photo from Wahlenberg 1946, p. 401; right photo from Heyward 1933.)

semihardpan was 4 to 5 feet below the surface and was permeable by the water and roots. As reported by Wahlenberg (1946, p. 217), his findings were as follows.

Maximum root depth was 8.7 feet (fig. 13-12B). Lateral roots were limited by competition from adjacent trees (fig. 13-12C) and none originated below the 26-inch level; most grew within 1 foot of the surface.

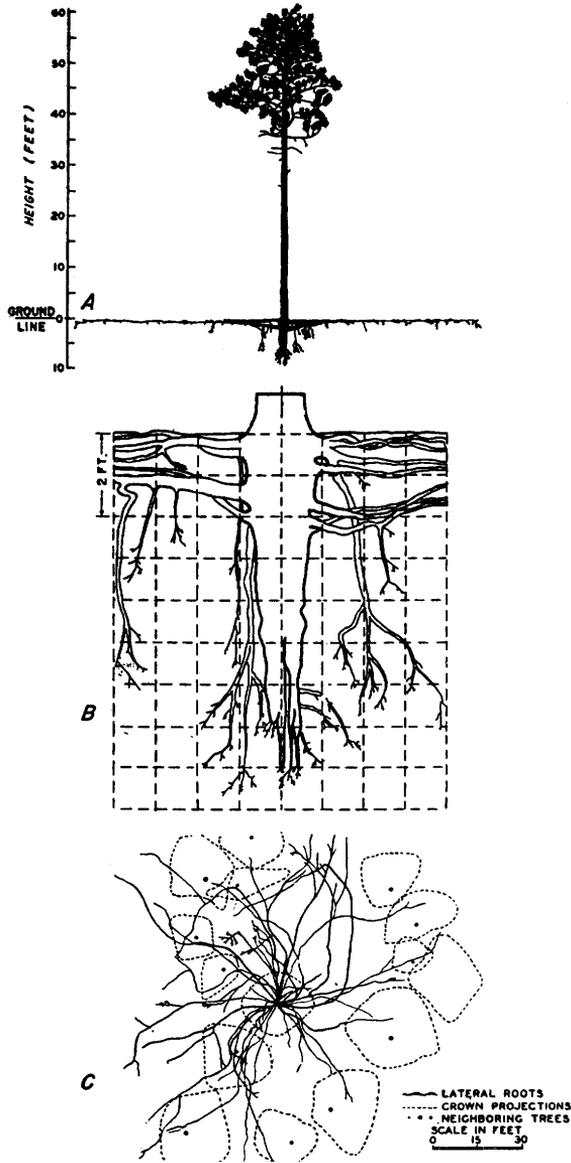


Figure 13-12.—Root development of a mature longleaf pine. (A) Roots, stem, and top. (B) Longitudinal section through central zone 8 feet in diameter. (C) Root distribution in relation to neighboring trees; viewed from above. (Drawings after Wahlenberg 1946, p. 220, based on data from Liefeld.)

Numerous fibrous vertical roots, however, entered the second foot or deeper layer of soil. The longest of 28 main lateral roots measured 87.4 feet; the average lateral root spread was 45 feet in radius, indicating that about $\frac{1}{7}$ -acre of soil was occupied—though not exclusively—by this tree.

PITCH PINE¹

The root system of a pitch pine tree growing in the pine-barren section of New Jersey consists of a taproot from which 15 to 30 lateral branches originate and extend radially in the surface layers of the soil. From these primary branches, horizontal and vertical secondary branches develop; these in turn give off tertiary branches, and so on. Normally, the root system occupies a roughly circular area of topsoil; in all of this area except the marginal parts vertical or sinker roots provide extensive contacts with the subsoil.

Pitch pine apparently differs from some of the other southern pines (including loblolly, longleaf, and shortleaf and perhaps others) in that it is capable of extensive root growth below the water table in saturated soils. The descending branches of taproots under water sometimes are arranged in a characteristic fan-shaped mass. McQuilken (1935) found that trees growing on saturated soils appeared to be in full health and vigor.

Root development on the more typical well-drained sandy soils is described below.

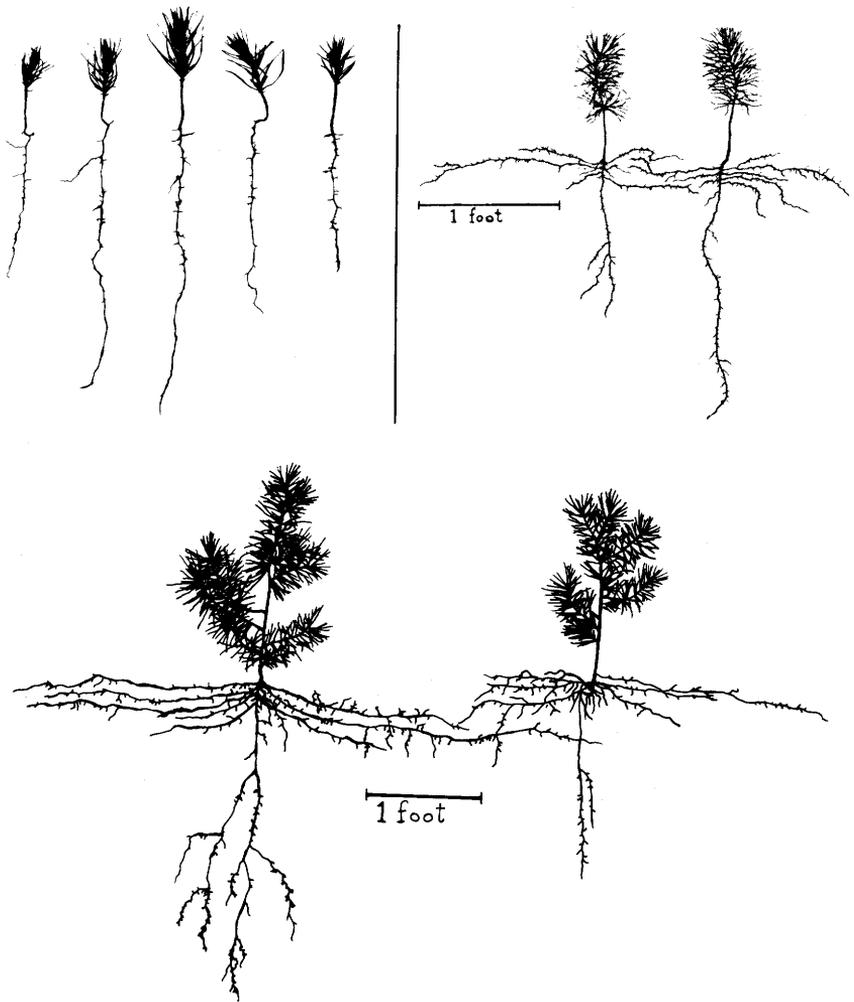
Seedlings to 8 years of age.—Seedlings develop prominent taproots which reach depths from 3 to 12 inches during the first season of growth (fig. 13-13 left). The taproots of seedlings 4 to 5 years old reach depths of 15 to 24 inches, and the strongest laterals approximate the same length (fig. 13-13 right); plants of this age have weak stems and tend to lie prone on the surface, and a permanent crook persists at the ground line long after they have become rigidly erect. Taproots of plants 8 to 10 years old reach depths of 1.5 to 2.5 feet, with some laterals attaining the same length (fig. 13-13 bottom); plants at this age usually are erect.

Plants 8 to 12 years of age.—Saplings 12 years of age begin to display regular whorls of stem branches and assume the aspect of a tree. Taproots reach depths of 3 to 4 feet, and the strongest laterals extend 6 to 8 feet. Between the 8th and 12th years, growth of primary lateral branches accelerates, the radial spread of the root system reaching about twice the taproot length and $1\frac{1}{2}$ to three times the stem length. The lateral roots thus displace the taproot as the most prominent feature of the root system. As the taproot penetrates the subsoil below the 3-foot level, its growth rate diminishes; the stem now exceeds the taproot in length, a difference that constantly increases with growth of the tree.

Secondary and tertiary branches on the stronger primary laterals grow to conspicuous size during this stage.

Trees 12 to 30 years of age.—As a pitch pine tree grows from 4 to 25 feet in height, corresponding to tree ages from about 12 to about 30 years, the primary laterals elongate to 25 or 30 feet, maintaining a ratio of about

¹ The text under this heading is condensed with minor editorial changes from McQuilken (1935, pp. 1013-1015).



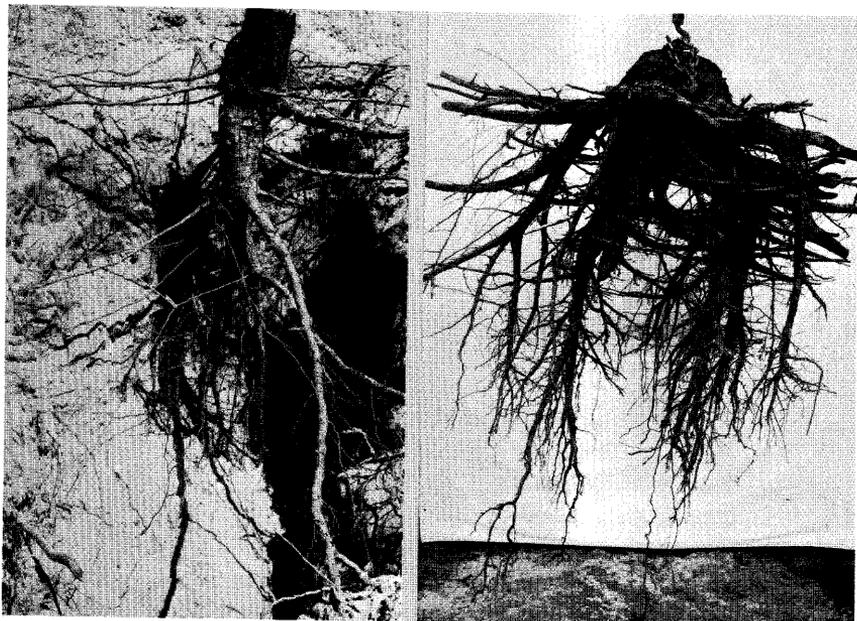
F-520950

Figure 13-13.—(Left) Pitch pine seedlings during June of first year's growth in open woods; length of the longest taproot is 5.5 inches. (Right) Four-year-old seedlings with practically complete root systems. (Bottom) Eight-year-old seedlings. (Photos from McQuilken 1935.)

1.5 to 1 between average lateral root length and tree height. Diameter of lateral roots (measured near the taproot) approximates 1 mm. for each foot of length. Density of roots within the occupied volume of soil increases due to continuous elongation of root branches.

Vertical roots, after reaching a depth of 3 to 4 feet, grow much more slowly than surface laterals, and practically cease to grow at depths of 8 to 9 feet. As a result of the foregoing developments, a constantly increasing proportion of the root system becomes localized in the surface soil.

Trees over 30 years of age.—At approximately age 30—when the tree is about 25 feet in height and 4 inches in d.b.h.—primary laterals, tap-



F-520951

Figure 13-14.—(Left) Taproot of a 30-year-old pitch pine exposed by an excavation 4.5 feet deep; the root system was subsequently excavated to 9-foot depth to recover the deepest roots. (Right) Central roots of a mature pitch pine associated with a weak taproot; the longer roots reached a depth of about 8 feet. The tree was 85 years old, 48 feet high, and 9 inches in diameter at breast height. (Photos from McQuilken 1935.)

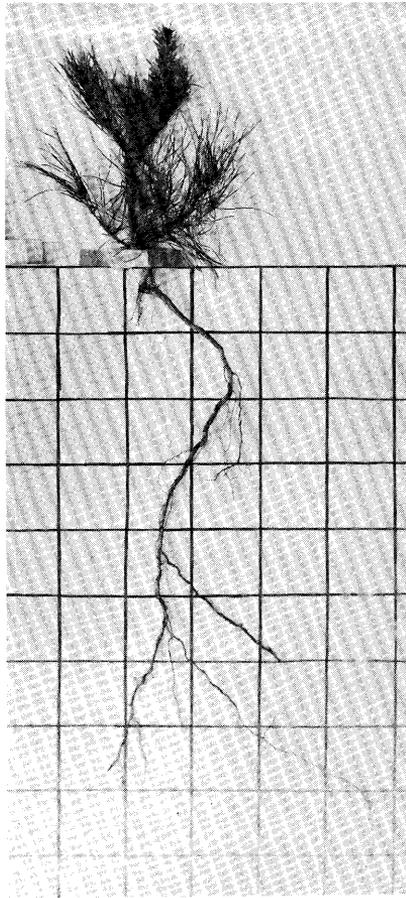
root, and stronger sinker roots cease to elongate. The basal 2 or 3 feet of the stronger primary laterals thicken markedly, especially in the vertical plane, forming narrowed, planklike roots. In many cases, the growth is almost entirely on the top side, resulting in eccentrically thickened, buttresslike supporting roots.

Smaller primary laterals continue to elongate to about the length of the stronger ones, after which they too undergo basal thickening. Secondary and tertiary root branches continue some elongation, resulting in increasing density of roots in both the topsoil and the subsoil (fig. 13-14 left). The innermost sinkers tend to become thicker, particularly in trees with a slender taproot (fig. 13-14 right).

SHORTLEAF PINE

Only brief reports have been published on the growth patterns of shortleaf pine roots.

Seedlings.—Little and Somes (1964), in a study comparing root growth of direct seeded and slit-planted shortleaf pines, illustrated early prominent development of the taproot in shortleaf pine, even when the original taproot had been damaged and replaced by a downward turning lateral (fig. 13-15); in 2 years the substitute taproot descended 2 feet below the soil surface.



F-520952

Figure 13-15.—Direct-seeded, 2-year-old shortleaf pine seedling on which the taproot soon died, possibly because of insect injury, and was replaced by a lateral root. Photographed against a 3-inch grid. (Photo from Little and Somes 1964.)

McQuilken (1935) observed that except for their inability to grow with roots below the water table, early development of shortleaf seedlings was similar to that of pitch pine. (See fig. 13-13.)

Mature trees.—McQuilken (1935) found that the taproot of older shortleaf pine is more massive than that of pitch pine, maintaining its diameter to a greater depth and displaying less tendency to divide into an array of descending branches (fig. 13-16). Vertical depths attained by roots of the two species were about equal, and the progression of root system development was similar.

Korstian and Coile (1938) made vertical trenches around a 1-milacre plot in a 42-year-old shortleaf pine stand with 450 trees per acre (averaging



F-520953

Figure 13-16.—Massive taproot of an 85-year-old shortleaf pine. The stump diameter is assumed to be about 10 inches based on a reported diameter breast height of 8½ inches. (Photo from McQuilken 1935.)

7 inches d.b.h.) to determine the number of roots, by size class, per square foot of trench wall; plots were on Whitestore sandy loam in the Duke Forest, N.C. As in loblolly stands, they found that feeder roots were concentrated near the surface; most were in the top 2 inches of soil. Most larger roots (0.1 to 1.0 inch in diameter) were at a depth less than 17 inches. Roots larger than 1 inch were rarely observed at any depth. Very few lateral roots of any size were found at depths greater than 33 inches.

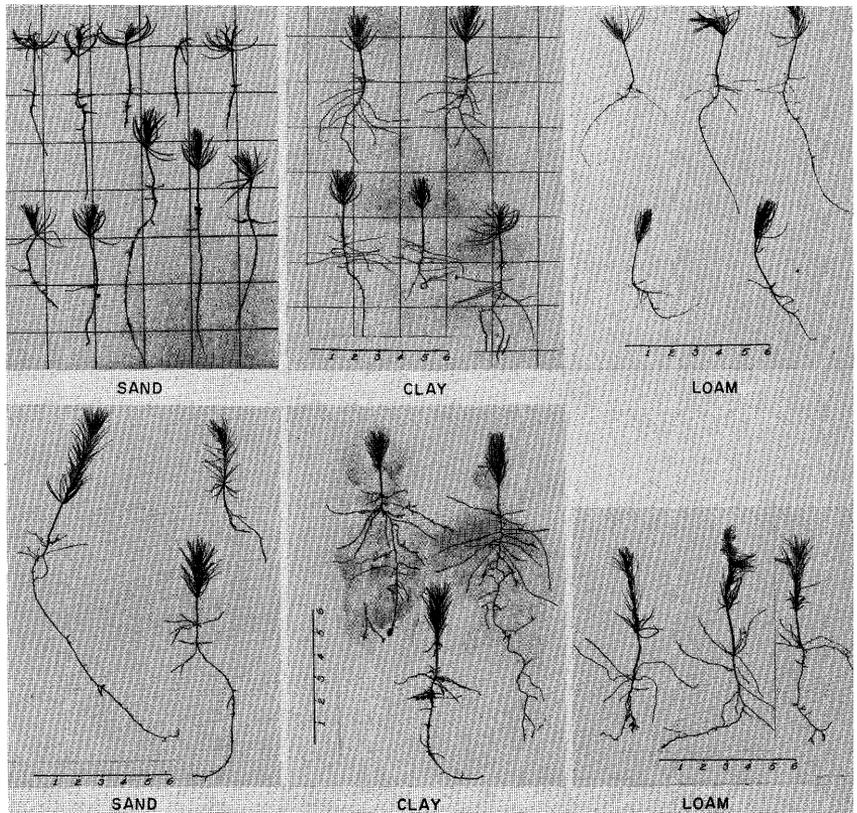
SLASH PINE

No data on root patterns of mature slash pine have been published; it seems likely, however, that trees of the species develop roots intermediate in character between loblolly and longleaf pines.

Seedlings to 5 months of age.—Jorgensen (1968) studied the effect of soil type (sand, loam, clay) on seedling root form in slash pine direct-seeded on scalped field sites kept free of grass with herbicides. The seed was sown in the spring of 1963 on the sand and clay soils and again the following spring on the same soils plus loam. His observations are summarized as follows.

In 1964, at the first lifting, taproots of slash pine seedlings were longest in the loam, shortest in the clay, and intermediate in the sand (table 13-3; fig. 13-17). At 60 and 100 days, there was little soil influence on taproot length.

Taproots in 1963 tended to be longer and more affected by soil than those excavated a year later. At 100 days of age, sand- and clay-grown



P-520954

Figure 13-17.—Direct-seeded slash pine seedlings grown in sand, clay, and loam soils. (Top row) Seedlings when 30 days old. (Bottom row) 100 days old. Scales show inches. (Photos from Jorgensen 1968.)

plants had taproots extending 8.4 and 11.4 inches, respectively, or 1.4 and 3.7 inches longer than those of comparable plants lifted the following year.

Thirty-day-old plants from the sand had 4.6 inches of total root length and 2.6 lateral roots in 1964, less than half the length and number possessed by seedlings from the loam and clay. By 60 days of age roots of seedlings from the sand and clay had more than doubled in size, while those from the loam had grown by only about a third. Modest increases in total root length occurred between the 60- and 100-day liftings, but the relationship between the soil and the root systems was not altered.

TABLE 13-3.—*Tap and total root length, and number of lateral roots on slash pine seedlings 30, 60, 100, and 150 days old, by soil and year*¹ (Jorgensen 1968)

Age (days) and soil	Taproot length		Total root length		Lateral roots	
	1963	1964	1963	1964	1963	1964
	Inches				Number	
30 days						
Sand.....	3.6	3.1	4.2	4.6	1.3	2.6
Loam.....		4.5		10.2		8.9
Clay.....	3.7	2.6	7.1	11.9	5.4	10.8
60 days						
Sand.....	3.0	5.4	5.6	10.8	3.2	7.6
Loam.....		5.6		16.6		12.6
Clay.....	6.9	5.5	19.7	32.8	20.6	22.0
100 days						
Sand.....	8.4	7.0	19.2	14.8	14.6	10.7
Loam.....		6.4		22.2		18.6
Clay.....	11.4	7.7	37.4	39.2	33.5	28.6
150 days						
Sand.....	12.0		31.8		22.6	
Loam.....						
Clay.....	18.8		70.7		53.6	

¹ Direct-seeded near Alexandria, La.

At 30 and 60 days, roots were considerably fewer, and total length was shorter in 1963 than in 1964, but at 100 days plants from the 2 years were similar. Roots grew rapidly from 100 to 150 days. Those of plants in the clay nearly doubled in size, while those in the sand increased about 50 percent.

Trees 3 to 5 years of age.—Feeder roots of young slash pine spread widely, even when plantation grown. Pritchett and Robertson (1960) observed that slash pine trees, 5 years after planting 6 feet apart in rows 10 feet apart, absorbed nutrients placed 30 feet or more away from stems. The trees were grown in Florida on Blanton fine sand. In a 3-year-old slash

pine plantation in northeastern Florida, Kaufman (1968) found that lateral roots extended to a radius of about 14 feet.

Little information on the weight of slash pine root systems has been published. White and Pritchett (1970) have provided some data on young trees, however. In their study of 5-year-old, plantation-grown slash pine, they found that the ratio of entire root system weight to weight of above-ground tree parts, averaged about 0.25 (ovendry basis).

Mature trees.—To provide some data on root patterns and weights in older trees, Howard² uprooted three 22-year-old slash pines growing in central Louisiana on well-drained sandy loam soil in an unthinned plantation (6- by 8-foot spacing); before they were uprooted with a bulldozer, a 30-inch deep circular trench was dug around each at a radius of 3 feet so that most of the lateral roots were severed. Data on the trees and extracted portions of the root systems are summarized in table 13-4.

² Howard, E. T. Some chemical and physical properties of slash pine tree parts. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.37 dated December 30, 1971.

TABLE 13-4.—*Dimensions and weights of parts of three plantation-grown slash pines including roots to 3-foot radius*

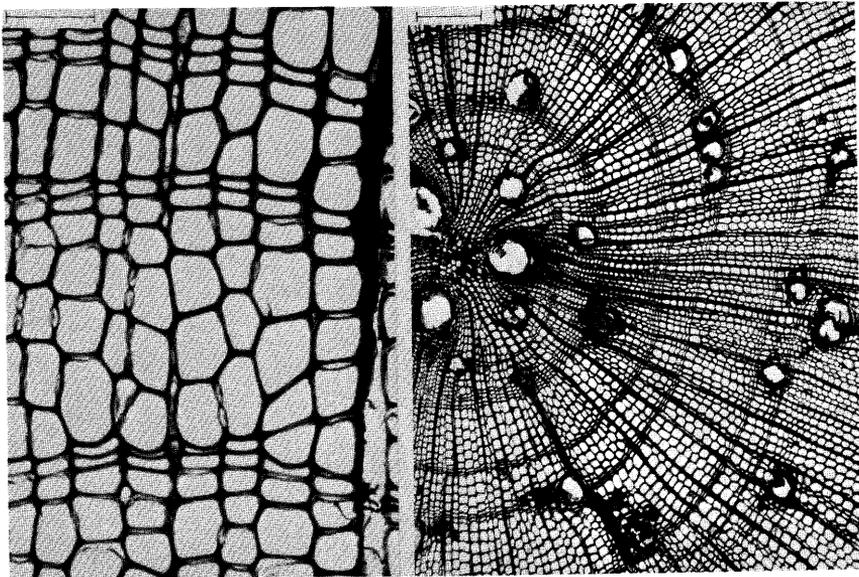
Tree portion and dimension or weight	Tree 1	Tree 2	Tree 3
Entire tree			
Annual rings at 6-inch stump.....	22	22	22
Height above ground, feet.....	62	64	63
Diameter at breast height, inches.....	7.9	7.6	7.8
Ovendry weight (entire including stem, needles, branches, bark, roots), pounds.....	327	340	283
Root system to 3-foot radius			
Ovendry weight including 6-inch stump, pounds....	54	65	38
Percent of entire tree weight.....	16.6	19.1	13.4
Length of taproot, feet.....	4.2	5.0	4.1
Bark-free stem			
Ovendry weight (6-inch stump to 4-inch top outside bark), pounds.....	191	203	163
Percent of entire tree weight.....	58.5	59.8	57.4
Length, feet.....	41.7	45.8	41.7
Stem from 4-inch top (outside bark)			
Ovendry weight, pounds.....	41	36	42
Percent of entire tree weight.....	12.3	10.6	14.8
Stem above 4-inch top			
Ovendry weight including bark, pounds.....	18	14	15
Percent of entire tree weight.....	5.4	4.1	5.5
Branches, entire			
Ovendry weight including bark, pounds.....	11	10	12
Percent of entire tree weight.....	3.5	2.9	4.2
Needles			
Ovendry weight, pounds.....	12	12	13
Percent of entire tree weight.....	3.7	3.5	4.7

13-3 ANATOMY³

The gross structure of southern pine rootwood to some extent resembles that of juvenile stemwood, but the rootwood is more variable. Moreover, roots lack a well-defined pith (the central core of parenchymatous tissue typically present in stemwood). Pine root centers are marked by primary xylem. Roots typically have several primary resin canals grouped in the center near the primary xylem and generally do not develop heartwood (figs. 13-18 right, 13-19).

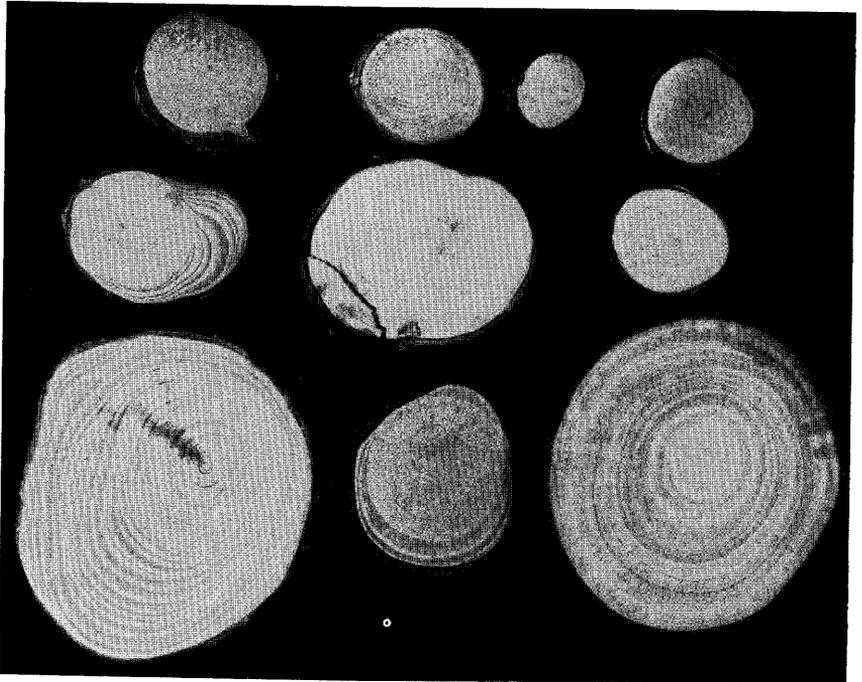
Cross sectional shapes of southern pine roots may vary substantially from circular (fig. 13-19). Lateral roots, particularly near their junction with the stem, frequently are elliptical—with long axis vertical. In these root sections the primary xylem may be eccentric. Observations by Pryor (1937) on Monterey pine (*Pinus radiata* D. Don), and by Fayle (1968) on red pine (*Pinus resinosa* Ait.), have indicated that the primary xylem is first near the lower surface of the root, and then—further out on the root—near the top (fig. 13-20). Beyond about 3 feet from the stump, the primary xylem may be nearly centered, although eccentric

³ The text under this heading is based on work done by E. T. Howard in preparation for her study FS-SO-3201-1.37; the photos are also from this study. (See text footnote ².)



F-520955

Figure 13-18.—(Left) Cross-section from large shortleaf pine root. Walls of earlywood and latewood cells are of equal thickness and growth increments are marked only by differences in radial dimensions. Scale mark shows 100 μ m. (Right) Cross-section from center of longleaf pine root. Pith is absent; primary resin canals are grouped at center of the root. Scale shows 0.5mm.



F-520956
 Figure 13-19.—Slices from roots of the various southern pines, showing eccentric growth and great variability in growth rings. The largest root shown measures $3\frac{1}{4}$ inches in diameter.

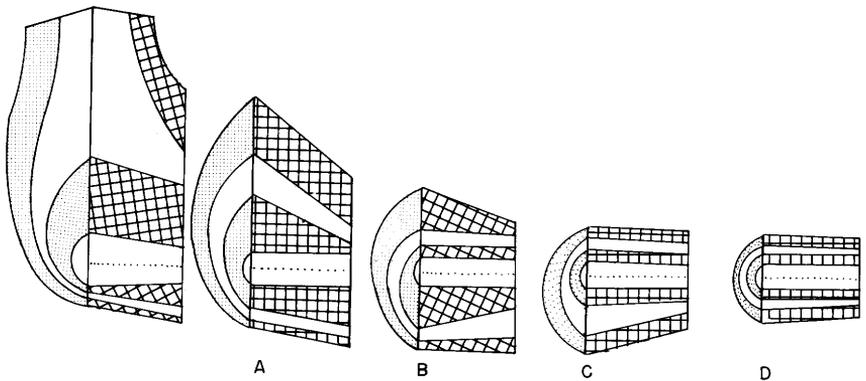


Figure 13-20.—Change in distribution of growth in basal portion of a main lateral root in red pine. Initially the distribution is more or less even, as shown in the unshaded central portion. Then (inner shading) near the stump, growth is greatest on top (A) and, further along, on the bottom (B), and variably even for the rest of the outward portion of the root. As the tree enlarges, the pattern of distribution progresses slightly along the root so that in time (outer shading) growth at (B) becomes greatest on top and at (C) on the bottom; at (D) and beyond, it is variable. It is likely that comparable variations are present in southern pine lateral roots. (Drawing after Fayle 1968, p. 25.)

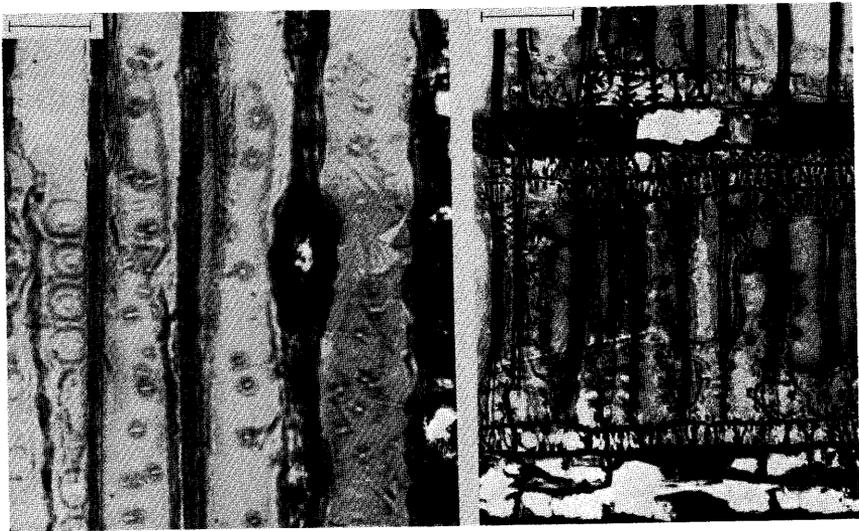
growth may continue to alternate between top and bottom for the length of the lateral root (Fayle 1968, p. 26).

Discontinuities and indistinct rings make root age determinations difficult and unreliable. Except near the base, there may be little or no correlation between root and stem growth patterns. Growth rings are often extremely narrow, but wide rings may be found (fig. 13-19).

The outer portions of large-diameter roots may or may not have well-defined growth rings (fig. 13-19). Distinct bands of latewood are sometimes found; more often, growth increments are distinguished only by several rows of radially flattened cells, whose walls may be no thicker than those of the earlywood (fig. 13-18 left). The lack of definition between most annual rings in southern pine roots all 12 months of the year, as observed by Turner (1936) and Reed (1939).

Orderly structure of roots is often disrupted by offshoots; spiral grain occurs frequently, and compression wood is sometimes present.

In minute structure, also, rootwood differs from stemwood. The frequency, size, and distribution of bordered pits in tracheid walls is more variable in roots than in stemwood. Tiny bordered pits (about 8 μm . in diameter) are spaced along the entire length of some root tracheids on both radial and tangential walls. Although they are about the same size as ray tracheid pits, most of them are not connected with rays. Their slitlike apertures are sometimes almost perpendicular to the long axis of the tracheid, indicating a large fibril angle in such cells (fig. 13-21 left).



F-520957

Figure 13-21.—(Left) Bordered pits of several sizes in tangential section of longleaf pine rootwood. Alignment of slit-like apertures of smaller pits indicates a large fibril angle in these cells. Scale mark shows 50 μm . (Right) Two rays in radial section of loblolly pine rootwood joined by abnormally shaped perpendicular ray tracheids. Scale mark shows 100 μm .

Although triseriate arrangement of the larger radial pits is found only occasionally in southern pine stemwood, tracheids with three or four pits abreast are not unusual in roots. Some cells with wide lumens, however, may have uniseriate pitting. Frequently radial pits are irregularly arranged within the cell. Crassulae may or may not be present.

Tangential pitting of tracheids is more abundant in rootwood than in stemwood. Profuse minute pits may be found in some areas of both earlywood and latewood in roots; elsewhere, however, tangential pits may be sparse, absent, or of normal size.

Rootwood rays and resin canals are generally similar in size and structure to those of stemwood. Along ray margins, however, abnormally shaped ray tracheids, elongated perpendicular to the rays, are more frequent and exhibit a greater degree of deformation than in juvenile stemwood (fig. 13-21 right). Many parenchyma cells contain darkly stained contents. Although parenchyma with thickened lignified walls occur frequently in the stem, virtually all parenchymatous cells of rootwood are thin-walled.

TRACHEID DIMENSIONS

Fayle (1968) reviewed the literature on tracheid dimensions in rootwood of conifers, and described his observations on red pine and Scotch pine (*Pinus sylvestris* L.). The only reference in the literature to tracheid length in rootwood of southern pine, however, is that of Gerry (1915), who noted that tracheids in longleaf pine roots were as long or longer than those in the stem.

To obtain additional data specific to the southern pines, Manwiller⁴ examined 20 southern pine root systems (species not identified but probably a mixture of shortleaf, loblolly, and longleaf pines) uprooted during highway construction in central Louisiana. The trees were from 12 to 89 years of age; most were 20 to 45. Stump tracheids drawn from chipped wedges cut 18 to 24 inches above ground level were compared to root tracheids taken from a representative sample chipped from disks from all root orientations—horizontal to vertical—and from various root sizes. Two hundred tracheids from each stump, and 200 from each root system were measured. Rootwood tracheids were one-third longer, and one-third larger in diameter, and had walls 18 percent thinner than stemwood tracheids sampled at stump height; rootwood tracheid lumens were nearly two-thirds larger than those of stumpwood tracheids, as follows:

<u>Tracheid dimension</u>	<u>Rootwood</u>	<u>Stumpwood</u>
Length, mm.	3.99	2.97
Cell diameter, μm	52.48	38.76
Lumen diameter, μm	41.69	25.66
Wall thickness, μm	5.40	6.55

⁴ Manwiller, F. G. Fiber dimensions in rootwood of southern pine. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.34 dated December 31, 1970.

All rootwood dimensions differed significantly (0.01 level) from stumpwood dimensions in all 20 trees sampled. Linear regression analysis of the data from this sampling failed to show a significant relationship between any root tracheid dimension and its stumpwood counterpart.

Within one root system taken from a tree measuring 8.1 inches in diameter and 16 years of age at stump height, trends were observed along the vertical taproot and along other roots of three orientations: horizontal, oblique, and vertical; these latter roots were sinkers from laterals. At each of several sample points along the roots, 200 tracheids from macerated disks were measured. Lateral roots were sampled to a 28-inch length, the taproot to a length of 25 inches.

Tracheids tended to be longest in horizontal roots, followed by the taproot, then by other vertical roots; they were shortest in oblique roots (fig. 13-22). Their length increased slightly with distance from origin in horizontal and oblique roots, but remained relatively constant in vertical roots. In the taproot, tracheid length increased to a maximum and then decreased irregularly with distance below the ground surface.

Cell diameter increased with distance along horizontal and vertical roots and decreased in oblique roots. In the taproot, cell diameter increased to a maximum and then decreased (fig. 13-22).

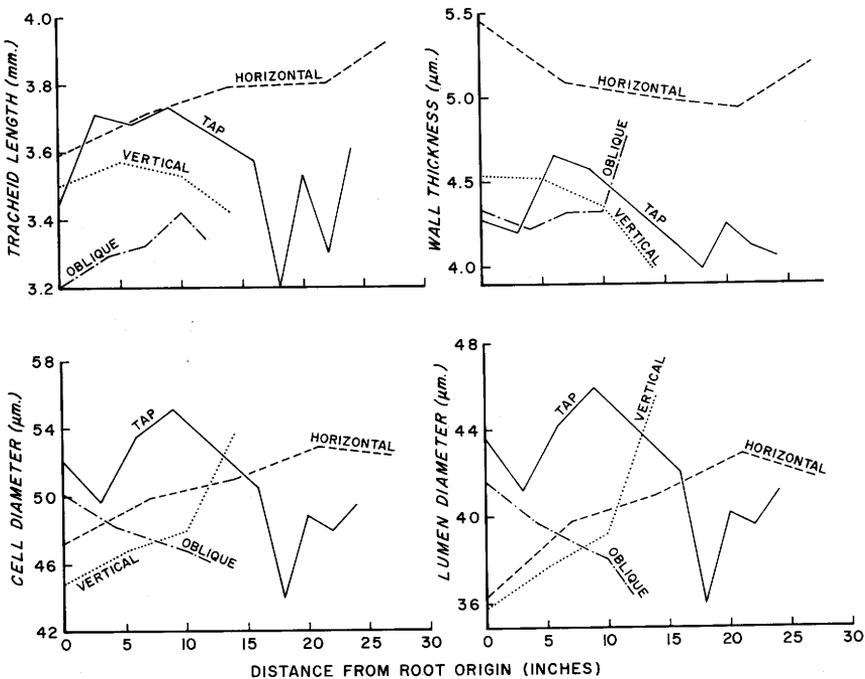


Figure 13-22.—Tracheid dimensions along the length of southern pine roots. Data are based on one taproot and two horizontal laterals, two verticals off lateral, and two oblique roots. Each taproot point is the average of 200 tracheid measurements; for the other roots, each point is the average of 400 observations. (Drawing after Manwiller³.)

Tracheids in horizontal roots had thicker walls than those of the other three orientations. In the taproot, wall thickness reached a maximum about 6 inches below the attachment point of major laterals and then decreased. Tracheids in the other vertical roots decreased in cell-wall thickness with increasing distance from their connections to laterals. Wall thickness in oblique roots increased along their lengths (fig. 13-22).

Lumen diameter in the taproot followed the trend of the other dimensions by increasing to a maximum and then decreasing. Lumen diameter increased with length in other vertical roots, but decreased in oblique roots. In the horizontal roots lumen diameter increased with length to a maximum at 21 inches in a pattern similar to that of cell diameter (fig. 13-22).

In the taproot, all cellular dimensions observed increased to a maximum 6 to 9 inches below the attachment point of major laterals and then decreased in the parts more distant from ground level (fig. 13-22).

13-4 CHEMICAL CONSTITUENTS

The literature contains virtually no information on the chemical constituents of southern pine rootwood except as related to naval stores steam-distilled from old-growth longleaf pine rootwood (sec. 28-1).

To provide some data on chemical constituents, Howard² uprooted three 22-year-old slash pines growing in central Louisiana on well-drained sandy loam soil in an unthinned plantation (6- by 8-foot spacing); before they were uprooted with a bulldozer, lateral roots were severed by a 30-inch-deep circular trench at a radius of 3 feet. Dimensions of each tree are given in table 13-4.

The uprooted portion of the root system from each tree—including a 6-inch-high stump—was analyzed for chemical content. The rootwood analysis was compared to that of stemwood representative of the portion from 6-inch stump height to a 4-inch top, and to branchwood. Howard's data are summarized in table 13-5.

13-5 MOISTURE CONTENT

Howard's² data on the three slash pine trees previously described provide an idea of the moisture content of roots compared to other tree parts; trees were felled in early summer of 1971. The data are summarized as follows (expressed as percent of unextracted oven-dry weight):

<u>Tree part</u>	<u>Moisture content</u>
	<i>Percent</i>
Needles	154
Top	153
Stem	116
Branches	115
Roots	111
Bark	67

TABLE 13-5.—*Chemical composition of rootwood compared to that of other tree parts; average for three 22-year-old slash pine trees.*

Component	Roots	Top	Branches	Stem	Bark	Needles
	----- <i>Percent</i> -----					
Extractives ^{1, 3}	11.7	11.0	13.6	9.1	13.0	26.2
Alpha-cellulose ^{2, 4}	44.6	41.5	36.9	51.1	23.7	42.5
Hemicellulose ^{2, 4}	25.6	31.2	33.7	26.8	24.9	22.3
Lignin ^{2, 5}	31.3	32.5	35.1	27.8	49.9	37.7
Ash ^{1, 6}	1.6	.8	1.2	.3	.9	2.4

¹ Percent of unextracted, oven-dry weight.

² Percent of extractive-free oven-dry weight.

³ TAPPI Standard T6 os-59.

⁴ Erickson (1962) sodium chlorite method.

⁵ Modified hydrolysis procedure of: Moore, W. E., and Johnson, D. B. 1967. Procedures for the chemical analysis of wood and wood products. USDA Forest Serv. Forest Prod. Lab., Madison, Wis. By this method other acid-insoluble substances would also be reported as "lignin".

⁶ Nitrated, then ashed at 480° C. for 6 hours.

13-6 MECHANICAL AND PHYSICAL PROPERTIES

Because rootwood cell walls are thin, extractive-free rootwood is lower in specific gravity and has less strength than stemwood.

SPECIFIC GRAVITY

Howard's² data on the specific gravity of rootwood from the three slash pines just described (see also table 13-4) are summarized and compared with those of other tree parts as follows (basis of green volume and oven-dry weight):

Tree part	Three-tree average	
	Unextracted	Extracted
Stemwood to a 4-inch top.....	0.47	0.43
Needles.....	.45	.33
Branches.....	.40	.35
Top.....	.38	.34
Rootwood to a 6-inch stump.....	.38	.34
Bark.....	.32	.28

STRENGTH

No data specific to southern pine rootwood are published. Fegel (1941), however, has reported strength properties of rootwood of a variety of coniferous trees.

fers including white pine (*Pinus strobus* L.) and red pine, and compared them to those of stemwood and branchwood. He concluded that rootwood in conifers is weaker in all respects than wood from stems and branches.

13-7 UTILIZATION

Roots of young pine trees are virtually unutilized. Old-growth longleaf pine rootwood, however, has long been a source of steam-distilled naval stores (see sec. 28-1). The extracted rootwood has also been used for roofing felt and insulating board. Because of low pulp yield and strength, however, chemical pulping of extracted rootwood chips for paper has seldom been done commercially. Kress and Mosher (1943) reviewed the literature on the subject; they attributed the low yields (30 percent on the basis of moisture-free chips) and low strength (about 50 percent of that of normal kraft pulp) achieved in their own experiments to a degraded condition of the rootwood prior to solvent extraction. They also concluded that extractives in the rootwood caused a modification in the mechanism of pulping, because wood containing extractives gave lower pulp yield and strength than extractive-free wood. The fibers of pulps obtained from rootwood hydrated immediately on contact with water but did not develop normal strength on beating. In short, early attempts to pulp old-growth longleaf pine rootwood—commonly harvested after 25 years or more in the ground—were discouraging. Since 1968, however, a mill in Riceboro, Georgia has found it feasible to utilize extracted longleaf pine stumpwood as a substantial portion (up to 30 percent) of their wood supply for kraft linerboard (Davis 1971).

With the passing of the virgin longleaf timber and the reestablishment of the pineries of the South, it now seems timely to reevaluate stumpwood and rootwood of young trees of the other major species. Because of their form, it is likely that roots can only be used if first chipped. Extractive content in roots of young pines is relatively low, so that chemical utilization is not likely; if properly mixed with other fibers, however, thin-walled, long rootwood tracheids might be advantageously used in some fiberboards or pulps. Gleaton and Saydah (1956) reported that good kraft pulp was made from unextracted stumpwood and rootwood of a 46-year-old longleaf pine. In an extension of these studies, Sproull et al. (1957) found that the stump and taproot of two slash pines and one longleaf pine yielded kraft pulp with nearly double the burst strength of similar pulp from matched stemwood; tear strength of the pulp from stump and taproot, however, was about one-third less than that from stem pulp. More recently, the good results obtained by Keays and Hatton (1971) in their studies of kraft pulping of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) roots should encourage expanded research on southern pine roots.

There is little information on the weight of below-ground parts of southern pine trees. For the closely related species of Monterey pine, Will (1966) reported that roots larger than 1/2-inch in diameter, together

with the stump, comprised nearly 10 percent of the oven-dry weight of entire 18-year-old trees. As previously noted (table 13-4), Howard² found that the central root systems from three 22-year-old slash pines averaged 16.5 percent of total dry tree weight (including roots, stem, top, bark, branches, and needles), and 28.2 percent of the weight of merchantable stemwood. Commercial utilization of this potentially large source of fiber will depend mainly on the economics of harvesting entire trees with roots attached.

Should demand for fiber require it, new techniques could probably be developed for harvesting the central mass of root systems from currently plentiful 20- to 30-year-old pines. The stem provides a convenient handle whereby small trees can be uprooted by sheer force; vibration of the stem—as in piling withdrawn by machinery—might reduce forces required, and would perhaps shake encrusting material loose from much of the root system. Alternatively, stems could first be sheared near ground level; in a secondary operation, lateral roots in the top 30 inches of soil could be severed by mechanically shearing a slit or routing a narrow trench concentric to the stem at a radius of perhaps 18 inches. This would be followed by plucking the root system from the ground with grappling tongs or a bulldozer blade. Stump bulldozers in current use do not require trenching for reasonably effective removal; the amount of lateral roots they extract is variable, however.

Freeing stumpwood and rootwood of rocks, dirt, and bark, will be a major problem; water jets might clean the wood effectively. Chipping of roots and stumpwood may not be such a difficult problem. When trimmed, the central root system of many young pines has a stout "carrot" shape and approximates in volume and green weight the butt 5-foot stem bolt. Roots of such shape should be chippable with a standard disk-type chipper.

13-8 LITERATURE CITED

- Addoms, R. M.
1950. Notes on the structure of elongating pine roots. *Amer. J. Bot.* 37: 208-211.
- Allen, R. M.
1967. Influence of the root system on height growth of three southern pines. *Forest Sci.* 13: 253-257.
- Ashe, W. W.
1915. Loblolly or North Carolina Pine. *N.C. Geol. and Econ. Surv. Bull.* 24, 176 pp.
- Barney, C. W.
1947. A study of some factors affecting root growth of loblolly pine (*Pinus taeda* L.). D. F. Thesis. Duke Univ., Durham, N.C. 125 pp.
- Barney, C. W.
1951. Effects of soil temperature and light intensity on root growth of loblolly pine seedlings. *Plant Physiol.* 26: 146-163.
- Bilan, M. V.
1960. Root development of loblolly pine seedlings in modified environments. Stephen F. Austin State Coll. *Forest. Dep. Bull.* 4, 31 pp.
- Box, B. H.
1967. A study of root extension and biomass in a six-year-old pine plantation in southeast Louisiana. Ph.D. Thesis. Duke Univ. Sch. Forest., Durham. 178 pp.

- Broadfoot, W. M.
1951. Forest planting sites in north Mississippi and west Tennessee. USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap. 120, 15 pp.
- Coile, T. S.
1937. Distribution of forest tree roots in North Carolina Piedmont soils. J. Forest. 35: 247-257.
- Copeland, O. L.
1952. Root mortality of shortleaf and loblolly pine in relation to soils and littleleaf disease. J. Forest. 50: 21-25.
- Davis, W. E.
1971. Utilization of stumpwood saves 100,000 cords per year of pulpwood. Pulp and Pap. 45(13): 111-112.
- Duncan, W. H.
1941. A study of root development in three soil types in the Duke Forest. Ecol. Monogr. 11(2): 143-164.
- Erickson, H. D.
1962. Some aspects of method in determining cellulose in wood. TAPPI 45(9): 710-719.
- Fayle, D. C. F.
1968. Radial growth in tree roots. Univ. Toronto Tech. Rep. 9, 183 pp.
- Fegel, A. C.
1941. Comparative anatomy and varying physical properties of trunk, branch, and root wood in certain northeastern trees. N.Y. State Coll. Forest. at Syracuse Univ. Tech. Pub. 55, pp. 5-20.
- Ferrill, M. D., and Woods, F. W.
1966. Root extension in a longleaf pine plantation. Ecology 47: 97-102.
- Gerry, E.
1915. Fiber measurement studies; length variations: where they occur and their relation to the strength and uses of wood. Science 41: 179.
- Gilmore, A. R.
1962. Root growth of transplanted loblolly pine (*Pinus taeda* L.) seedlings in relation to chemical root reserves. Ill. State Acad. Sci. Trans. 55: 38-41.
- Gilmore, A. R.
1965. The apparent source of a root growth stimulus in loblolly pine seedlings. Ill. Agr. Exp. Sta. Forest. Note 112, 4 pp.
- Gleaton, E. N., and Saydah, L.
1956. Fiber dimensions and paper-making properties of the various portions of a tree. TAPPI 39(2): 157A-158A.
- Greene, G. E.
1953. Soil temperatures in the South Carolina Piedmont. USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap. 29, 16 pp.
- Gruschow, G. F.
1959. Observations on root systems of planted loblolly pine. J. Forest. 57: 894-896.
- Heyward, F.
1933. The root system of longleaf pine on the deep sands of western Florida. Ecology 14: 136-148.
- Hough, W. A., Woods, F. W., and McCormack, M. L.
1965. Root extension of individual trees in surface soils of a natural longleaf pine-turkey oak stand. Forest Sci. 11: 223-242.
- Huberman, M. A.
1940a. Normal growth and development of southern pine seedlings in the nursery. Ecology 21: 323-334.
- Huberman, M. A.
1940b. Studies in raising southern pine nursery seedlings. J. Forest. 38: 341-345.
- Jorgensen, J. R.
1968. Root growth of direct-seeded southern pine seedlings. USDA Forest Serv. Res. Note SO-79, 7 pp. South. Forest Exp. Sta., New Orleans, La.
- Kaufman, C. M.
1968. Growth of horizontal roots, height, and diameter of planted slash pine. Forest Sci. 14: 265-274.
- Keays, J. L., and Hatton, J. V.
1971. Complete-tree utilization studies. I. Yield and quality of kraft pulp from the components of *Tsuga heterophylla*. TAPPI 54: 99-104.
- Korstian, C. F., and Coile, T. S.
1938. Plant competition in forest stands. Duke Univ. Sch. Forest. Bull. 3, 125 pp.

- Kostler, J. N., Brückner, E., and Biberriether, H.
1968. [The root system of forest trees.] 284 pp. Hamburg: Paul Parey.
- Kozlowski, T. T.
1943. Transpiration rates of some forest tree species during the dormant season. *Plant Physiol.* 18: 252-260.
- Kozlowski, T. T.
1949. Light and water in relation to growth and competition of Piedmont forest tree species. *Ecol. Monogr.* 19: 207-231.
- Kozlowski, T. T.
1964. Water metabolism in plants. 227 pp. N.Y.: Harper and Row.
- Kozlowski, T. T., and Scholtes, W. H.
1948. Growth of roots and root hairs of pine and hardwood seedlings in the Piedmont. *J. Forest.* 46: 750-754.
- Kramer, P. J.
1942. Species differences with respect to water absorption at low soil temperatures. *Amer. J. Bot.* 29: 828-832.
- Kramer, P. J.
1946. Absorption of water through suberized roots of trees. *Plant Physiol.* 21: 37-41.
- Kramer, P. J., and Bullock, H. C.
1966. Seasonal variations in the proportions of suberized and unsuberized roots in trees in relation to the absorption of water. *Amer. J. Bot.* 53: 200-204.
- Kramer, P. J., and Hodgson, R. H.
1954. Differences between mycorrhizal and nonmycorrhizal roots in loblolly pine. Eighth Int. Bot. Congr., Sect. 13, pp. 133-134. Paris.
- Kress, O., and Mosher, R. H.
1943. The pulping of extracted yellow pine wood chips. *Pap. Trade J.* 117(15): 29-34.
- Lenhart, D. Y.
1934. Initial root development of longleaf pine. *J. Forest* 32: 459-461.
- Little, S., and Somes, H. A.
1964. Root systems of direct-seeded and variously planted loblolly, shortleaf, and pitch pines. USDA Forest Serv. Res. Pap. NE-26, 13 pp. Northeast. Forest Exp. Sta., Upper Darby, Penn.
- McQuilken, W. E.
1935. Root development of pitch pine, with some cooperative observations on shortleaf pine. *J. Agr. Res.* 51: 983-1016.
- Maki, T. E., and Marshall, H.
1945. Effects of soaking with indolebutyric acid on root development and survival of tree seedlings. *Bot. Gaz.* 107: 268-276.
- Marth, P. C., Audia, W. V., and Mitchell, J. W.
1956. Effects of gibberellic acid on growth and development of plants of various genera and species. *Bot. Gaz.* 118: 106-111.
- Marx, D. H.
1967. Ectotrophic mycorrhizae as biological deterrents to pathogenic root infections by *Phytophthora cinnamomi*. Fourteenth IUFRO Congr., Part V, Sect. 24, pp. 172-181. Munich.
- Mirov, N. T.
1967. The genus *Pinus*. 602 pp. N.Y.: Ronald Press Co.
- Miller, L., and Woods, F. W.
1965. Root-grafting in loblolly pine. *Bot. Gaz.* 126: 252-255.
- Monk, C. D.
1966. Root-shoot dry weights in loblolly pine. *Bot. Gaz.* 127: 246-248.
- Pessin, L. J.
1928. Mycorrhiza of southern pines. *Ecology* 9: 28-33.
- Pessin, L. J.
1935. Root habits of longleaf pine seedlings. USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap. 43, 7 pp.
- Pessin, L. J.
1938. Effect of soil moisture on the rate of growth of longleaf and slash pine seedlings. *Plant Physiol.* 13: 179-189.
- Pessin, L. J.
1939. Root habits of longleaf pine and associated species. *Ecology* 20: 47-57.
- Pritchett, W. L., and Robertson, W. K.
1960. Problems relating to research in forest fertilization with southern pine. *Soil Sci. Soc. Amer. Proc.* 24: 510-512.
- Pryor, L. D.
1937. Some observations on the roots of *Pinus radiata* in relation to wind resistance. *Aust. Forest.* 2: 37-40.

- Reed, J. F.
1939. Root and shoot growth of shortleaf and loblolly pines in relation to certain environmental conditions. Duke Univ. Sch. Forest. Bull. 4, 52 pp.
- Schultz, R. P., and Woods, F. W.
1967. The frequency and implications of intraspecific root-grafting in loblolly pine. Forest Sci. 13: 226-239.
- Shoulders, E.
1959. Root-pruning boosts longleaf survival. USDA Forest Serv. Tree Planters' Notes 36, pp. 15-19.
- Shoulders, E.
1963. Root-pruning southern pines in the nursery. USDA Forest Serv. Res. Pap. SO-5, 6 pp. South. Forest Exp. Sta., New Orleans, La.
- Snyder, E. B.
1961. Racial variation in root form of longleaf pine seedlings. Sixth South. Forest Tree Impr. Conf. Proc. 1961: 53-59.
- Sproull, R. C., Parker, R. B., and Belvin, W. L.
1957. Whole tree harvesting. Forest Prod. J. 7: 131-134.
- Stransky, J. J., and Wilson, D. R.
1967. Soil moisture and texture affect root and shoot weights of transplanted pine seedlings. USDA Forest Serv. Res. Note SO-62, 3 pp. South. Forest Exp. Sta., New Orleans, La.
- Sutton, R. F.
1969. Form and development of conifer root systems. Commonwealth Forest Bur. Tech. Commun. 7, 131 pp. Oxford, England.
- Turner, L. M.
1936. Root growth of seedlings of *pinus echinata* and *Pinus taeda*. J. Agr. Res. 53: 145-149.
- Ursic, S. J.
1963. Modifications of planting technique not recommended for loblolly on eroded soils. USDA Forest Serv. Tree Planters' Notes 57, pp. 13-17.
- Wahlenberg, W. G.
1946. Longleaf pine. 429 pp. Wash., D. C.: Charles Lathrop Pack Forest. Found. in coop. with USDA Forest Serv.
- Wahlenberg, W. G.
1960. Loblolly Pine. 603 pp. N.C.: Duke Univ. Sch. Forest.
- Wakeley, P. C.
1935. Artificial reforestation in the southern pine region. USDA Tech. Bull. 492, 114 pp.
- Wakeley, P. C.
1954. Planting the southern pines. USDA Agr. Monogr. 18, 233 pp.
- Wakeley, P. C.
1965. The less obvious problems of nursery stock production. Nursery Soil Improvement Sess., pp. 77-92. Syracuse Univ. Coll. Forest.
- Wenger, K. F.
1952. Effect of moisture supply and soil texture on the growth of sweetgum and pine seedlings. J. Forest. 50: 862-864.
- Wenger, K. F.
1955. Light and mycorrhiza development. Ecology 36: 518-520.
- White, E. H., Pritchett, W. L.
1970. Water table control and fertilization for pine production in the flatwoods. Univ. Fla. Agr. Exp. Sta. Bull. 743, 41 pp.
- Will, G. M.
1966. Root growth and dry-matter production in a high-producing stand of *Pinus radiata*. New Zeal. Forest Serv. New Zeal. Forest. Res. Notes 44, 15 pp.
- Woods, F. W.
1959. Slash pine roots start growth soon after planting. J. Forest. 57: 209.
- Zahner, R.
1956. Root development of thinned pines. USDA Forest Serv. South. Forest Exp. Sta. South. Forest. Notes 101.
- Zon, R.
1905. Loblolly pine in eastern Texas, with special reference to the production of cross-ties. USDA Forest Serv. Bull. 64, 53 pp.

14

Needles

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14

Needles¹

The utilization potential of southern pine needles has not been intensively explored, and data on their properties are meager.

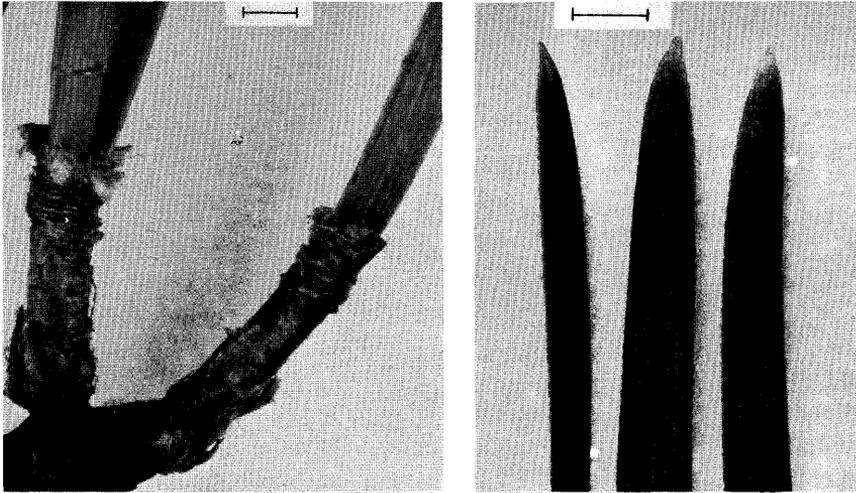
14-1 ANATOMY AND FORMATION

As noted in chapter 4, water from tree roots is conducted upward in the outer portion of the woody stem by tensions created through transpiration in the leaves, and is distributed to the cambial cells and to other living cells by osmotic forces. Food mainly in the form of sugars, photosynthesized in the leaves, is transported through the living inner bark to the cambium and to the horizontal rays.

The gross structure of foliage of each species is illustrated in figures 3-21 through 3-30. Adult leaves of the southern pines are normally persistent for 2 to 3 years. They are needlelike, have serrated edges, and are borne in clusters of two to five near the apex of short shoots; a sheath of scales surrounds the base of each cluster or **fascicle** (fig. 14-1).

Rudimentary tissues for a fascicle of needles and its sheath scales form in midsummer and then become dormant. When active growth begins the following spring, the elongating leaves perforate their enclosing layers of scales. Needle growth is by cell division at the base. The sheath scales continue to grow from their bases after the leaves have emerged. They serve as a strengthening splint to support the weight of the elongating needles and prevent desiccation of the young parts, which are as yet without a protective cuticle. After needles have matured and developed mechanical and epidermal tissues, the sheaths are no longer necessary and cease growth (Doak 1935). In southern pines, the fascicle sheath is retained throughout the life of the needle, but it becomes wrinkled and progressively shortened. First-year needles may thus be distinguished from older ones by the length and condition of the fascicle sheath (DeVall 1940). Since the base is cylindrical, the number of needles in a fascicle determines the needle shape—those in clusters of two have semicircular cross sections; those in fascicles of three or more are pie shaped, with a sharp central angle and a

¹ Chapter 14 is adapted from: Howard, E. T. Some observations on southern pine needles as related to utilization. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.36 dated April 15, 1971.

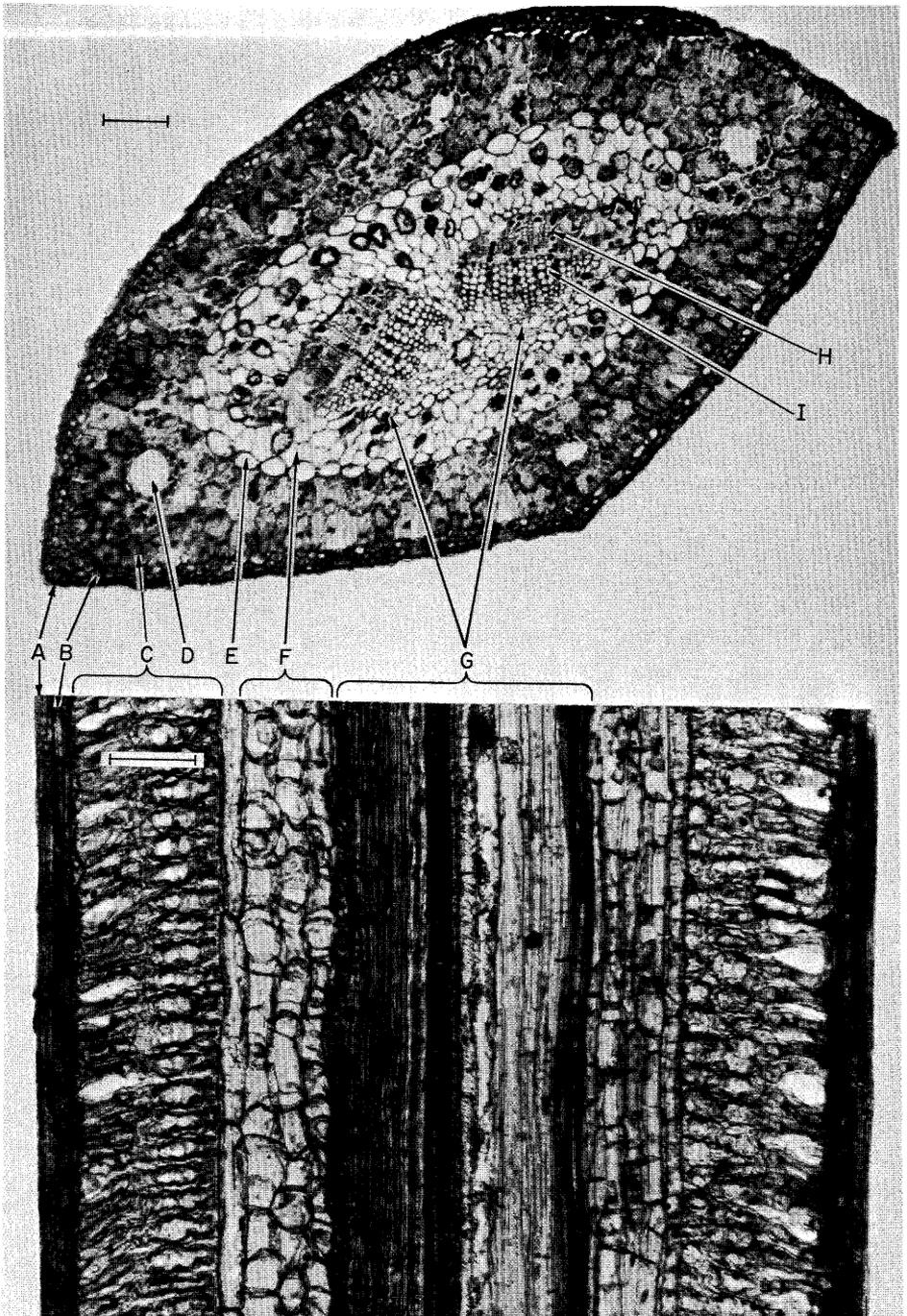


F-520958
 Figure 14-1.—(Left) Spruce pine twig with two clusters of needles, showing wrinkled fascicle sheaths. (Right) Tips of shortleaf pine needles (side, dorsal, and ventral views). Longitudinal rows of stomata appear as white dots on all surfaces. Fine toothlike serrations are visible along the sides. Scale marks show 1 mm. (Photos from Howard¹.)

rounded outer surface. More detailed information on needle formation may be found in Masters (1891), Soar (1922), Esau (1965), and Mirov (1967).

A pine needle has a hard, fibrous outer shell, a delicate interior, and a fibrous central core. The various tissues are illustrated in figure 14-2. The outer protective layer, **epidermis**, is composed of somewhat elongated cells with a thick layer of waterproof cutin on the outside. Sunken **stomata** (figs. 14-1, 14-3) are arranged in longitudinal rows on all surfaces. These structures have openings which provide gaseous exchange with the atmosphere. Beneath the epidermis is the **hypoderm**—several compact layers of long, thick-walled, fiberlike cells, which give rigidity to the needle. The **mesophyll** is a fairly uniform tissue containing chlorophyll which is active in photosynthesis. Its thin-walled cells have peculiar involutions of the walls projecting into their lumens. They are arranged in transverse strata with intercellular spaces (fig. 14-2 bottom C). Resin canals (two to 10 in number) are located in the mesophyll. They extend the length of the needle but are not connected with resin canals of the stem. The resin canals are surrounded by thin-walled, secretory epithelial cells and long fiberlike cells.

The **endoderm**—a single layer of somewhat elongated cells with slightly thickened walls—forms a boundary between the mesophyll and the vascular portion of the needle (fig. 14-2E). Just inside the endoderm is the transfusion tissue, which surrounds each vascular bundle. The transfusion tissue contains thin-walled parenchyma cells and thick-walled tracheids of varying dimensions.



F-520959

Figure 14-2.—Cellular structure of southern pine needles. (Top) Cross section, pitch pine. (Bottom) Longitudinal section, longleaf pine. A, epidermis; B, hypoderm; C, mesophyll; D, resin canal; E, endoderm; F, transfusion tissue; G, vascular bundles; H, phloem; I, xylem. Scale marks show 0.1 mm. (Photos from Howard¹.)



F-520960

Figure 14-3.—Open stoma cut through the center in transverse needle section. A closed stoma and a resin canal are at the extreme right. A, subsidiary cell; B, guard cell; C, substomatal chamber; D, epidermis; E, hypoderm. Table-Mountain pine. (Photo from Howard¹.)

Two parallel vascular bundles in the center of each needle are characteristic of all hard pines including the southern pines; each bundle is comprised of **phloem** (toward the outer surface) and **xylem** (toward the fascicle axis). A vascular cambium separates the two tissues.

Figure 14-4 illustrates some of the cell types found in macerated southern pine needles. Of particular interest are the long fiberlike cells. In Howard's¹ observations of longleaf pine needles, these cells were mostly 1.2 to 3 mm. in length with occasional cells as long as 5.1 mm. The epidermal cells are much shorter; adherence of the outer layers (epidermis and hypoderm) makes chemical and mechanical separation rather difficult.

Internal morphology of needles has been used in numerous taxonomic and evolutionary classification systems, but it is only of supplementary value in identification of trees, as other characteristics are more obvious and reliable. Keys separating species by internal structure have been prepared by Masters (1904), Doi and Morikawa (1929), Sutherland (1934), and Harlow (1931). Mergen (1958, 1959) and Keng and Little (1961) found that needle anatomy aided in identification of putative hybrids. Others have examined intraspecies variation of internal characters (DeVall 1941; Little and Dorman 1954; Thorbjornsen 1961; Thames 1963; White



F-520961

Figure 14-4.—Macerated tissue of loblolly pine needles prepared by treatment with equal parts of glacial acetic acid and 6 percent hydrogen peroxide at 60° C. for 1 week. Thick-walled and thin-walled fibers as well as shorter cells are evident. Scale mark shows 1 mm. (Photo from Howard¹.)

and Beals 1963; Squillace 1966). Other work on southern pine needles includes descriptions of epidermal structure (Florin 1931) and internal structure (Mohr 1896; Dolivo 1948; Garcia 1963). Variation in the number and size of the needle resin ducts has been correlated with essential oil yield (Schorger 1916) and resistance to attack by needle-eating insects (Bennett 1954).

Length and number of needles per fascicle are of value in field identification. Needle characteristics were used in conjunction with other features in keys by Masters (1904), Pilger (1926), Fitzpatrick (1929), Dalli-

more and Jackson (1948), Small (1933), Coker and Totten (1937), Harrar and Harrar (1946), Little and Dorman (1952), and Ward (1963). Usual needle number and length are given below for each species.

<u>Pine species</u>	<u>Needles per fascicle</u>	<u>Length</u>
		<i>Inches</i>
Loblolly.....	Mostly 3	6 to 9
Longleaf.....	3	8 to 18
Pitch.....	3	3 to 5
Pond.....	3	6 to 8
Sand.....	2	2 to 3-½
Shortleaf.....	2, sometimes 3	3 to 5
Slash.....	2, 3	Over 5, usually 7 to 10
Spruce.....	2	About 3
Table-Mountain.....	2	1-½ to 3-½
Virginia.....	2	1-½ to 3

14-2 NEEDLE VOLUME

Since needles are retained on southern pine only 2 or 3 years, far more tonnage is dropped to the forest floor over a period of years than is retained on the trees.

WEIGHT PER TREE

Metz and Wells (1965) observed that needles comprised about one-third the total oven-dry weight of above-ground parts of 7-year-old loblolly pines; with older trees, the percentage was much less, e.g., 4.7 percent in a 9.6-inch, 21-year-old tree. Their data on 10 young loblolly pines from the Piedmont section of South Carolina follow:

<u>Tree age (years) and diameter at base</u>	<u>Height</u>	<u>Oven-dry weight of above-ground tree parts</u>	<u>Fraction of above-ground weight in needles, oven-dry</u>
<i>Inches</i>	<i>Feet</i>	<i>Pounds</i>	<i>Percent</i>
7 years			
2.8.....	8	4	38.0
2.8.....	10	6	43.3
4.1.....	11	13	29.8
4.3.....	13	20	29.5
5.0.....	17	29	26.5
8 years			
5.6.....	21	31	24.2
6.9.....	23	54	14.5
13 years			
8.3.....	36	96	9.7
21 years			
7.5.....	46	122	5.0
9.6.....	46	194	4.7

From the foregoing tabulation, a 6-inch loblolly pine carried about 8 pounds of needles (oven-dry).

Rogerson (1964) published formulas for estimating foliage weight of 25-year-old planted loblolly pine in Mississippi through correlation with diameter at breast height; from his computations (fig. 14-5), a 6-inch loblolly pine may carry about 4 pounds of needles, and an 11-inch tree may have close to 22 pounds, ovendry basis.

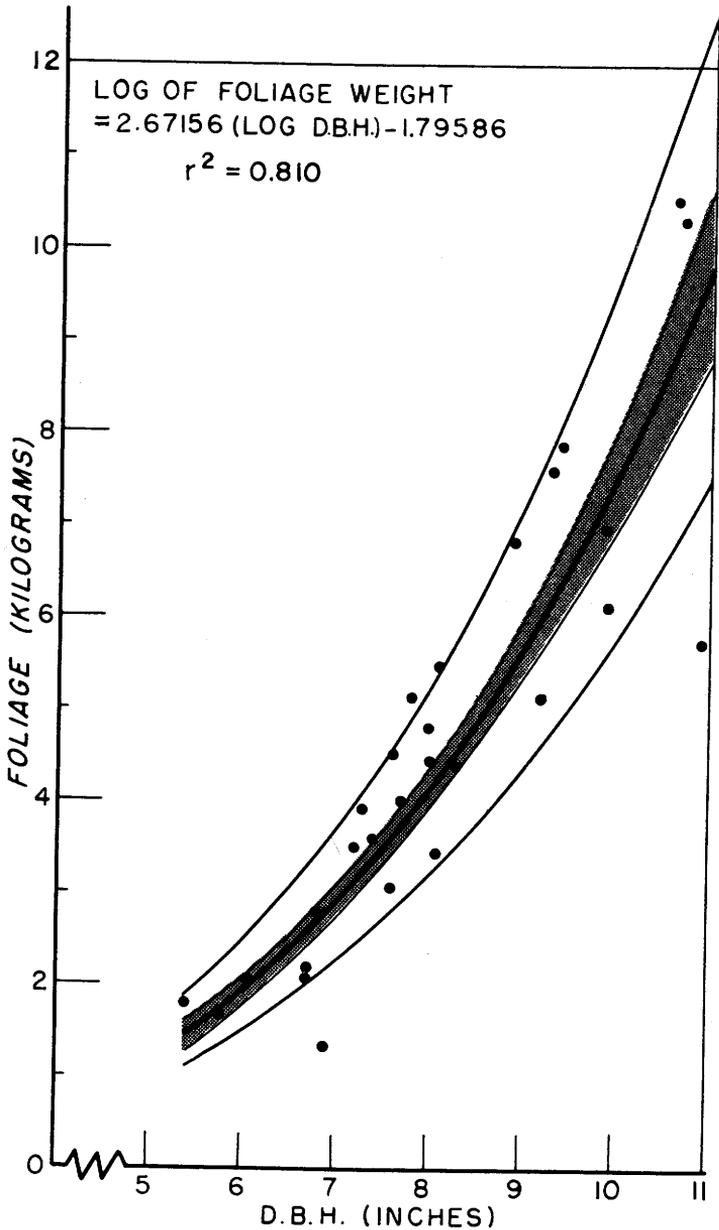


Figure 14-5.—Regression of ovendry foliage weight on tree diameter at breast height with 67-percent confidence bands for mean foliage weight of population (shaded band) and of individual observations (wide band). Loblolly pine. (Drawing after Rogerson 1964.)

Monk's (1966) study of the relationship between tree diameter at breast height and dry weight of roots, stems, and leaves of loblolly pine, yielded the linear equations shown in figure 14-6; from his data, a 6-inch tree carried about 16 pounds of needles (ovendry basis).

Wendel (1960) presented similar data for pond pine; from figure 14-7 it is evident that the pond pines he measured carried more foliage than the

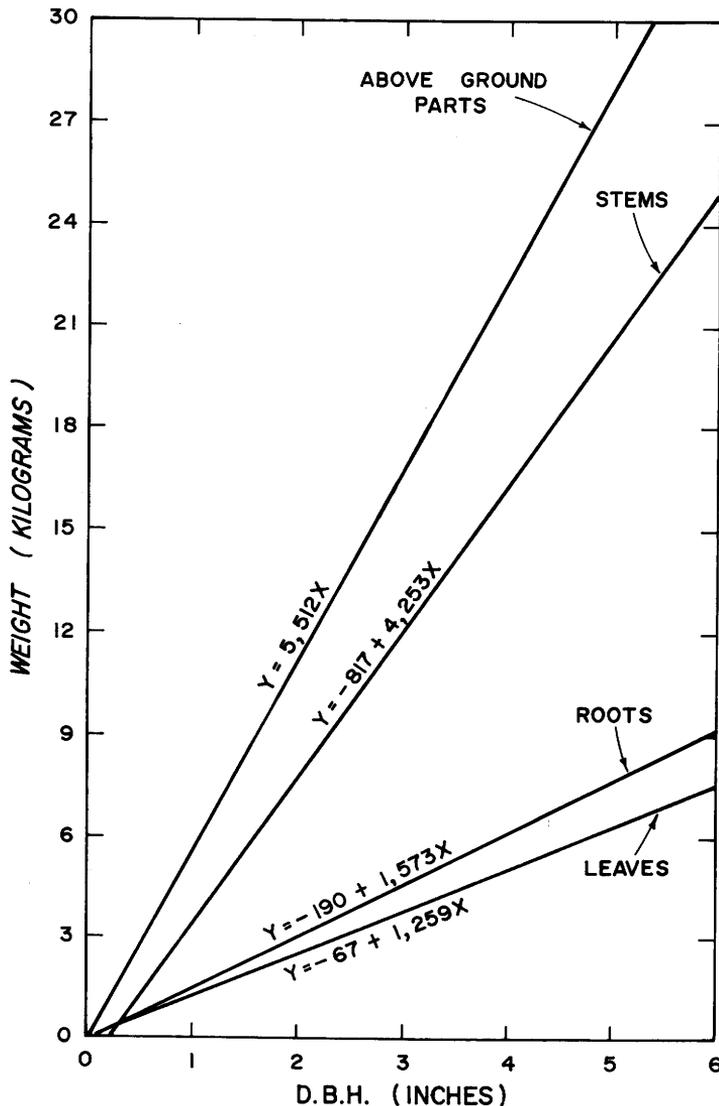


Figure 14-6.—Relationships between breast-height diameter (inches) of loblolly pine in Aiken County, N.C., and the ovendry weight (grams) of their leaves, roots, stems, and entire above-ground parts. Correlation coefficients for the four regression equations ranged from 0.92 to 0.96. Trees studied were 21 feet in height or shorter. (Drawing after Monk 1966.)

loblolly pines measured by Rogerson, i.e., 10 pounds on 6-inch trees and close to 30 pounds on 11-inch trees.

Loomis et al. (1966) found that the weight (pounds, dry) of winter foliage on shortleaf pine in southeast Missouri could be accurately estimated from diameter at breast height outside bark (D , inches) and ratio of live crown length to total tree height (C , percent) according to the following regression equation:

$$\text{Weight of dry foliage} = \frac{(D^{1.7 + .007D}) (C^{.98})}{125} \quad (14-1)$$

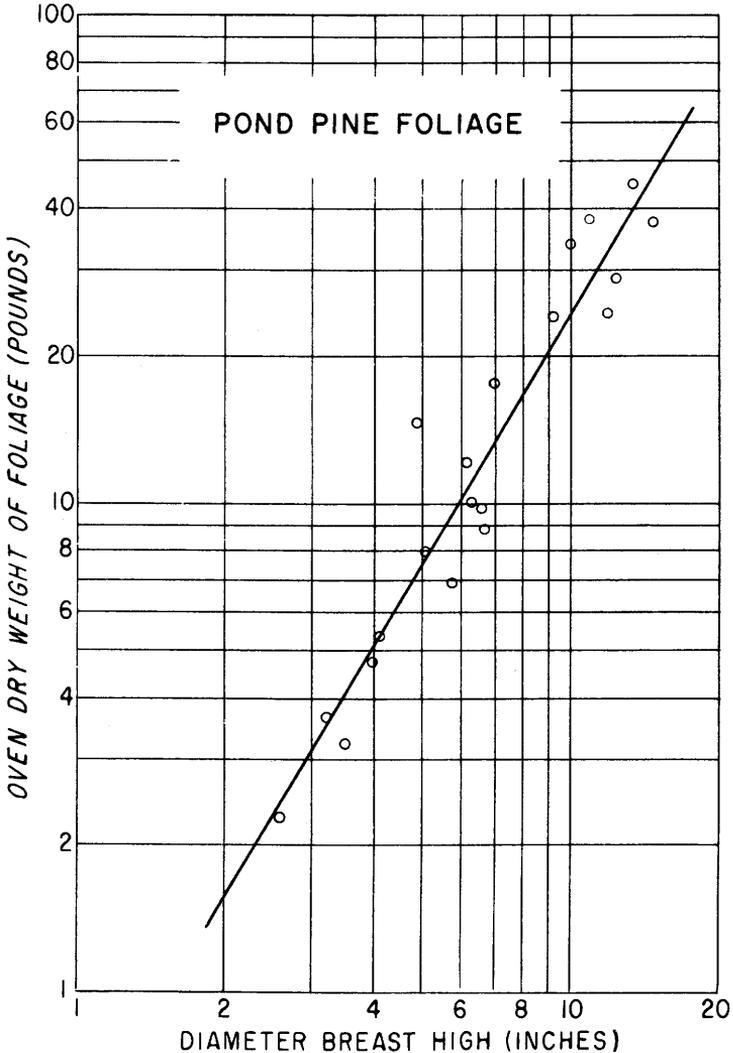


Figure 14-7.—Relation between the oven-dry weight of pond pine foliage and tree diameter at breast height. Weight of oven-dry foliage = $0.486 (\text{d.b.h.})^{1.697}$. (Drawing after Wendel 1960.)

This equation accounted for 99 percent of the observed variation, with standard error of the estimate of 0.08 pounds. From equation 14-1, computed weights of ovendry winter foliage were as follows:

Breast height diameter	Crown ratio, percent		
	30	50	70
<i>Inches</i>		<i>Pounds</i>	
3	1.5	2.4	3.4
6	5.1	8.4	12.0
9	11.0	18.0	25.0
12	19.0	31.0	43.0
15	30.0	49.0	68.0

Branches collected in September carried about 50 percent more foliage by weight than those measured in winter. From their data, summer foliage weight could be estimated by multiplying the winter weight by the factor 1.5; this ratio probably varies from year to year.

Lodewick (1931) found that irrigation of longleaf pine during a dry season increased needle length and that trees on fertilized sites had longer needles than unfertilized trees; needle diameter was not measurably affected by irrigation or fertilization.

In a study of three 22-year-old slash pines from an unthinned plantation in central Louisiana, Howard (see table 13-4) found that dry needle weight averaged about 4 percent of entire dry tree weight.

ANNUAL PRODUCTION

Boyer (1968) observed that in 45- to 60-year-old longleaf pine stands with nine to 47 trees per acre, an average of 13.2 cubic feet of wood per year was produced per thousand pounds of new needles (ovendry basis); annual needle production per tree ranged from 45 to 60 pounds and tended to be inversely correlated with number of trees per acre, as follows:

Trees per acre	Annual foliage produced per tree (ovendry)	Annual growth in stem volume per 1,000 pounds foliage
<i>Number</i>	<i>Pounds</i>	<i>Cubic feet</i>
9	69	14.6
18	46	14.4
26	48	12.5
36	46	12.7
47	45	11.7
—	—	—
Average 27	51	13.2

Since the ovendry weight of 13 cu. ft. of wood is about 500 pounds, these stands of longleaf pine annually produced about 2 pounds of needles for each pound of wood.

Heyward and Barnette (1936) found that Florida stands of longleaf and slash pines with 360 to 972 trees per acre produced 2,400 to 3,500 pounds of needles (ovendry) per acre.

Nelson et al. (1970) observed that dry matter production of young loblolly pines grown on 4- by 6-foot spacing on Mississippi bottomland was as follows:

<u>Tree age</u>	<u>Foliage</u>	<u>Bark</u>	<u>Wood</u>
<i>Years</i>	- - - - - Pounds per acre - - - - -		
4	2,280	1,140	2,170
5	4,610	2,800	6,570

Switzer et al. (1966) found that on a dry weight basis, annual production of loblolly pine foliage exceeded annual production of loblolly stemwood in most age classes and on most sites; in the important age classes between 10 and 30 years, however, production of foliage was approximately equal to that of stemwood.

<u>Tree age class</u>	<u>Poor sites</u>	<u>Good sites</u>
<i>Years</i>	-Pounds foliage per pound of stemwood-	
0-10	2.0	1.3
10-20	1.0	.7
20-30	1.3	.6
30-40	2.5	1.1
40-50	4.8	2.4
50-60	14.3	3.5

Metz (1952) observed annual needle fall (ovendry basis) in two natural stands and one plantation, as follows:

<u>Pine species</u>	<u>Age of stand</u>	<u>Basal area per acre</u>	<u>Needle fall per acre</u>
	<i>Years</i>	<i>Square feet</i>	<i>Pounds</i>
Loblolly (75 percent) and shortleaf (25 percent).....	20 to 25	102	4,476
Loblolly (planted).....	10	103	3,771
Shortleaf.....	30 to 40	124	2,938

At an assumed annual growth of 114 cu. ft. of wood (1.5 cords) in these pine stands, annual production of wood (about 3,600 pounds when ovendry) would be not much different than annual needle fall per acre.

Pine litter is resistant to decay and is only slightly attacked by insects; decomposition is therefore slow, and it accumulates on the soil surface. Heyward and Barnette (1936) observed that needles begin to disintegrate during the third year on the ground; by the end of the fifth year, they are reduced to fragments. A period of 8 to 12 years is necessary to establish an approximate balance between accumulation and decomposition.

Under pure pine stands, biological activity incorporates only small amounts of organic material into the mineral soil (Metz 1954).

14-3 PHYSICAL AND MECHANICAL PROPERTIES

Since pine needles have not generally been regarded as an industrial raw material, their physical and mechanical properties have not been studied thoroughly.

MOISTURE CONTENT

Metz and Wells (1965), in their study of young loblolly pines, observed no relationship between needle moisture content and location on the tree; neither did they find a relationship between needle age and moisture content.

Various investigators have reported a wide range of moisture contents (96 to 300 percent) in southern pine needles (table 14-1). It appears that needle moisture content is highest in the spring and lowest in the winter (Blair and Epps 1969), and that high soil moisture content is correlated with high moisture content in needles (Schopmeyer 1939).

Because moisture content in needles is dependent on soil moisture content, season of the year, and even time of day, it is difficult to interpret the physiological significance of needle moisture content. For utilization purposes, it is perhaps sufficient to know that the moisture content in fresh southern pine needles is generally in the range from 100 to 300 percent of oven-dry weight with average values near 150 percent.

LONGITUDINAL SHRINKAGE

Howard¹ measured longitudinal shrinkage in 20 needles sampled from single 35-year-old trees of the four major species. Length shrinkage from green to oven-dry, expressed as a percentage of green length, was as follows:

<u>Pine species</u>	<u>Longitudinal shrinkage</u>
	<i>Percent</i>
Loblolly -----	1.58
Longleaf -----	1.65
Shortleaf -----	1.85
Slash -----	2.31

Longitudinal shrinkage in needles is thus substantially greater than that in wood, which is usually less than 0.5 percent.

SPECIFIC GRAVITY

Howard¹ used a pycnometer to measure the specific gravity of 20 green needles from single trees of each of the four major species; results were as follows (basis of green volume and oven-dry weight):

<u>Pine species</u>	<u>Specific gravity</u>
Loblolly -----	0.34 to 0.45
Longleaf -----	.36 to .41
Shortleaf -----	.34 to .41
Slash -----	.35 to .42

TABLE 14-1.—*Moisture content in needles of the southern pines*

Species and description	Moisture content ¹	Reference
	<i>Percent</i>	
Loblolly		
Single 35-year-old tree.....	97	Howard (text footnote ¹)
416 5- and 21-year-old trees.....	107 to 142	McLemore et al. (1961)
Less than 1 year old.....	108	Metz and Wells (1965)
More than 1 year old.....	105	Metz and Wells (1965)
Soil moisture, 30 percent.....	189 ² to 223 ³	Schopmeyer (1939, p. 454)
Soil moisture, 15 percent.....	172	Schopmeyer (1939, p. 454)
Spring.....	300 ⁴	Blair and Epps (1969)
Winter.....	140 ⁴	Blair and Epps (1969)
Longleaf		
Single 35-year-old tree.....	112	Howard (text footnote ¹)
Pitch		
Several 25-year-old trees sampled throughout a year.....	134 to 165	Meyer (1928, 1932)
Shortleaf		
Single 35-year-old tree.....	122	Howard (text footnote ¹)
Soil moisture, 30 percent.....	197 ² to 232 ³	Schopmeyer (1939, p. 454)
Soil moisture, 15 percent.....	187	Schopmeyer (1939, p. 454)
Slash		
Single 35-year-old tree.....	121	Howard (text footnote ¹)

¹ Percent of oven-dry weight.

² Drought hardened.

³ Before drought hardening.

⁴ Values estimated from graph.

TENSILE STRENGTH

To determine tensile strength parallel to the needle axis, Howard ¹ conditioned 50 loblolly pine needles for 3 weeks at 50-percent relative humidity and 72° F. before evaluating 1-inch-long specimens cut at midlength from each needle. One-fourth inch of each end of a sample was sandwiched between two ½-inch squares of notecard and secured with epoxy glue, so that needle length under test was ½-inch. After loading to failure with grips moving at 0.004 inch per minute, cross-sectional area of each failed section was measured under a microscope. Results were as follows:

Property	Range	Average
Ultimate stress (p.s.i.).....	4,630 to 6,980	5,970
Maximum load (pounds)....	3.0 to 5.2	4.1
Modulus of elasticity (p.s.i.)..	167,400 to 277,800	220,300

These loblolly pine needles therefore had about one-half the ultimate tensile strength and one-eighth the modulus of elasticity of loblolly pine wood at 12-percent moisture content (see table 10-2).

HEAT OF COMBUSTION

Evaluation by Howard¹ of mixed samples containing equal weights of loblolly, longleaf, shortleaf, and slash pine needles indicated a heat of combustion of about 9,030 B.t.u. per oven-dry pound. Madgwick (1970) found an almost identical value (9,035 B.t.u. per oven-dry pound) for Virginia pine needles. Hough (1969) measured heat of combustion of needles from three other pine species with results as follows: loblolly, 8,900 B.t.u.; sand, 9,615 B.t.u.; and slash, 9,370 B.t.u. per oven-dry pound.

It appears, therefore, that the heat of combustion of oven-dry needles from southern pines is considerably higher than that of their wood (8,600 B.t.u. per oven-dry pound) but only slightly higher than that of their bark (8,900 B.t.u. per oven-dry pound).

SPECIFIC HEAT

The specific heats of oven-dry needles of three species have been published as follows:

<u>Pine species</u>	<u>Temperature of observation</u>	<u>Specific heat</u>	<u>Reference</u>
Loblolly.....	-20 to +20° C.	0.213	Schopmeyer (1939)
Pitch.....	-20 to +20° C.	.300	Meyer (1932)
Shortleaf.....	-20 to +20° C.	.208	Schopmeyer (1939)

There are no published data relating needle specific heat to temperature, but it is reasonable to assume a positive correlation as is the case with wood (fig. 9-15) and bark (fig. 12-27) of the southern pines.

14-4 CHEMICAL COMPOSITION

Since foliar analysis is an established technique for evaluating the nutritional status of trees, and because there has been commercial interest in needle oils, the literature contains some information on mineral and oil content of needles.

MINERAL CONTENT

Concentration of elements in foliage varies with the availability of soil nutrients, and with the season. Published data on inorganic constituents of southern pine needles are summarized in table 14-2.

The species apparently differ in their tendency to accumulate particular elements in their needles. Young (1948) found that total ash content for slash pine needles was only two-thirds that for loblolly grown on the same

site. The loblolly needles contained 10 times more silica than the slash pine leaves, and were much harder. Loblolly needles had much more calcium than slash pine needles, but considerably less magnesium and only half as much chlorine.

Green and dead needles differ in their content of certain elements. It is thought that a large percentage of the nitrogen, phosphorus, and potassium is translocated from the needles immediately before abscission (Wells and Metz 1963). In dead needles, Young (1948) found twice as much calcium and 20 percent more silica, but only one-fifth as much potassium and one-third as much phosphorus as in green needles; he observed approximately the same amount of magnesium in dead needles as in green. Dead needles analyzed by Wells and Metz (1963) contained about half as much potassium, phosphorus, and nitrogen, but the same amount of calcium as green needles. Metz (1954) estimated that annual leaf fall in pine stands contains 18 pounds of calcium and 13 pounds of nitrogen per acre.

TABLE 14-2.—*Inorganic components of southern pine needles*

Component and pine species (or condition of needles)	Portion of oven-dry weight	References
Total ash, percent		
Loblolly, green.....	2.3 to 4.0	3 10 35 36 41
Loblolly, dead.....	4.1	3
Sand.....	2.1	36
Slash.....	1.2 to 2.5	3 36
Aluminum, percent.....	.02 to .13	2 39 40
Calcium, percent		
Green.....	.03 to .79	2 3 6 7 9 10 14 15 16 17 19 22 23 25 31 35 37 38 39
Dead.....	.25 to .78	1 3 4 19
Chlorine, percent.....	.02 to .04	3
Magnesium, percent.....	.02 to .62	2 3 4 7 10 14 15 16 19 22 31 37 38 39
Manganese, percent.....	.01 to .10	2 7 14 20 22 37 39 40
Nitrogen, percent		
Green.....	.72 to 3.94	2 5 6 9 10 11 12 14 15 17 18 19 22 23 24 25 26 27 29 30 33 34 37 38 39
Dead.....	.31 to 1.00	1 4 12 19 27

¹ Coile (1940)—loblolly.

² Roth et al. (1948)—shortleaf.

³ Young (1948)—loblolly, slash.

⁴ Metz (1952)—loblolly, shortleaf.

⁵ Switzer and Nelson (1956)—loblolly.

⁶ Roth and Copeland (1957)—shortleaf.

⁷ Duncan and Epps (1958)—longleaf.

⁸ Baur (1959)—loblolly, slash.

⁹ Fowells and Krauss (1959)—loblolly,
Virginia.

¹⁰ Thompson (1959)—loblolly.

¹¹ Zahner (1959)—loblolly.

¹² Maki (1960)—loblolly.

¹³ Schopmeyer (1961)—loblolly.

¹⁴ Vail et al. (1961)—loblolly.

¹⁵ May et al. (1962)—loblolly, longleaf
slash.

TABLE 14-2.—*Inorganic components of southern pine needles—Continued*

Component and pine species (or condition of needles)	Portion of ovendry weight	References
Phosphorus, percent		
Green.....	.03 to .94	2 3 5 7 8 9 10 11 12 13 14 15 17 19 22 23 24 25 26 28 31 32 35 37 38 39
Dead.....	.04 to .19	3 12 19
See footnotes at end of table.		
Potassium, percent		
Green.....	.20 to 1.56	2 3 5 7 9 10 11 12 14 15 16 17 19 22 23 24 25 26 31 37 38 39
Dead.....	.06 to .23	3 12 19
Silica, percent		
Slash, green.....	.15	3
Loblolly, green.....	1.44	3
Loblolly, dead.....	1.79	3
Sodium, percent.....	Trace to .32	3 9 15
Sulfur, percent.....	.05 to .42	7 14 38
Boron, p.p.m.....	4 to 100	2 14 21 22
Cobalt, p.p.m.....	.7	7
Copper, p.p.m.....	2 to 33	2 7 14 22 37 40
Iron, p.p.m.....	Trace to 486	2 7 14 20 22 40
Molybdenum, p.p.m.....	.1	7
Zinc, p.p.m.....	12 to 99	7 14 20 22 37 39 40

¹⁶ Sucoff (1962)—Virginia.

¹⁷ Ralston and Prince (1963)—loblolly.

¹⁸ Smith et al. (1963)—loblolly.

¹⁹ Wells and Metz (1963)—loblolly.

²⁰ Dixon and Wear (1964)—loblolly, longleaf, shortleaf, slash.

²¹ Stone and Will (1965)—longleaf.

²² Van Goor (1965)—slash.

²³ Wells (1965)—loblolly.

²⁴ Carter and Lyle (1966)—loblolly.

²⁵ Metz et al. (1966)—loblolly.

²⁶ Miller (1966)—loblolly.

²⁷ Moehring (1966)—loblolly.

²⁸ Pritchett and Llewellyn (1966)—slash.

²⁹ Switzer et al. (1966)—loblolly.

³⁰ Barnes and Bengston (1968)—loblolly, slash.

³¹ Brendemuehl (1968)—longleaf, sand, slash.

³² Pritchett (1968)—loblolly, sand, slash.

³³ Switzer et al. (1968)—loblolly.

³⁴ Wells (1968)—loblolly.

³⁵ Blair and Epps (1969)—loblolly.

³⁶ Hough (1969)—loblolly, sand, slash.

³⁷ Magdwick (1970b)—Virginia.

³⁸ Nelson et al. (1970)—loblolly.

³⁹ White and Pritchett (1970)—loblolly, slash.

⁴⁰ White et al. (1970)—loblolly.

⁴¹ Howard (see text footnote¹)—loblolly.

OIL

The resin ducts of needles are not connected with those of the stem, and the volatile oil contained in them differs considerably from that of the wood. Needle volatile oil is more complicated in composition than turpentine from the same species; little is known about the nonvolatile portion (Mirov 1967). Some data on the yield, composition, and characteristics of steam-distilled needle oil are given in tables 14-3, 14-4, and 14-5. The pleasant odor of pine needle oil is attributed primarily to borneol and bornyl esters. Some of the volatiles are emitted into the

atmosphere (α -pinene, β -pinene, myrcene, Δ^3 -carene, and limonene) and contribute to the fresh smell of a forest and the seasonal haze above it (Rasmussen and Went 1965).

TABLE 14-3.—Yield and physical properties of oil distilled from needles and twigs of the southern pines¹

Species and component	Yield ²	Specific gravity ³	Refractive index	Optical rotation α_{D28}°
	<i>Percent</i>			<i>Degrees</i>
Loblolly				
Needles.....	0.35	0.883	1.474 ⁴	-----
Longleaf				
Needles only.....	.42	.884	1.483 ³	-32.5
Needles and twigs.....	.40	.884	1.482 ³	-28.9
Pitch				
Needles.....	.10 ⁵	-----	-----	-----
Shortleaf				
Needles.....	.32	.883	1.483 ⁴	-12.6 ⁷
Slash ⁶				
Needles only.....	.19	.890	1.488 ³	-36.5
Needles and twigs.....	.27	.888	1.485 ³	-34.0
Virginia				
Needles.....	.28	.877	1.480 ⁴	-10.2 ⁷

¹ Data for slash, longleaf, and pitch pines from Schorger (1914, 1916); those for the other species from Bailey (1948).

² Percent of green weight.

³ At 15° C.

⁴ At 20° C.

⁵ Value questioned by Schorger.

⁶ Schorger used name "Cuban" pine.

⁷ Conditions not stated.

TABLE 14-4.—Chemical composition of oil distilled from slash¹ and longleaf pine needles and twigs (Schorger 1914, 1916)

Component	Slash pine needles and twigs	Longleaf pine	
		Needles and twigs	Needles
		<i>Percent</i>	
Furfural.....	Trace	Trace	Trace
l- α -pinene.....	4	8 to 9	2
l-camphene.....	10	13 to 14	12 to 13
l- β -pinene.....	35 to 36	44	50
Dipentene.....	8	5	5
Bornyl ester (as acetate)....	3.5	2.4	2
Free alcohol (as l-borneol).....	11.4	10	9.8
d-cadinene.....	18 to 19	10 to 11	11
Losses and residue.....	9	6	7.5
Total	100	100	100

¹ Schorger called it "Cuban" pine.

TABLE 14-5.—*Fraction of slash and longleaf pine needle oils distilled at various temperatures*
(Schorger 1914)

Temperature range	Slash pine ¹	Longleaf pine
°C.	Percent	
159.0 to 165.0	31	38
165.0 to 170.0	18	25
170.0 to 180.0	7	5
180.0 to 197.5	3	
180.0 to 198.5		2
197.5 to 250.0	16	
198.5 to 250.0		16
250.0 to 280.0	19	11
Residue	6	3
Total	100	100

¹ Schorger called it "Cuban" pine.

Oleoresin content of needles is positively correlated with number and size of resin canals. In pond pine, White and Beals (1963) found that the number of resin canals per needle increased with tree age up to about 58 years, then decreased; needles produced during periods of rapid growth had canals of greatest diameter; the number of canals was negatively correlated with rings per inch growth rate; needles from the north side of the crown had a slightly higher average number of canals than those from the south side; and needles from upper portions of the crown had more canals than those from lower branches.

Bailey (1948) obtained best yield of oil from foliage collected in winter from dominant trees of merchantable size. Yield data are shown in table 14-3.

OTHER ORGANIC COMPONENTS

Analysis of other organic constituents of southern pine needles remains incomplete; most of the work to date has been in conjunction with physiological studies.

Free and protein amino acids found in loblolly needles (Barnes 1962; Pharis et al. 1964; Barnes and Bengtson 1968) were glutamic acid, glutamine, proline, citrulline, arginine, aspartic acid, alanine, serine, glycine, γ -aminobutyric acid, cysteic acid, threonine, leucine, proline, lysine, ethanolamine, histidine, tyrosine, asparagine, cysteine, β -alanine, and tryptophan.

Meyer (1928) found that the total sugars in pitch pine leaves varied seasonally from 2.58 to 4.15 percent of the fresh weight. Of this, reducing sugars constituted 1.49 to 2.77 percent and nonreducing sugars 0.7 to 2.34

percent. Sugar content reached a minimum in late summer or early autumn, increased in late autumn, and was relatively high during winter.

Carbohydrate level in needles collected in April from healthy shortleaf pines was 16.6 percent of oven-dry weight or 7.3 percent of fresh weight; if affected by littleleaf disorder, however, they contained only 11.5 percent carbohydrate on an oven-dry basis or 4.7 percent of fresh weight (Hepting 1945).

Takahashi et al. (1960) used paper chromatography to detect flavonoids and stilbenoids in conifer leaves, with the following results (a + indicates presence of the compound, and a numeral indicates that none, one, or two were found) :

Pine species	Quercetin	Kaempferol	Other spots	Glycoside
Loblolly.....	+	+	1	2
Longleaf.....	+	+	1	1
Pitch.....			1	1
Shortleaf.....			2	1
Slash.....			2	2
Table-Mountain.....	+	+	0	2
Virginia.....			1	1

Myricetin, common in other pine needles, was absent in needles of southern pine.

Alcohol-benzene extractive content measured by Howard¹ was 28.8 percent of an oven-dry sample composed of equal weights of loblolly, longleaf, shortleaf, and slash pine needles.

14-5 USES

At this time it is not clear what effect systematic removal of needles from the forest floor might have on wood production and forest ecology. Since no major economic uses for needles exist, the problem has not received attention. Some minor uses—past and present—are outlined below.

Pine needles find limited use as a material from which craftsmen weave decorative trays, baskets, and similar articles (Reyer 1962). Vegetative rooting of shortleaf and slash pine fascicles has been accomplished experimentally (Zak and McAlpine 1957; Reines and McAlpine 1959), but has not yet proven to be a practical method of propagation.

OIL

Production of oil from the needles of southern pines was once considered a potential byproduct industry. Formerly, pine needle oil was used as a major ingredient of cough syrups and tonics, for medicinal baths, and as a scenting agent in soaps, polishes, and cosmetics (Dallimore and Jackson 1948). Because of low yields, labor costs, and the competition of cheaper and more readily available products, however, distillation of southern pine needles is no longer practiced.

PINE FIBER

In addition to oil, it is possible to obtain from southern pine needles a fibrous product known as **pine wool**. If distilled without preliminary chopping, the spent crushed needles can be freed of nonfibrous material by boiling in a soda solution, followed by washing, drying, and heating. The resulting fiber (about 13 percent of the fresh needle weight) is reported to be fine, strong, and elastic—resembling hemp—and can be felted or woven. Though darkened by the soda treatment, it can be bleached and dyed (Record 1916). **Pine hair**, a grade of pine fiber for upholstery, often was prepared so as to preserve the aromatic odor. Another grade was used as a substitute for hair in plaster, and some was claimed to be “the nearest approach to natural wool ever made from vegetable fiber.” This quality was intended for spinning and weaving into carpets and was said to retain dyes without a mordant (Record 1916). By 1896, 29 looms had been installed to use needle fiber (Mohr 1896). It was sometimes also woven into medicated underclothing, surgical dressings, and coarse mats resembling coconut matting (Dallimore and Jackson 1948).

A patented pine felt process was used in a Hattiesburg, Miss. plant in the mid-1930's to produce needle fiber by boiling in strong alkaline solution and shredding in carding machines. The material was then washed, dried, and baled. Delivery price for needles was \$4 per ton, and yields were one-half of the needle weight (dry weight presumed). The fiber was said to be an excellent material for upholstery, filling mattresses, and similar purposes (Mississippi Forests and Parks 1936).

Although southern pine needles have not been used in composition boards, investigators successfully used leaves of foreign species (alone and mixed with sawdust) to produce fiberboard; in other experiments, leaves were autoclaved with phenol, then powdered and pressed into boards (Jain and Gupta 1969).

MULCH

Southern pine needles find their major use as a mulch material for truck crops and ornamentals. Spillers (1935) estimated that about 2 acres of pines produce enough mulch for 1 acre of strawberries.

FODDER FOR WILDLIFE

In forests managed for multiple use, utilization of foliage as wildlife food is important. Blair and Epps (1969), in a study of seven browse species utilized by white-tailed deer in the South, studied the needles of loblolly pine, which are regarded as unpalatable, but are often ingested

in over-used ranges. Observations of nutrient content, by season, were as follows:

<u>Component</u>	<u>Comment on content</u>
Dry matter	Minimum at about 25 percent of green weight in spring and maximum at about 42 percent in winter.
Protein	Fairly uniform throughout the year at about 10 percent of ovendry weight; very slightly higher in spring.
Ether extract, i.e., crude fat	Lowest in spring (about 4 percent), and highest in winter (about 10 percent of ovendry weight).
Crude fiber, i.e., the more or less indigestible portion	Lowest in the winter (about 20 percent), and near 25 percent of ovendry weight the rest of the year.
Nitrogen-free extract (includes the readily digestible carbohydrates as well as some indigestible lignin)	Fairly uniform at about 55 percent of ovendry weight.
Ash	Highest in spring (about 4 percent), and about 3 percent of ovendry weight the rest of the year.
Calcium	Fairly uniform at about 0.3 percent of ovendry weight.
Phosphorus	About 0.2 percent in spring, dropping with cessation of growth to about 0.1 percent of ovendry weight.

14-6 LITERATURE CITED

- Bailey, L. F.
1948. Leaf oils from Tennessee Valley conifers. *J. Forest.* 46:882-889
- Barnes, R. L.
1962. Ornithine-2-C¹⁴ metabolism in loblolly pine needles. *Forest Sci.* 8: 284-287.
- Barnes, R. L., and Bengtson, G. W.
1968. Some aspects of nitrogen nutrition and metabolism in relation to fertilizer responses in southern pines. *In* Forest fertilization, pp. 58-63. Tenn. Val. Auth., Muscle Shoals, Ala.
- Baur, G. N.
1959. A soil survey of a slash pine plantation, Barcoongere, N.S.W. *Aust. Forest.* 23: 78-87.
- Bennett, W. H.
1954. The effect of needle structure upon the susceptibility of hosts to the pine needle miner (*Exoteleia pinifoliella* (Chamb.)) (Lepidoptera: Gelechiidae). *Can. Entomol.* 86: 49-54.
- Blair, R. M., and Epps, E. A.
1969. Seasonal distribution of nutrients in plants of seven browse species in Louisiana. *USDA Forest Serv. Res. Pap. SO-51*, 35 pp. South. Forest Exp. Sta., New Orleans, La.
- Boyer, W. D.
1968. Foliage weight and stem growth of longleaf pine. *USDA Forest Serv. Res. Note SO-86*, 2 pp. South. Forest Exp. Sta., New Orleans, La.

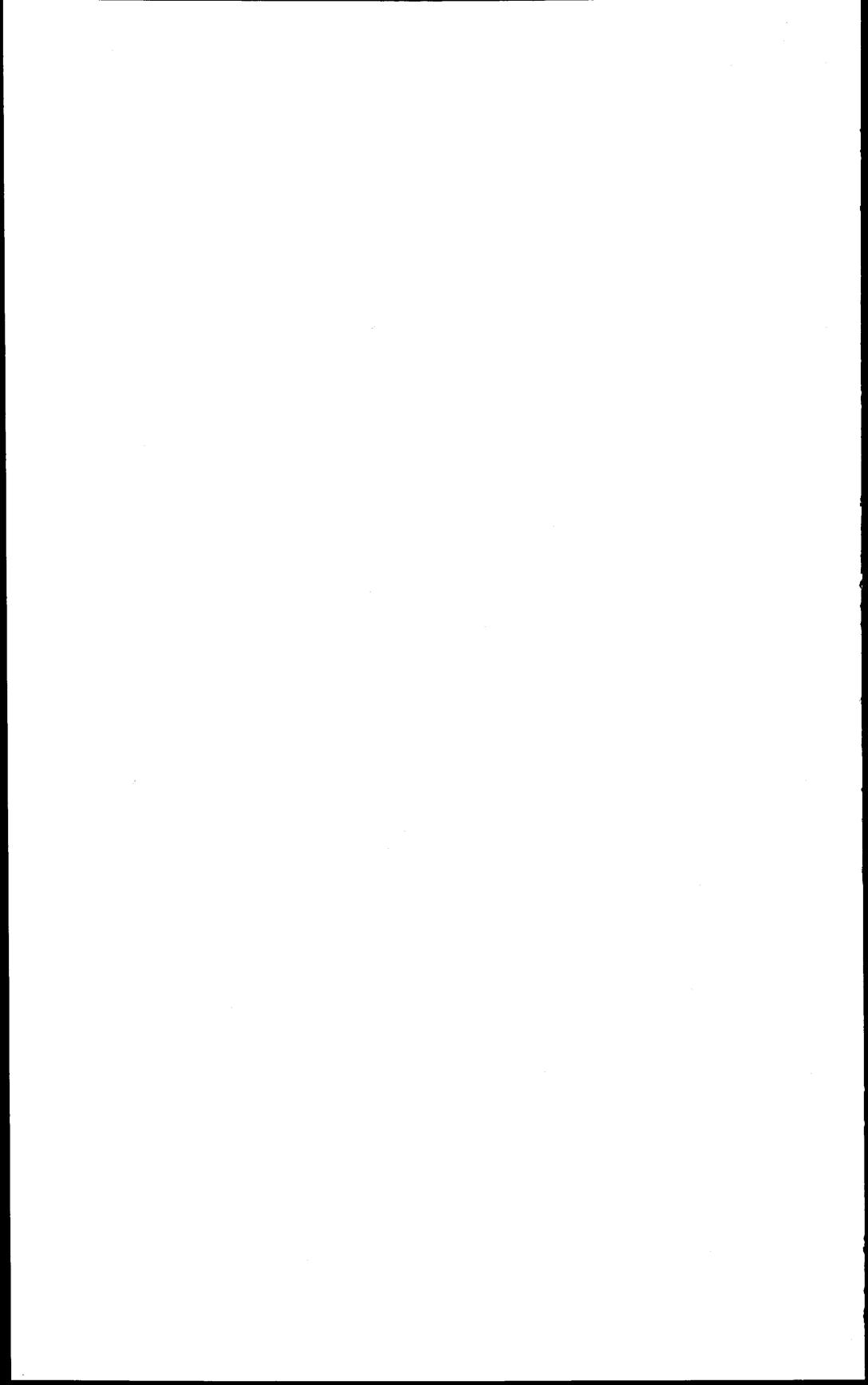
- Brendemuehl, R. H.
1968. Research progress in the use of fertilizers to increase pine growth on the Florida sandhills. *In* Forest fertilization, pp. 191-196. Tenn. Val. Auth., Muscle Shoals, Ala.
- Carter, D. M., and Lyle, E. S.
1966. Fertilization of loblolly pine on two Alabama soils: effects on growth and foliar mineral content. Auburn Univ. Agr. Exp. Sta. Bull. 370, 17 pp.
- Coile, T. S.
1940. Soil changes associated with loblolly pine succession on abandoned agricultural land of the Piedmont plateau. Duke Univ. Sch. Forest. Bull. 5, 85 pp.
- Coker, W. C., and Totten, H. R.
1937. Trees of the Southeastern States. Ed. 2, 417 pp. Chapel Hill, N.C.: Univ. N.C. Press.
- Dallimore, W., and Jackson, A. B.
1948. A handbook of *Coniferae* including ginkgoaceae. Ed. 3, 682 pp. London: Edward Arnold & Co.
- De Vall, W. B.
1940. A diagnostic taxonomic constant for separating slash and longleaf pines. Fla. Acad. Sci. Proc. 1939: 113-115.
- DeVall, W. B.
1941. The taxonomic status of *Pinus caribaea* Mor. Proc. Fla. Acad. Sci. 5: 121-132.
- Dixon, J. B., and Wear, J. I.
1964. X-ray spectrographic analysis of zinc, manganese, iron, and copper in plant tissue. Soil Sci. Soc. Amer. Proc. 28: 744-746.
- Doak, C. C.
1935. Evolution of foliar types, dwarf shoots, and cone scales of *Pinus*, with remarks concerning similar structures in related forms. Univ. Ill. Biol. Monogr. 13(3): 1-106.
- Doi, T., and Morikawa, K.
1929. An anatomical study of the leaves of the genus *Pinus*. J. Dep. Agr., Kyushu Imp. Univ. 2(6): 149-198.
- Dolivo, A.
1948. Anatomie comparée des aiguilles de douze espèces de pins. Soc. Bot. Genève Bull. (Ser. 2) 39: 8-33.
- Duncan, D. A., and Epps, E. A., Jr.
1958. Minor mineral elements and other nutrients on forest ranges in central Louisiana. La. State Univ. Agr. Exp. Sta. Bull. 516, 19 pp.
- Esau, K.
1965. Plant anatomy. Ed. 2, 767 p. N.Y.: John Wiley and Sons, Inc.
- Fitzpatrick, H. M.
1929. Coniferae: keys to the genera and species, with economic notes. Sci. Proc. Roy. Dublin Soc. 19(19): 189-260.
- Florin, R.
1931. Untersuchungen zur Stammesgeschichte der coniferales und cordaitales. I. Morphologie und epidermisstruktur der assimilationsorgane bei den rezenten koniferen. Kgl. Svenska Vetenskapsakademi. Handl. Ser. 3, Vol. 10, No. 1, 588 p. Stockholm: Almqvist & Wiksells Boktryckeri-A.-B.
- Fowells, H. A., and Krauss, R. W.
1959. The inorganic nutrition of loblolly pine and Virginia pine with special reference to nitrogen and phosphorus. Forest Sci. 5: 95-112.
- Garcia, M. J.
1963. Las acículas de los pinos. Montes 19(113): 367-378.
- Harlow, W. M.
1931. The identification of the pines of the United States, native and introduced, by needle structure. N.Y. State Coll. Forest. at Syracuse Univ. Tech. Pub. 32, 59 pp.
- Harrar, E. S., and Harrar, J. G.
1946. Guide to southern trees. 712 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Hepting, G. H.
1945. Reserve food storage in shortleaf pine in relation to little-leaf disease. Phytopathology 35: 106-119.

- Heyward, F., and Barnette, R. M.
1936. Field characteristics and partial chemical analyses of the humus layer of longleaf pine forest soils. Fla. Agr. Exp. Sta. Bull. 302, 27 pp.
- Hough, W. A.
1969. Caloric value of some forest fuels of the southern United States. USDA Forest Serv. Res. Note SE-120, 6 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Jain, N. C., and Gupta, R. C.
1969. A note on complete utilization of trees. Indian Forest. 95: 841-848.
- Keng, H., and Little, E. L.
1961. Needle characteristics of hybrid pines. Silvae Genet. 10: 131-146.
- Little, E. L., Jr., and Dorman, K. W.
1952. Slash pine (*Pinus elliottii*), its nomenclature and varieties. J. Forest. 50: 918-923.
- Little, E. L., Jr., and Dorman, K. W.
1954. Slash pine (*Pinus elliottii*), including South Florida slash pine—nomenclature and description. USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap. 36, 82 pp.
- Lodewick, J. E.
1931. Some effects of irrigation and fertilization on the size of longleaf pine needles. Forest Worker 7(1): 12-13.
- Loomis, R. M., Phares, R. E., and Crosby, J. S.
1966. Estimating foliage and branchwood quantities in shortleaf pine. Forest Sci. 12: 30-39.
- McLemore, B. F., Crow, A. B., and Wakeley, P. C.
1961. Dry-matter content of loblolly pine needles appears unrelated to geographic seed source. Forest Sci. 7: 373-375.
- Madgwick, H. A.
1970a. Caloric values of *Pinus virginiana* as affected by time of sampling, tree age, and position in stand. Ecology 51: 1094-1097.
- Madgwick, H. A. I.
1970b. The nutrient contents of old-field *Pinus virginiana* stands. In Tree growth and forest soils, pp. 275-282. Third North Amer. Forest Soils Conf. Proc.
- Maki, T. E.
1960. Some effects of fertilizers on loblolly pine. Seventh Int. Congr. Soil Sci. Trans. 3: 363-375.
- Masters, M. T.
1891. Review of some points in the comparative morphology, anatomy, and life-history of the *Coniferae*. Linn. Soc. J. Bot. 27: 226-332.
- Masters, M. T.
1904. A general view of the genus *Pinus*. Linn. Soc. J. Bot. 35: 560-659.
- May, J. T., Johnson, H. H., and Gilmore, A. R.
1962. Chemical composition of southern pine seedlings. Ga. Forest Res. Pap. 10, 11 pp.
- Mergen, F.
1958. Genetic variation in needle characteristics of slash pine and in some of its hybrids. Silvae Genet. 7: 1-9.
- Mergen, F.
1959. Applicability of the distribution of stomates to verify pine hybrids. Silvae Genet. 8(4): 107-109.
- Metz, L. J.
1952. Weight and nitrogen and calcium content of the annual litter fall of forests in the South Carolina Piedmont. Soil Sci. Soc. Amer. Proc. 16: 38-41.
- Metz, L. J.
1954. Forest floor in the Piedmont region of South Carolina. Soil Sci. Soc. Amer. Proc. 18: 335-338.
- Metz, L. J., and Wells, C. G.
1965. Weight and nutrient content of the aboveground parts of some loblolly pines. USDA Forest Serv. Res. Pap. SE-17, 20 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- Metz, L. J., Wells, C. G., and Swindel, B. F.
1966. Sampling soil and foliage in a pine plantation. Soil Sci. Soc. Amer. Proc. 30: 397-399.

- Meyer, B. S.
1928. Seasonal variations in the physical and chemical properties of the leaves of the pitch pine, with special reference to cold resistance. *Amer. J. Bot.* 15: 449-472.
- Meyer, B. S.
1932. Further studies on cold resistance in evergreens, with special reference to the possible role of bound water. *Bot. Gaz.* 94: 297-321.
- Miller, W. F.
1966. Annual changes in foliar nitrogen, phosphorus, and potassium levels of loblolly pine (*Pinus taeda* L.) with site and weather factors. *Plant and Soil* 24: 369-378.
- Mirov, N. T.
1967. The genus *Pinus*. 602 pp. N.Y.: Ronald Press Co.
- Mississippi Forest and Parks.
1936. Pine needle products—new state industry. Savannah Weekley Nav. Stores Rev. and J. Trade 45(45): 14.
- Moehring, D. M.
1966. Diameter growth and foliar nitrogen in fertilized loblolly pines. USDA Forest Serv. Res. Note SO-43, 3 pp. South. Forest Exp. Sta., New Orleans, La.
- Mohr, C.
1896. The timber pines of the Southern United States. USDA Div. Forest. Bull. 13, 160 pp.
- Monk, C. D.
1966. Root-shoot dry weights in loblolly pine. *Bot. Gaz.* 127: 246-248.
- Nelson, L. E., Switzer, G. L., and Smith, W. H.
1970. Dry matter and nutrient accumulation in young loblolly pine (*Pinus taeda* L.). In *Tree growth and forest soils*, pp. 261-273. (C. T. Youngberg and C. B. Davey, eds.) Third North Amer. Forest Soils Conf. Proc.
- Pharis, R. P., Barnes, R. L., and Naylor, A. W.
1964. Effects of nitrogen level, calcium level and nitrogen source upon the growth and composition of *Pinus taeda* L. *Physiol. Plant.* 17: 560-572.
- Pilger, R.
1926. Pinaceae. In *Die natürlichen Pflanzenfamilien*, pp. 271-342. Ed. 2, Vol. 13. (A. Engler and K. Prantl, eds.) Leipzig: Verlag von Wilhelm Englemann.
- Pritchett, W. L.
1968. Progress in the development of techniques and standards for soil and foliar diagnosis of phosphorus deficiency in slash pine. In *Forest fertilization*, pp. 81-87. Tenn. Val. Auth., Muscle Shoals, Ala.
- Pritchett, W. L., and Llewellyn, W. R.
1966. Response of slash pine (*Pinus elliotii* Engelm. var. *elliottii*) to phosphorus in sandy soils. *Soil Sci. Soc. Amer. Proc.* 30: 509-512.
- Ralston, C. W., and Prince, A. B.
1963. Accumulation of dry matter and nutrients by pine and hardwood forests in the lower Piedmont of North Carolina. In *Forest-soil relationships in North America*, pp. 77-94. Second North Amer. Forest Soils Conf. Proc.
- Rasmussen, R. A., and Went, F. W.
1965. Volatile organic material of plant origin in the atmosphere. *Proc. Nat. Acad. Sci.* 53: 215-220.
- Record, S. J.
1916. The pine needle oil industry: how the thrifty Europeans utilize a waste product of the lumbering industries. *Scientif. Amer.* 114: 100-101.
- Reines, M., and McAlpine, R. G.
1959. The morphology of normal, callused, and rooted dwarf shoots of slash pine. *Bot. Gaz.* 121: 118-124.
- Reyer, K. D.
1962. Unusual small businesses: adaptive behavior by small businessmen. *La. State Univ.*, 42 pp.
- Rogerson, T. L.
1964. Estimating foliage on loblolly pine. USDA Forest Serv. Res. Note SO-16, 3 pp. South. Forest Exp. Sta., New Orleans, La.
- Roth, E. R., Copeland, O. L.
1957. Uptake of nitrogen and calcium by fertilized shortleaf pine. *J. Forest.* 55: 281-284.

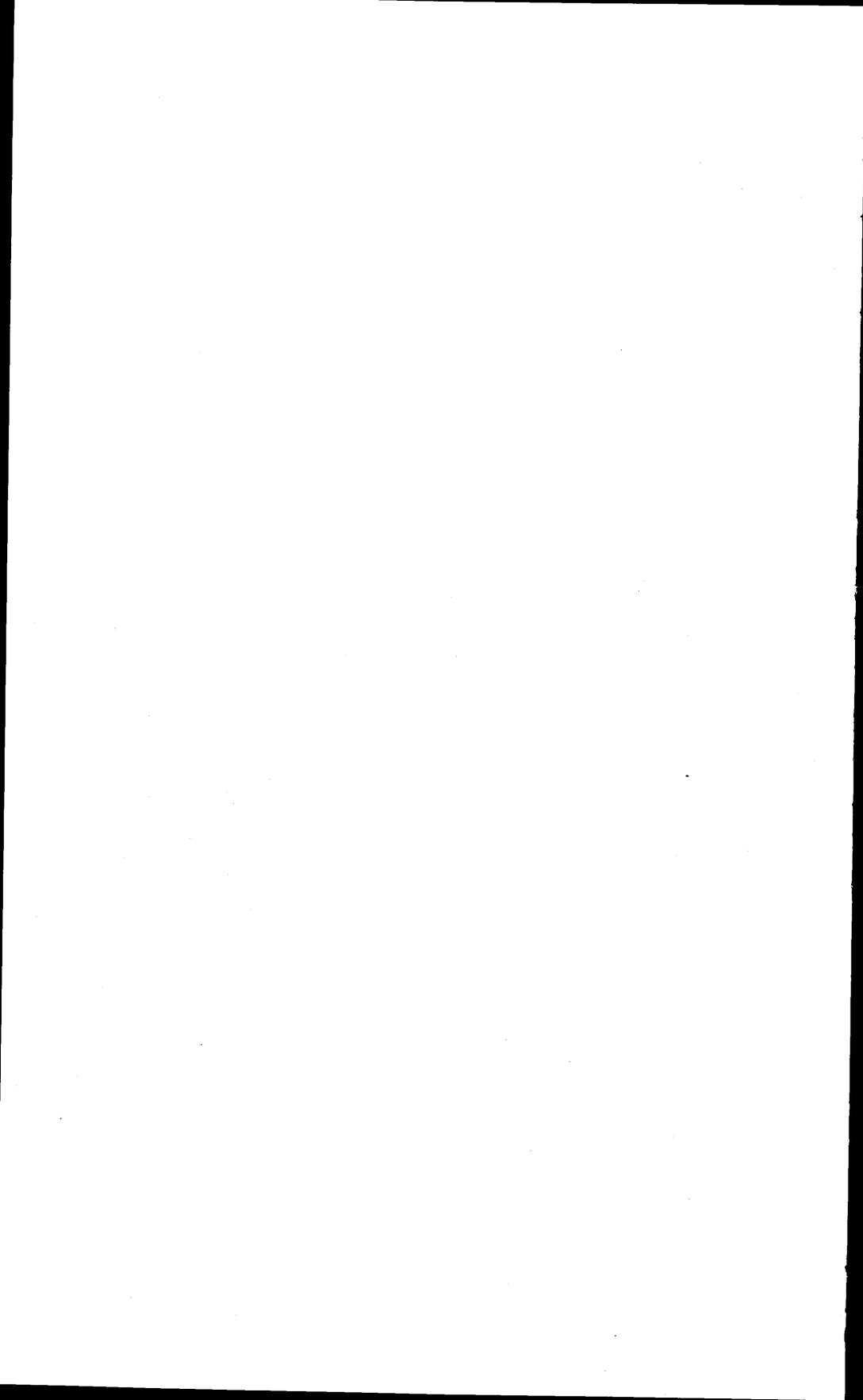
- Roth, E. R., Toole, E. R., and Hepting, G. H.
1948. Nutritional aspects of the littleleaf disease of pine. *J. Forest.* 46: 578-587.
- Schopmeyer, C. S.
1939. Transpiration and physicochemical properties of leaves as related to drought resistance in loblolly pine and shortleaf pine. *Plant Physiol.* 14: 447-462.
- Schopmeyer, C. S.
1961. Foliar absorption and translocation of phosphorus by loblolly pine seedlings. *Forest Sci.* 7: 330-336.
- Schorger, A. W.
1914. Oils of the coniferae. I. The leaf and twig oils of Cuban and longleaf pines and the cone oil of longleaf pine. *Ind. and Eng. Chem.* 6: 723-727.
- Schorger, A. W.
1916. The conifer leaf oil industry. *Amer. Lumberman*, April 29, pp. 28-29.
- Small, J. K.
1933. *Manual of the southeastern flora.* 1554 pp. N.Y.: Published by author.
- Smith, W. H., Nelson, L. E., and Switzer, G. L.
1963. The characterization of dry matter and nitrogen accumulation by loblolly pine (*Pinus taeda* L.) on poor sites. *Soil Sci. Soc. Amer. Proc.* 27: 465-468.
- Soar, I.
1922. The structure and function of the endodermis in the leaves of the *Abietineae*. *New Phytol.* 21: 269-292.
- Spillers, A. R.
1935. Pine straw used in strawberry culture. *South. Agr.* 45(1): 23.
- Squillace, A. E.
1966. Geographic variation in slash pine. *USDA Forest Sci. Monogr.* 10, 56 pp.
- Stone, E. L., and Will, G. M.
1965. Boron deficiency in *Pinus radiata* and *P. pinaster*. *Forest Sci.* 11: 425-433.
- Sucoff, E. I.
1962. Potassium, magnesium, and calcium requirements of Virginia pine. *USDA Forest Serv. Northeast. Forest Exp. Sta., Sta. Pap.* 169, 16 pp.
- Sutherland, M.
1934. A microscopical study of the structure of the leaves of the genus *Pinus*. *New Zeal. Inst. Trans. and Proc.* 63: 517-568.
- Switzer, G. L., and Nelson, L. E.
1956. The effect of fertilization on seedling weight and utilization of N, P, and K by loblolly pine (*Pinus taeda* L.) grown in the nursery. *Soil Sci. Soc. Amer. Proc.* 20: 404-408.
- Switzer, G. L., Nelson, L. E., and Smith, W. H.
1966. The characterization of dry matter and nitrogen accumulation by loblolly pine (*Pinus taeda* L.). *Soil Sci. Soc. Amer. Proc.* 30: 114-119.
- Switzer, G. L., Nelson, L. E., and Smith, W. H.
1968. The mineral cycle in forest stands. *In Forest fertilization*, pp. 1-9. *Tenn. Val. Auth., Muscle Shoals, Ala.*
- Takahashi, M., Ito, T., Mizutani, A., and Isoi, K.
1960. Chemical constituents of the plants of coniferae and allied orders. XLIII. Distribution of flavonoids and stilbenoids of coniferae leaves. *J. Pharm. Soc. Jap.* 80: 1488-1492.
- Thames, J. L.
1963. Needle variation in loblolly pine from four geographic seed sources. *Ecology* 44: 168-169.
- Thompson, E. F.
1959. Relation of soil and foliar nutrient levels to growth of loblolly pine (*Pinus taeda* L.) on different sites. *MF Thesis. N.C. State Univ., Raleigh.* 55 pp.
- Thorbjornsen, E.
1961. Variation patterns in natural stands of loblolly pine. *Sixth South. Forest Tree Impr. Conf. Proc.* 1961: 25-44.
- Vail, J. W., Parry, M. S., and Calton, W. E.
1961. Boron-deficiency dieback in pines. *Plant and Soil* 14: 393-398.

- Van Goor, C. P.
1965. Reflorestamento com coníferas no Brazil. Aspectos ecológicos dos plantios na Região Sul. particularmente, com *Pinus elliottii* Araucaria angustifolia. Departamento de Recursos Naturais Renováveis Boletim 9, 58 pp. Brasil.
- Ward, D. B.
1963. Contributions to the flora of Florida—2, *Pinus* (*Pinaceae*). CASTANEA 28(1): 1-10.
- Wells, C. G.
1965. Nutrient relationships between soils and needles of loblolly pine (*Pinus taeda*). Soil Sci. Soc. Amer. Proc. 29: 621-624.
- Wells, C. G.
1968. Techniques and standards for foliar diagnosis of N deficiency in loblolly pine. In Forest fertilization, pp. 72-76. Tenn. Val. Auth., Muscle Shoals, Ala.
- Wells, C. G., and Metz, L. J.
1963. Variation in nutrient content of loblolly pine needles with season, age, soil, and position on the crown. Soil Sci. Soc. Amer. Proc. 27: 90-93.
- Wendel, G. W.
1960. Fuel weights of pond pine crowns. USDA Forest Serv. Res. Note SE-149, 2 pp. Southeast. Forest Exp. Sta., Asheville, N.C.
- White, J. B., and Beals, H. O.
1963. Variation in number of resin canals per needle in pond pine. Bot. Gaz. 124: 251-253.
- White, E. H., and Pritchett, W. L.
1970. Water table control and fertilization for pine production in the flatwoods. Univ. Fla. Agr. Exp. Sta. Bull. 743, 41 pp.
- White, J. D., Wells, C. G., and Clark, E. W.
1970. Variation in the inorganic composition of inner bark and needles of loblolly pine with tree height and soil series. Can. J. Bot. 48: 1079-1084.
- Young, H. E.
1948. The response of loblolly and slash pines to phosphate manures. Queensland J. Agr. Sci. 5: 77-105.
- Zahner, R.
1959. Fertilizer trials with loblolly pine in southern Arkansas. J. Forest. 57: 812-816.
- Zak, B., and McAlpine, R. G.
1957. Rooting of shortleaf and slash pine needle bundles. USDA Forest Serv. Res. Note SE-112, 2 pp. Southeast. Forest Exp. Sta., Asheville, N.C.



PART IV—REACTION TO ENVIRONMENT

<i>Chapter</i>	<i>Title</i>
15	EFFECTS OF CHEMICALS, HEAT AND RADIATION
16	ATTACK BY PLANT ORGANISMS
17	ATTACK BY INSECTS, MARINE BORERS, AND BIRDS



15

Effects of chemicals, heat, and radiation

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15

Effects of chemicals, heat, and radiation

Because southern pine wood is an industrial material of many and diverse uses, it is frequently exposed to a variety of chemicals, hot atmospheres, and radiations. Its successful use in these exposures requires some knowledge of the degree of degradation to be expected.

15-1 EXPOSURE TO CHEMICALS¹

Alkalis—and to a lesser extent acids—react with southern pine wood to change its composition and reduce its strength. Exposure to certain inorganic salts and contact with some metals also have adverse effects. In general, however, the wood of the southern pines—in comparison to other commercial woods—is relatively resistant to chemical attack.

ACIDS

Wood is resistant to low concentrations of most strong mineral acids and is particularly resistant to organic acids. For example, Welch (1936)—in a study of Monterey pine (*Pinus radiata* D. Don)—found that prolonged exposure to 100 percent acetic acid affected swelling only slightly and had no effect on appearance.

Effect on chemical composition.—Lignin is resistant to most acids, especially if cold and dilute (Baechler 1954). Lignin content of wood is unaffected by concentrated sulfuric acid; its determination is based on resistance to a 72-percent solution of this acid (Technical Association of the Pulp and Paper Industry Standard T 13m-54).

Hemicellulose content is reduced—particularly in hardwoods—by exposure to acids. There is evidence that the greater resistance of coniferous woods is related to their lower content of pentosans, e.g., xylans (Thompson 1969, p. 2; Kass et al. 1970).

¹ Secs. 15-1 and 15-2 are taken with minor editorial changes and some additions from Thompson (1969) by permission of Warren S. Thompson and Mississippi State University.

Data from Wangaard (1966) show changes in chemical constituents of Caribbean pine (*Pinus caribaea* More.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and 11 species of hardwoods after treatment with 10-percent hydrochloric acid; specimens measured $\frac{1}{2}$ - by $\frac{1}{2}$ -inch by 9 inches along the grain and after saturation with water were soaked in the acid for 32 days at 20° C. or 4 days at 50° C. Caribbean pine is a species closely related to the southern pines. Retention of chemical constituents was as follows:

Duration and temperature of treatment, and constituent	Caribbean pine	Douglas-fir	Average for 11 hardwoods
--- Percent (by weight) of original content ---			
After 32 days at 20° C.			
Holocellulose.....	89	93	82
Hemicellulose.....	104	100	72
Alpha-cellulose....	82	88	90
Lignin.....	99	104	108
After 4 days at 50° C.			
Holocellulose.....	83	74	70
Hemicellulose.....	74	58	48
Alpha-cellulose....	87	85	84
Lignin.....	111	106	110

The hemicellulose content in pine was not diminished by exposure to the hydrochloric acid at 20° C.; at 50° C., however, pine retained 74 percent of its hemicellulose—a considerably higher retention than that for the other 12 species. Alpha-cellulose content was about equally reduced in all species by both treatments (82- to 90-percent retention). Lignin content was undiminished in all 13 species.

Campbell and Bamford (1939) studied the hydrolysis of longleaf pine wood flour by sulfuric acid. The chemical composition of longleaf pine following exposure for 5 hours in 1 percent acid at 100° C. is shown in table 15-1. Of the 10.06-percent loss in weight by the highly resinous wood, most was attributable to loss of holocellulose content; some extractives were lost, but lignin remained unchanged. In slightly resinous wood, however, only about half the total weight loss of 13.88 percent occurred in the holocellulose; the rest was attributable to extractives loss, as lignin content remained unchanged. In table 15-1, pentosans (such as xylan) comprise part of the total hemicellulose content.

There is a lack of agreement on the contribution of extractive materials to the chemical resistance of wood. Baechler (1954) stated that—depending upon chemical reactivity and the manner in which they are distributed—extractives may contribute materially to resistance. This view is shared

TABLE 15-1.—*Effect of 1 percent sulfuric acid (5 hours at 100°C) on the composition of longleaf pine wood (Campbell and Bamford 1939)*

Material	Highly resinous		Slightly resinous	
	Original wood	Hydrolyzed wood	Original wood	Hydrolyzed wood
	----- Percent of original oven-dry weight -----			
Total loss due to treatment		10.06		13.88
Cold water soluble.....	.92	.26	2.29	.20
Hot water soluble.....	3.03	2.53	3.51	.74
1 percent NaOH soluble.....	35.79	35.04	15.19	14.51
Alcohol-benzene soluble.....	23.98	21.90	1.74	.80
Hollocellulose.....	45.41	37.71	52.92	46.09
Alpha-cellulose.....	33.44	26.15	40.50	34.33
Lignin.....	21.18	21.43	29.60	29.89
Pentosans.....	7.22	5.17	11.40	7.34

by Martin (1954). Campbell and Bamford (1939) however, found no evidence that extractives have any appreciable protective effect on the cell wall substance, once the chemical diffuses into the cell wall (table 15-1). On the contrary, they found the holocellulose of highly resinous pine specimens somewhat less resistant to acids than that of slightly resinous specimens.

Extractives decrease the permeability of wood, and thus contribute to the utility of wood for vats and tanks (Campbell and Bamford 1939; Gobie 1954). Permeability and other physical properties such as density, however, have not been found to contribute directly to chemical resistance (Wangaard 1966).

Strength retention.—If the lengths of cellulose molecules in wood are reduced, tensile strength is diminished (Ifju 1964). According to McBurney (1954), the primary action of acid solutions on cellulose is the hydrolytic scission of the B-glucosidic linkage, thus reducing the degree of polymerization of the chain molecules. Hydrolytic action is rapid at first, being centered in the easily swollen, amorphous regions of the cell wall. As the amorphous regions disappear, the rate of hydrolysis is reduced, and further cleavage of bonds occurs only as the acid solution diffuses into the crystalline regions of the fiber.

This mode of action of acids on wood suggests that resistance to chemical degradation may more logically be accounted for by the degree of molecular compactness, as suggested by Wangaard (1966), than by alpha-cellulose content per se. Wangaard reasoned that in wood of a given gross density work-to-maximum load values should vary inversely with molecular compactness, since the strain (deformation) potential of the ordered lattice in the crystallites is relatively small. He concluded that a species with a

high ratio of modulus of rupture to work-to-maximum load should have relatively compact cell walls, and hence a high resistance to chemical attack. He presented experimental evidence which supports this hypothesis.

Because of the action of acids on the carbohydrate constituents of the cell wall, wood subjected to acid degradation becomes embrittled (Wise and Jahn 1952, p. 954). The extent to which this characteristic is manifested varies with the acid concentration, exposure time, and temperature (Baechler 1954; Gobie 1954; Ross 1956; Breyer and Banks 1957; Wangaard 1966).

Strength retained following treatment with acids has been studied in five of the southern pines and one closely related species.

In their study of Caribbean pine, Douglas-fir, and 11 species of hardwoods, Wangaard (1966) and Kass et al. (1970) found that strength retention was highly correlated with changes in total carbohydrate content; they also found, as have other workers (Leopold and McIntosh 1961; Davis and Thompson 1964), that strength retention was correlated with hemicellulose content. The 1970 work indicated that a low pentosan content and a high pentosan retention correlate well with resistance to acid degradation as measured by strength retention. Wangaard's (1966) strength retention data from 1/2- by 1/2- by 9-inch specimens follow; specimens were first water-soaked, then immersed in the hydrochloric acid solution, and finally tested in bending while still wet.

Duration and temperature of treatment, and concentration of hydrochloric acid (percent)	Modulus of rupture		
	Caribbean pine	Douglas-fir	Average of 11 species of hardwoods
	----- <i>Percent of untreated control</i> -----		
After 32 days at 20° C.			
2-----	102	91	87
10-----	72	76	56
After 4 days at 50° C.			
2-----	75	85	70
10-----	60	57	42

Dilute hydrochloric acid at low temperature had little effect on modulus of rupture of the pine. The stronger solution, or the weaker solution at higher temperature, caused substantial weakening, but less than that caused in the hardwoods.

Thompson (1969, p. 9) evaluated the strength change in specimens of the four major southern pine species following exposure to hydrochloric acid. He used the same general procedure as Wangaard (1966) and reported strength retentions as follows (each value is the average for 10 specimens):

Duration and temperature of treatment, and pine species	Modulus of rupture		Work to maximum load	
	2 percent HCl	10 percent HCl	2 percent HCl	10 percent HCl
----- <i>Percent of control</i> -----				
After 30 days at 20° C.				
Slash.....	105	85	108	57
Longleaf.....	104	83	98	51
Shortleaf.....	97	80	79	36
Loblolly.....	87	67	80	28
Average.....	98	79	91	43
After 4 days at 50° C.				
Slash.....	91	68	53	34
Longleaf.....	90	73	54	31
Shortleaf.....	84	67	45	31
Loblolly.....	79	60	47	26
Average.....	86	67	50	31

Thompson observed that his samples of slash and longleaf pine wood retained more strength than did shortleaf and loblolly pine. In all cases strength retention was reduced by increasing acid concentration or by increasing temperature of exposure. Work to maximum load was reduced more than modulus of rupture.

Manwiller and Godfrey² studied the effects of five acids on the tensile strength and modulus of elasticity of microtensile specimens of spruce pine. Dry specimens—300 to 400 μm . thick—were covered with 10-percent concentrations of acid held at 90° C.; after exposure for 1, 2, or 3 hours, the specimens were water-washed free of acid, dried, and tested at about 10-percent moisture content. A total of 1,080 observations were made on acid-treated earlywood and latewood specimens drawn from 12 trees cut at a number of locations within the commercial range of the species.

They found (table 15-2) that tensile strength of both earlywood and latewood was diminished significantly by hydrochloric and sulfuric acids; latewood—but not earlywood—tensile strength was diminished by exposure to nitric acid. Work to maximum load was diminished significantly in latewood by all acids tested except acetic; in earlywood, only hydrochloric and sulfuric acids significantly reduced work to maximum load. Modulus of elasticity of the acid-treated wood was not significantly different than that of the untreated controls except that both earlywood and latewood treated with nitric acid had significantly higher values than those of the untreated controls; the reason for these higher values is not clear.

The evidence described thus far—and that shown in table 15-3 which

² Manwiller, F. G., and Godfrey, P. R. Tensile properties of microspecimens of spruce pine as affected by position in stem and chemical degradation. USDA Forest Service, Southern Forest Experiment Station, Alexandria, La., Final Report FS-SO-3201-1.7 dated May 1, 1972.

TABLE 15-2.—Retention of original dry strength by microtensile specimens of spruce pine after 1- to 3-hour immersion in acid solutions¹ at 90°C.² (Data from Manwiller and Godfrey; see text footnote²)

Acid	Tensile strength		Modulus of elasticity		Work to maximum load	
	Early-wood	Late-wood	Early-wood	Late-wood	Early-wood	Late-wood
	----- Percent of untreated control -----					
Acetic.....	100	96	104	96	102	77
Hydrochloric.....	73	64	94	95	58	36
Nitric.....	103	84	128	130	95	54
Phosphoric.....	103	86	101	96	94	64
Sulfuric.....	83	61	103	95	60	34

¹ 10-percent concentration, basis of weight of solute/volume of solution.

² Averages for specimens immersed 1, 2, and 3 hours. Each number is the average for 108 specimens.

permits comparison of strength retentions observed by four additional investigators—indicates that strength of southern pine wood is less affected by acetic acid than by most other acids. It is also evident that hydrochloric and sulfuric acids at high temperature can diminish the strength of southern pine wood substantially; effects are not great if the acids are of low concentration and at low temperature. Guy (1946) studied the use of treated wood exposed to 30-percent hydrochloric acid and found that only southern pine and southern cypress (*Taxodium distichum* (L.) Rich) could be employed successfully in contact with acid of this strength. He reported that the service life of all species tested decreased 5 to 6 days for every 1° C. increase in exposure temperature. The service life of all wood was so short at temperatures above 35° C. that for such exposure he recommended the use of other construction materials whenever possible.

While available data are not extensive, it appears from table 15-2 that short exposure to hot nitric or phosphoric acid may cause less strength loss than similar exposure to sulfuric or hydrochloric acid. Data in table 15-3, however, suggests that longer exposure to solutions of nitric acid damages southern pine heartwood more than equivalent exposure to sulfuric acid.

ALKALIS

Alkalis affect wood much more drastically than acids of the same concentration (Narayanamurti and Ranganathan 1947; Baechler 1954; Gobie 1954; Ross 1956; Stamm 1964; Wangaard 1966). According to Wise and Jahn (1952, p. 954), alkalis at room temperature dissolve part of the hemicellulose and attack the lignin slightly to form alkali-lignin complexes.

TABLE 15-3.—*Percent retention of original wet strength of southern pine wood after exposure to various chemicals under the conditions noted¹*

Reference, solution concentration, and duration of exposure	HNO ₃	H ₂ SO ₄	CH ₃ - COOH	HCl	NaOH	Na ₂ CO ₃	Number of species tested and relative resistance of southern pine ²
----- Percent -----							
Baechler (1954) ³							(4 softwoods)
2%, 7 days ⁴ ---	81	96	106		29	70	
2%, 14 days ⁴ --	39	70	92		26	64	Average rank of 2.3
2%, 35 days ⁴ --	49	72	94		25	73	
6%, 7 days ⁴ ---	36	82	82		---	69	
6%, 7 days ⁵ ---	---	---	---		24	---	
6%, 35 days ⁵ --	85	97	94		28	83	
6%, 70 days ⁵ ---	---	102	106		---	90	
Breyer and Banks (1957)							(3 softwoods)
3%, 30 days---		105					1
3%, 210 days--		101					2
3%, 365 days--		94					1
Alliott (1926)							(teak, oak, pine)
10%, 82 days--		111					1
20%, 82 days--		84					1
5%, 82 days--				82			1
15%, 82 days--				54			1
50%, 135 days-			80				1
80%, 135 days-			102				1
Ross (1956)							(16 soft- woods)
5%, 105 days-		92					5
20%, 62 days--		67					8
5%, 71 days--	56			(73)			16(3)
20%, 23 days--				27			10
20%, 41 days--	28						2
5%, 176 days-			102				2
20%, 94 days--			82				7
1%, 87 days--					53		7
10%, 79 days--					34		4
20%, 22 days--					18		1

¹ All were exposed at 25° C. unless otherwise noted; for a description of test modes, readers should consult the references.

² Rank 1 indicates the most resistant species in the group tested.

³ Heartwood.

⁴ 50° C.

⁵ 28° C.

At high temperatures and pressures most of the hemicellulose and a high percentage of the lignin are removed, as in the commercial alkaline pulping of wood. Wood exposed for a prolonged period of time to caustic solutions at high temperatures approaches complete solubility (Wise and Jahn 1952, p. 937). Alternate exposure to acid and alkali is the most severe service condition to which wood can be subjected (Gobie 1954). Hydrolysis by the acid produces products soluble in the alkali, which in turn swells the fiber, making the wood more permeable to the acid.

Most studies specific to southern pine wood have been concerned with the effects of sodium hydroxide (Baechler 1954; Ross 1956; Wangaard 1966; Thompson 1969; and Manwiller and Godfrey²). The effect of calcium hydroxide and potassium hydroxide were also observed by Manwiller and Godfrey² in their study of spruce pine wood.

Effect on chemical composition.—Wangaard (1966), determined the retention of chemical constituents in wood of 13 species after exposure to 10-percent sodium hydroxide. Specimens measured 1/2-inch square and 9 inches along the grain. Retention was as follows:

Duration and temperature of treatment, and constituent	Caribbean pine	Douglas-fir	Average for 11 hardwoods
--- Percent (by weight) of original content ---			
After 32 days at 20° C.			
Holocellulose.....	97	95	80
Hemicellulose.....	83	80	49
Alpha-cellulose.....	104	106	104
Lignin.....	98	91	90
After 4 days at 50° C.			
Holocellulose.....	92	88	79
Hemicellulose.....	75	71	49
Alpha-cellulose.....	101	100	98
Lignin.....	94	88	85

Hemicellulose content was substantially reduced, and lignin content slightly reduced, by the alkali treatment. Compared to the other species, however, the pine retained a relatively high proportion of both hemicellulose and lignin. Alpha-cellulose content is, by definition, unchanged by exposure to sodium hydroxide in concentrations of 17.5 percent or less (American Society for Testing and Materials Designation D 588-42, reaffirmed 1955).

Strength retention.—There have been several studies of the strength retained by pine wood following treatment with sodium hydroxide. In addition, one study included effects of calcium hydroxide and potassium hydroxide (Manwiller and Godfrey²).

Strength retention in wood of 13 species treated with sodium hydroxide was reported by Wangaard (1966); his specimens, which measured 1/2-inch square and 9 inches along the grain, were tested wet in bending following immersion in the alkali. Retention of modulus of rupture was as follows:

Duration and temperature of treatment, and concentration of sodium hydroxide (percent)	Caribbean pine	Douglas-fir	Average of 11 species of hardwoods
	----- Percent of untreated control -----		
After 32 days at 20° C.			
2.....	65	56	29
10.....	53	39	25
After 4 days at 50° C.			
2.....	53	40	32
10.....	37	28	22

While pine had the greatest strength retention at both concentrations and temperatures, it was weakened substantially by exposure to low concentrations of sodium hydroxide, even at room temperature.

Thompson (1969, p. 9), using the same general procedure as Wangaard (1966), studied the strength change in wood specimens from the four major southern pine species caused by exposure to sodium hydroxide. He reported strength retentions as follows (each value is the average for 10 specimens) :

Duration and temperature of treatment, and pine species	Modulus of rupture		Work to maximum load	
	2 percent NaOH	10 percent NaOH	2 percent NaOH	10 percent NaOH
	----- Percent of control -----			
After 30 days at 20° C.				
Slash.....	65	57	91	77
Longleaf.....	72	60	95	79
Shortleaf.....	62	55	67	60
Loblolly.....	63	45	63	54
Average.....	66	54	79	68
After 4 days at 50° C.				
Slash.....	73	57	71	57
Longleaf.....	80	62	80	63
Shortleaf.....	73	55	70	56
Loblolly.....	77	55	78	36
Average.....	76	57	75	53

These modulus of rupture retentions are lower than his comparable figures for southern pine wood exposed to hydrochloric acid; work to maximum load, however, was less adversely affected by exposure to sodium hydroxide than by exposure to hydrochloric acid. Slash and longleaf pine specimens tended to resist degradation from sodium hydroxide somewhat better than shortleaf and loblolly; the differences were not pronounced.

Baechler (1954) and Ross (1956) also published quantitative information on the substantial reduction in strength caused by exposure of southern pine to sodium hydroxide (table 15-3).

Manwiller and Godfrey² studied the effects of three alkalis on the tensile

strength and modulus of elasticity of microtensile specimens of spruce pine. Dry specimens—300 to 400 μm . thick—were covered with alkali held at 90° C.; after exposure, the specimens were water-washed free of alkali, dried, and tested at about 10-percent moisture content. A total of 648 observations were made on alkali-treated earlywood and latewood specimens drawn from 12 trees.

They found (table 15-4) that tensile strength and work to maximum load of earlywood, but not latewood, specimens was increased significantly by treatment with all three alkalis tested. Modulus of elasticity of both earlywood and latewood was significantly improved by treatment with either sodium or calcium hydroxide. This improvement in tensile properties was perhaps attributable to alkali attack on hemicellulose and lignin, and lack of attack on alpha-cellulose; softening of the cell wall matrix materials may permit more equitable load sharing by S_2 -layer microfibrils than is possible in untreated wood.

ORGANIC LIQUIDS

The effect of organic liquids on the physical properties of wood is determined in part by their polarity and molecular structure. Based on studies with a series of alcohols, acetone, ethylene glycol, and benzene, Erickson and Rees (1940) concluded that the higher the molecular weight and the more complicated the molecular structure, the less is the effect of organic materials on the strength properties and swelling characteristics of wood. Their data showed a relationship between swelling and crushing

TABLE 15-4.—Retention of dry strength by microtensile specimens of spruce pine after 1- to 3-hour immersion in alkalis at 90°C.¹ (Data from Manwiller and Godfrey; see text footnote²)

Alkali ²	Tensile strength		Modulus of elasticity		Work to maximum load	
	Early-wood	Late-wood	Early-wood	Late-wood	Early-wood	Late-wood
----- Percent of untreated control -----						
Calcium hydroxide.....	138	114	136	119	145	103
Potassium hydroxide.....	120	112	97	114	150	110
Sodium hydroxide.....	140	112	142	118	140	108

¹ Averages for specimens immersed 1, 2, and 3 hours. Each number is the average for 108 specimens.

² The calcium hydroxide solution was saturated at room temperature; both the potassium hydroxide and sodium hydroxide were 10-percent concentrations (on a weight basis).

strength and indicated that there is a close association between degree of polarity of the liquid and the swelling and strength of wood. They attributed to the organic materials studied some distinctive action which did not weaken wood to the extent that water does for the same degree of swelling.

SALTS

Both acid and neutral salts have an effect on wood similar to that of acids under certain exposure conditions (Wise and Jahn 1952, pp. 892, 893). Under other conditions, salts may significantly increase certain strength properties of wood, particularly maximum crushing strength (Erickson and Rees 1940). The exact effect varies with the solubility of the salts, the pH of their solutions, and the position that they occupy in the lyotropic series. Apparently the extent of swelling caused by salt treatment is little related to strength of the treated wood.

Information specific to southern pine wood is limited. Baechler (1954) reported that southern pine exposed to 2- and 6-percent solutions of sodium carbonate for as short a period as 5 weeks retained an even lower percentage of its original strength (64 to 83 percent) than specimens exposed under identical conditions to sulfuric acid (table 15-3). Strength losses incurred by specimens exposed to 6-percent solutions at 28° C. approximately equaled losses caused by nitric acid. Much higher strength retentions (80 to 112 percent) were reported by Ross (1956) for southern pine exposed at room temperature to concentrations of sodium carbonate of 1 to 20 percent for periods of 93 to 175 days. Only by boiling southern pine for 36 days in a 5-percent solution was he able to achieve strength reductions in pine on the order of those reported by Baechler. Ross found an inverse relationship between solution concentration and strength retention. Evidence of a similar relationship was likewise apparent from Baechler's data.

Strong solutions of certain inorganic salts can apparently increase certain strength properties of wood. Erickson and Rees (1940) reported that all chloride salts tested caused increases in the maximum crushing strength of red pine (*Pinus resinosa* Ait.), the greatest as high as 46 percent (table 15-5). Ross (1956) also found rather striking increases in the breaking strength of certain species following prolonged exposure at room temperature to sodium chloride and calcium chloride solutions.

Only the thiocyanate and iodide salts tested by Erickson and Rees (1940) decreased wood crushing strength parallel to the grain. The authors suggested that this result might be related to the ability (peptizing power) of these salts to dissolve proteinaceous materials. Interestingly, crushing strength was not correlated with the extent of swelling caused by the chemical tested. Chloral hydrate, which was also included in the study, caused greater swelling than any of the salts, but increased crushing strength 42 percent. They concluded that mere excessive swelling of wood does not alone cause a decrease in crushing strength.

TABLE 15-5.—*Effect of concentrated aqueous solutions of mineral salts on the maximum crushing strength parallel to the grain of red pine (Erickson and Rees 1940)*

Solute	Concentration	Average strength	Change in
			crushing strength (compared to controls)
	Percent	P.s.i.	Percent
Water ¹		2,300	
LiCl.....	43.3	2,680	+16.5
CaCl ₂	39.6	3,355	+46.0
MgCl ₂	32.6	3,295	+43.3
MnCl ₂	38.6	2,880	+25.2
NaCl.....	26.3	2,830	+23.0
KCl.....	25.5	2,485	+ 8.1
KCNS.....	68.3	2,065	-10.2
KI.....	59.1	1,975	-14.1
KBr.....	39.6	2,340	+ 1.3
K ₂ SO ₄	10.3	2,540	+10.4

¹ This value was for water-swollen wood; the value reported for oven-dry wood was 11,225 p.s.i.

Because many formulations of preservatives and fire retardants contain inorganic salts, their effects on wood strength have more than academic interest. A partial list of salts used in fire-retardant formulations includes the following: ammonium chloride, ammonium phosphate, ammonium sulfate, sodium tetraborate, magnesium chloride, magnesium phosphate, and zinc chloride. Preservative salts include copper chromate, chromated zinc chloride, mercuric chloride, sodium dichromate, sodium chromate, zinc chloride, zinc meta arsenite, copper sulfate, and sodium arsenate. There are very limited published data describing the effect of these chemicals on strength properties of southern pine.

Although Thompson (1964) has shown that the impact strength and toughness of some hardwoods are seriously reduced by treatment (to retentions of 0.5 to 4.0 pounds per cubic foot) with some commercial formulations such as Chemonite, Celcure, and Boliden Salt, comparable data are not available for southern pine.

METALS

Since water in contact with wood always contains electrolytes derived from the wood, when two dissimilar metals are embedded in wood a simple galvanic cell may be formed. If the wood is dampened with salt water, sodium hydroxide forms at the cathode metal and attacks the wood adjacent to it. Chlorine is liberated at the anode and, due to secondary

reactions, may form hydrochloric acid, which attacks both the anode and the adjacent wood. Damage of this type is common where copper and ferrous metals are used together, as in boats or marine structures. Less serious results may ensue, however, under nonmarine exposure where two dissimilar metals are in contact with damp wood (Evans 1960). Uhlig (1963) cites an example of the deterioration of wood adjacent to a gutter composed in part of copper and in part of iron.

Much more common is the deterioration of wood in contact with rusting iron. According to Farmer (1967), iron in an electrolyte such as moist wood develops a high hydroxyl ion concentration in the surrounding medium. The initial chemical reaction between iron and wood is believed to be auto-oxidative and autocatalytic; iron catalyzes oxidation and depolymerization by molecular oxygen (Bell and Gibson 1957). Ferrous hydroxide, the first formed product of corrosion, is oxidized to the ferric form on exposure to air. While changing from one state to the other, iron very actively catalyzes the oxidation of cellulose to form oxycellulose. The formation of this product causes embrittlement and loss of tensile strength in the wood (Farmer 1967).

In studying the withdrawal resistance of nails driven into green oak (*Quercus* spp.), beech (*Fagus* spp.), and southern pine, Stern (1950) found major reductions in nail-holding properties after the wood had been seasoned for 3 to 7 months. The reduction in southern pine was 73 percent compared to values obtained immediately after nailing. Stern attributed this reduction to chemical digestion of the cellulose at the wood-nail interface. He reported that resin acids in green or partially seasoned southern pine may result in deterioration of the cellulose along the nail shank without any discoloration of the wood. Deterioration varied directly with the moisture content of the wood.

Studies by Marian and Wissing (1960abcd) with Scotch pine (*Pinus sylvestris* L.) veneer provide data whose trends are probably applicable to the southern pines. Wood in contact with iron under moist conditions showed reduced tensile strength, but compressive strength was unaffected. Tensile strength continued to decline with time up to 9 months. Heartwood was less affected than sapwood during the first 3 months, but at 9 months differences were not significant. Analysis showed that attack was primarily on the carbohydrate fraction of the wood, which contributes most to tensile strength. Either galvanizing or a synthetic resin coating on the iron prevented deterioration of the laboratory samples. Creosote treatment lessened deterioration, but salt-type preservatives promoted it.

Acids in woods increase the rate of corrosion of metals and, by increasing the solubility of the primary corrosion products, may accelerate the degradation of the wood itself (Evans 1960). Acetic acid, the most common acid found in wood (Packman 1960; Farmer 1962ab), may be liberated spontaneously under proper atmospheric conditions. Free carbonic and formic acids have likewise been identified in wood (Shreir 1963, p. 19.75).

Under conditions of oxidative degradation, the following additional acids may be isolated from wood (Merriman et al. 1966): oxalic, succinic, fumaric, benzoic, isophthalic, hemimellitic, and trimellitic.

Temperature and humidity affect the quantity of free acid in wood, and its tendency to corrode metals. According to Packman (1960) any sample of wood, regardless of its past history, will give rise to some free acetic acid under appropriate conditions of humidity and temperature. The tendency of wood to corrode metals is not necessarily nor invariably related to its pH (Farmer 1962ab) because a given pH value may represent either a small quantity of a strong acid, such as oxalic or formic, or a large quantity of weaker acids, such as carbonic or acetic (Shreir 1963, p. 19.75).

The pH of commercial timber species ranges from about 3.0 to 6.0 (Gray 1958; Packman 1960; Farmer 1962b; Shreir 1963, p. 19.76). A few species, such as western red cedar, have pH values of less than 3.0, and a few hardwoods have values above 7.0. The rate of corrosion of metal in contact with wood increases markedly when the pH falls below about 4.0 if moisture is present (Gray 1958; Farmer 1962b). Included among the conifers with pH values of 4.0 or lower are Caribbean pine, Douglas-fir, and western red cedar (*Thuja plicata* Donn). The pH of southern pine wood is about 4.7 to 5.0 (McCool 1948; Stamm 1961).

The pH of wood is reported to be decreased by kiln-drying (Farmer 1962b) and prolonged exposure to ultraviolet light (Webb and Sullivan 1964).

METHODS OF IMPARTING CHEMICAL RESISTANCE

Various methods of protecting wood in contact with corrosive chemicals have been investigated.

Acid and alkalis.—Guy (1946) reported that impregnating wood with coke-oven coal tar with a viscosity of 1,250 to 1,450 Saybolt seconds at 200° F. will increase the service life of wood exposed to hydrochloric acid 150 to 175 percent. An additional 15-second dip in hot asphalt can further increase service life by 50 to 100 percent. Southern pine treated by a similar process was not attacked after exposure in a spray-type pickling machine to 10 to 15 percent sulfuric acid at 180° C. for 18 months. Treatments with molten paraffin were found to be less effective and applications of acid-resistant paints ineffective.

Goldstein (1955) reports that impregnation of wood with a furfuryl alcohol resin imparts high resistance to both acids and alkalis. Apparently the relatively small furfuryl alcohol molecule penetrates the cell wall where it is polymerized. Resin-treated southern pine, after boiling in 10-percent sodium hydroxide for 24 hours, lost only 9 percent of its crushing strength; in untreated control specimens, crushing strength was reduced 75 percent.

Asphalt and coal tar are resistant to acids, but it is difficult to apply them as coatings so that acids cannot gain contact with the wood (Hauser and Bahlman 1931).

Wood impregnated with phenol-formaldehyde resin is resistant to acids, but not to sodium hydroxide (Narayanamurti and Ranganathan 1947).

Metals.—Degradation caused by electrolytic action between copper and ferrous metals can be minimized if wood is kept dry in service.

Treatment with creosote has been reported to lessen the deterioration of wood in contact with iron (Marian and Wissing 1960c). Service conditions that cause wood to have a pH higher than 4.0 diminish deterioration of wood in contact with iron.

If ferrous nails and fittings are galvanized, deterioration of attached wood is lessened. Aluminum or stainless steel nails are particularly effective in eliminating nail-associated discoloration.

15-2 EXPOSURE TO HEAT¹

There is a range of temperature—generally above 150° F. and short of that required for outright destruction—within which wood undergoes chemical degradation and sustains permanent losses in strength. This is in contrast to the temporary effect illustrated in figure 10-7. The degree of degradation is dependent on the heating medium, as well as the duration and temperature of exposure. In general, heating in dry air causes less degradation than heating in water at the same temperature. A steam atmosphere is more damaging to wood than either air or water at the same temperature (MacLean 1951).

MacLean (1953, 1954), in tests of Douglas-fir and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) heated in air, water, and steam, has shown that strength properties in bending are affected by heat in the following order—beginning with the property suffering most reduction: (1) work to maximum load; (2) modulus of rupture; (3) fiber stress at proportional limit; and (4) modulus of elasticity.

DEGRADATION FROM OVEN HEATING

Millett and Gerhards (1972) observed that small specimens of clear southern pine ($\frac{1}{4}$ by $\frac{1}{2}$ by $6\frac{1}{2}$ inches long) lose a substantial amount of weight and bending strength if exposed for extended periods to temperatures above the boiling point of water; modulus of rupture of their specimens was reduced by nearly half if exposed 255 days at 115° C., 48 days at 135° C., 12 days at 155° C., or 3 days at 175° C. (table 15-6). Modulus of elasticity was less drastically affected.

A 1954 report by J. D. MacLean, titled "Effect of oven heating and hot pressing on strength properties of wood" (on file in the USDA Forest Products Laboratory, Madison, Wis.), indicated that exposure in a hot press caused a little more strength loss than the same temperature and duration of heating in an oven.

TABLE 15-6.—*Residual weight and flexural properties of clear southern pine wood heated in air at 115° to 175°C.*¹ (Millett and Gerhards 1972)

Temperature and duration of exposure (days)	Moisture content at test	Residual modulus of elasticity	Residual modulus of rupture	Residual weight of heated specimens
		----- Percent -----		
115° C.				
64-----	6.0	100.0	82.8	97.9
128-----	5.3	102.6	75.0	96.6
192-----	5.2	97.4	65.2	95.5
255-----	5.1	97.4	56.4	94.5
135° C.				
16-----	6.7	101.3	79.9	97.2
34-----	5.1	97.4	63.7	95.0
48-----	4.8	93.2	52.0	93.7
64-----	4.5	96.6	52.4	92.3
155° C.				
4-----	5.4	99.1	74.0	96.5
8-----	5.0	96.6	60.8	94.3
12-----	4.6	94.5	54.4	92.3
16-----	4.5	91.9	44.6	90.9
175° C.				
1-----	-----	101.7	76.0	-----
2-----	-----	95.3	61.8	-----
3-----	-----	95.3	52.9	-----
4-----	-----	87.6	44.1	-----

¹ Specimens measured $\frac{1}{4}$ inch tangentially, $\frac{1}{2}$ inch radially, and 6- $\frac{1}{2}$ inches longitudinally. Strength values are relative to controls tested at 8.6-percent moisture content; MOE and MOR of controls proved to be 2,350,000 and 20,400 p.s.i. respectively.

Data from Millett and Gerhards (1972), and from MacLean, were obtained from small specimens heated when initially dry (12-percent moisture content or less). In green lumber subjected to hot air temperatures, evaporation of the water content helps cool the wood during initial exposure; this diminishes the rate of degradation.

Koch (1971) exposed green 8-foot southern pine 2 by 4's for 21 hours in a steam-air mixture at 240° F. (160° F. wet-bulb temperature) followed by 3 hours at 195° F. dry-bulb and 185° F. wet-bulb temperature; this schedule reduced the moisture content of the wood to 9 percent. The bending strength of these 2 by 4's—which had been cut from veneer cores and small logs—was compared with a matched control set of 2 by 4's dried on a 100-hour schedule during which the temperature never exceeded 180° F. Strength values of 2 by 4's dried at high temperatures proved not significantly different (by analysis of variance) from those 2 by 4's dried at low temperature, as follows:

Property	Strength retention of 2 by 4's dried at 240° F. compared to 2 by 4's dried at temperatures not in excess of 180° F.	
	Percent	
Modulus of rupture.....	95.7	
Fiber stress at proportional limit.....	95.8	
Modulus of elasticity.....	98.1	

The 288 studs evaluated for bending strength were all in the Common and Stud grades (Southern Pine Inspection Bureau rules). The test would have been more sensitive had the lumber been straight-grained and knot-free, i.e., the variation among boards would have been less. Toughness values for small clear specimens cut from the 2 by 4's dried at 240° F. averaged 102.6 percent of those for similar specimens cut from 2 by 4's dried on the low-temperature schedule; this difference was not statistically significant.

DEGRADATION FROM HEATING IN WATER

Wood immersed in water heated to temperatures in excess of 150° F. loses weight and strength. Work to maximum load and modulus of rupture are reduced most; fiber stress at proportional limit and modulus of elasticity are less affected.

MacLean (1954) studied the effect of hot water on clear Douglas-fir and Sitka spruce specimens that measured about 0.16 inch thick, 2 inches wide, and 13 inches long. His conclusions—which he considered applicable to southern pine—are summarized as follows:

Property and water temperature (°F.)	Heating period required to cause degradation		
	Before initiation of decrease	To reduce value by 10 pct.	To reduce value by 20 pct.
Modulus of rupture			
150.....	30 days	600 days	-----
200.....	15 hours	10 days	200 days
250.....	2 hours	8 hours	35 hours
300.....	15 minutes	45 minutes	144 minutes
350.....	5 minutes	12 minutes	26 minutes
Ovendry weight			
150.....	250 days	-----	-----
200.....	4 days	25 days	250 days
250.....	6 days	30 hours	160 hours
300.....	2 hours	6 hours	26 hours
350.....	48 minutes	105 minutes	4.5 hours

MacLean's (1954) data indicate that below 250° F. steam and hot water degrade wood at about the same rate. At 250° F. and above, however, steam causes more rapid degradation than water. Typically, modulus of rupture values for softwood might be 3 percent (at 250° F.) to 8 percent

(at 350° F.) lower in steam-exposed wood than in water-exposed wood.

DEGRADATION FROM STEAMING

The report of Hatt (1906) was possibly the first published information available in this country on the degradation of southern pine wood caused by steaming. Since that time, numerous reports have dealt with the subject (e.g., Buckman and Rees 1938; MacLean 1952, 1953; Wood et al. 1960; Davis and Thompson 1964).

Steam-caused reductions in the strength of southern pine wood are of practical importance to those who process and use preserved wood. For this reason, most of the literature is oriented toward the wood preservation field.

Because wood is not a perfect conductor of heat, it takes a significant amount of time for the central portion of large timbers or poles to equilibrate with steam temperature. MacLean (1930, 1932, 1934) has published many equations and charts specific to southern pine that facilitate prediction of wood temperatures 2, 2½, 3, 3½, and 4 inches in from the external surfaces of poles and timbers after various periods of exposure to steam. For example, if green, round, southern pine poles are steamed at 260° F. and the initial wood temperature is 60°, MacLean's (1934, p. 357) data show the following times are required for wood 2 inches in from the surface to reach 240° F.

<u>Pole diameter</u> <i>Inches</i>	<u>Duration of steaming</u> <i>Hours</i>
4	2
6	4½
8	7
10	10
12	13
14	16
16	19
18	22
20	26
22	30
24	32

Mechanical damage.—Steaming of timbers and poles may reduce their strength by chemical degradation and by mechanical damage in the form of burst checks and pith checks (fig. 17-37). Such mechanical defects are common in poles steam-conditioned prior to full-cell treatment with water-borne preservative (Blew et al. 1961, figs. 1 through 10). Poles conditioned by boiling in oil under vacuum are particularly prone to internal checking.

Wood et al. (1960, pp. 48, 49, 61) found that class 6, 30-foot southern pine poles lost as much as 40 percent of their bending strength (modulus of rupture) during prolonged steaming at 259° F. They observed that strength of re-treated poles differed little from that of poles treated but once. Steaming small clear wood specimens reduced their strength only

about half as much as did steaming poles. They concluded that the difference could be explained by the strength-reducing shakes and other defects that develop during steam treatment of poles; these defects do not develop in small clear specimens similarly treated.

Chemical degradation.—Wood heated in an atmosphere of steam undergoes changes in its chemical and physical properties not unlike those caused by exposure to mineral acids (Baechler 1954). The wood loses weight and strength, becomes discolored, and undergoes chemical degradation. Steam at atmospheric pressure causes mild hydrolysis; the hydrolysis is catalyzed by natural acids in the wood and becomes progressively more severe with increasing temperature and time of exposure. The carbohydrate fraction of wood, and more especially the hemicellulose components, are particularly susceptible to hydrolysis, and are decomposed into various degradation products (MacLean 1951).

MacLean (1951) investigated weight loss—a manifestation of chemical degradation—in small specimens of southern pine and 10 other species subjected to steaming at temperatures of 250 to 350° F. for periods of from 8 to 240 hours. Southern pine consistently sustained more loss in weight than the other three conifers included in the study. Its average weight loss for all temperatures and heating periods, 33.4 percent, exceeded the average for all species, seven of which were hardwoods. Loss of resin during steaming probably accounted in large part for this result. Southern pine steamed for 15 hours lost 8, 20, and 30 percent of its oven-dry weight at steaming temperatures of 250, 300, and 350° F., respectively. Comparable values for Douglas-fir were 5, 15, and 26 percent.

Thompson (1969, p. 20) reported the effect of steaming on the chemical content of southern pine wood. Small clear specimens were subjected to steaming periods of 0, 4, 8, 12, 16, and 20 hours at 245° F. Steaming changed all chemical components. Each of the three carbohydrate fractions (holocellulose, alpha-cellulose, and hemicellulose) was reduced by several percentage points, while the apparent lignin content increased. Changes in percent composition varied more or less linearly with duration of steaming. Hemicellulose content decreased steadily with steaming time; changes in alpha-cellulose content, however, were largely confined to exposure periods of 12 hours and longer (fig. 15-1).

Thompson concluded that steaming small specimens of southern pine wood for 20 hours at 245° F. has approximately the same effect, in terms of changes in chemical composition, as soaking for 4 days at 50° C. in either 10-percent sodium hydroxide or 10-percent hydrochloric acid.

Correlation between toughness and chemical composition.—Thompson (1969, p. 20) related the diminished toughness he observed in steamed southern pine wood to levels of holocellulose, alpha-cellulose, and hemicellulose (fig. 15-2). The positive linear correlations he found between toughness and all three cellulose components were highly significant, with r values of 0.92 to 0.94.

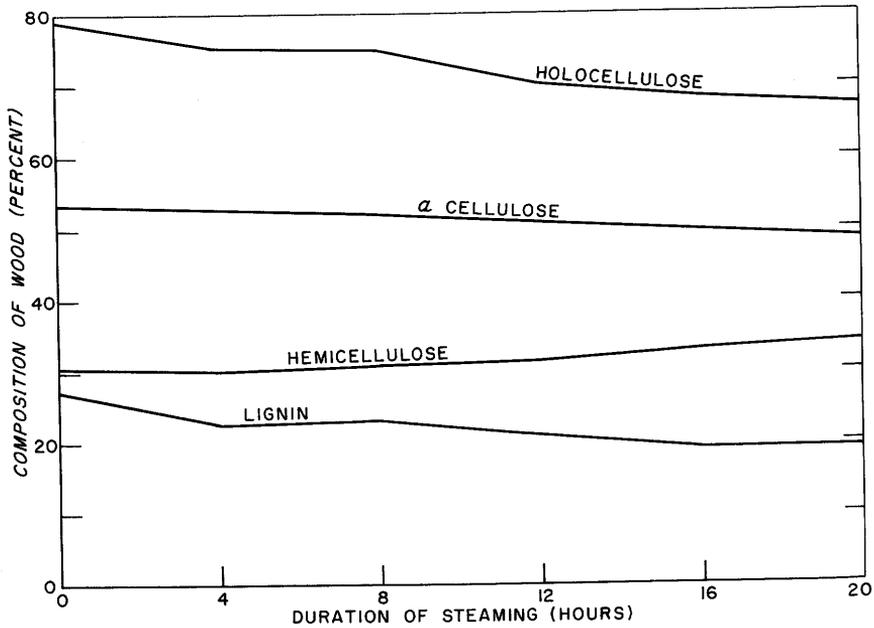


Figure 15-1.—Influence of steaming time at 245° F. on chemical composition of small clear specimens of southern pine wood. (Drawing after Thompson 1969, p. 22.)

Strength reduction.—MacLean (1953) observed the loss of bending strength in 0.16- by 2- by 13-inch clear specimens of southern pine wood steamed at temperatures of 250, 300, and 350° F. for periods of from 8 to 32 hours. Work to maximum load was most affected; modulus of rupture was next, followed by fiber stress at proportional limit. Modulus of elasticity was least affected (fig. 15-3). Steaming at 350° F. caused substantially more strength loss than steaming at 250° F. (table 15-7). Beginning at 250° F., the duration of steaming required to cause a given reduction in strength is about halved for each 10 to 15° F. increase in temperature.

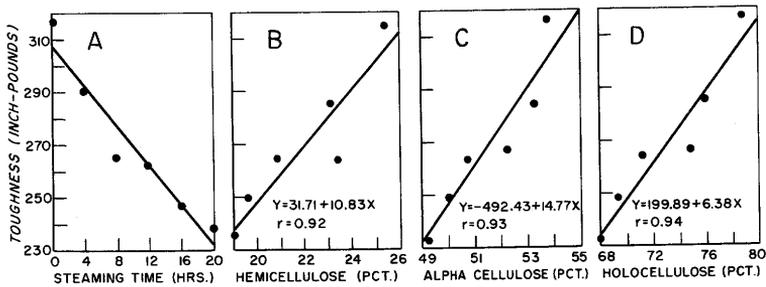


Figure 15-2.—Relationship between toughness of small clear specimens of southern pine wood steamed at 245° F. and: (A) duration of steaming; (B) hemicellulose content; (C) alpha-cellulose content; (D) holocellulose content. (Drawing after Thompson 1969, pp. 21, 23, 24, 25.)

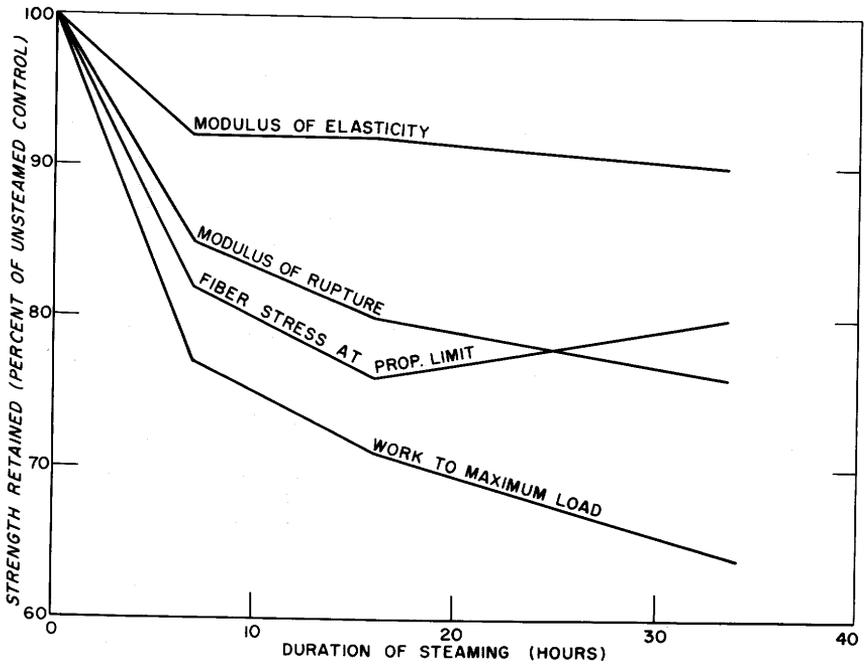


Figure 15-3.—Bending strength of small clear specimens of southern pine as related to duration of steaming at 250° F. (Drawing adapted from MacLean 1953.)

TABLE 15-7.—Strength retention in small clear specimens of southern pine wood steamed for 8, 16, and 32 hours (adapted from MacLean 1953)

Property	Steaming period	Strength retention		
		250° F.	300° F.	350° F.
	<i>Hours</i>	<i>Percent of control</i>		
Work to maximum load..	8	78	41	24
	16	71	40	----
	32	63	----	----
Modulus of rupture.....	8	83	63	42
	16	80	56	----
	32	77	----	----
Fiber stress at proportional limit.....	8	81	69	50
	16	76	58	----
	32	80	----	----
Modulus of elasticity.....	8	91	85	65
	16	91	78	----
	32	90	----	----

Davis and Thompson (1964) found that steaming periods of less than 1 hour at 260 to 300° F. significantly reduced toughness and changed chemical composition of 3/4- by 3/4- by 10-inch specimens of southern pine wood. Similar relationships, reported by Thompson (1969), are shown in figure 15-2.

MacLean found that the several species of softwoods he steamed had similar patterns of strength retention; in general, hardwoods lost more strength than softwoods when steamed.

As mentioned previously, mechanical damage due to internal stresses causes large pieces such as poles and piling to sustain greater strength losses from commercial steaming than small laboratory specimens.

Thompson (1969) compared reductions in strength of 30-foot, class 6 southern pine poles following conditioning by kiln-drying at low temperatures and by steaming at 245° F. for 14 hours. The temperature and duration of steaming conformed to Designation C4-67 of the American Wood Preservers Association (1969). His results are summarized in table 15-8.

Poles thus steamed (as permitted under current standards) had significantly lower values than kiln-dried poles for all strength properties except modulus of elasticity. Modulus of rupture was most affected, followed by fiber stress at proportional limit.

The maximum fiber stress at the groundline for poles kiln-dried at 152° F. was 7,902 p.s.i. The comparable value for poles steam conditioned for 14 hours at 245° F. was 5,747, a 37-percent reduction attributable to the steaming. The reductions in modulus of rupture at the point of failure (breakpoint) and the proportional limit were 32 and 26 percent respectively. Maximum crushing strength parallel to the grain, which was determined on 3-foot sections cut from the test poles, was reduced 14 percent by steaming. In a related test of 300 southern pine piling sections, steaming for 16 hours at 245° F. reduced crushing strength 29 percent compared to matched, untreated specimens (Thompson 1969).

Unlike strength in bending and compression, the stiffness of the test poles was not significantly affected by steaming. The average modulus of elasticity of kiln-dried poles exceeded that for steamed poles by only 4 percent. Similar results were obtained in tests on small, clear bending and compression specimens, for which values for steamed and kiln-dried poles differed by less than 1 percent. Similarly, tests of the 300 piling sections (Thompson 1969, p. 20) revealed differences in modulus of elasticity between steamed and matched untreated sections of about 1 percent.

15-3 EXPOSURE TO LIGHT

Light is a component of the **electromagnetic spectrum** (fig. 15-4). While the waves shown in figure 15-4 are all electromagnetic in nature and have the same speed in free space, they differ in length and in fre-

face contains ultraviolet light with waves generally not shorter than about 0.29 μm . or 2900 A. (an angstrom is 10^{-10} m.).

When exposed to the sun's radiation—visible and invisible—the surface layer of wood changes color and suffers both physical and chemical degradation. The ultraviolet component of sunlight appears to be the principal cause of the observed changes. Surface wetting, if combined with ultraviolet radiation, accelerates degradation of wood surfaces (fig. 25-9).

COLOR CHANGES

When southern pine is exposed to light, it darkens; figures 9-4 and 9-5 illustrate the change quantitatively. This change occurs rapidly in sunlight; it also occurs, but at a much slower rate, in the more subdued natural light within buildings, which lacks most of the ultraviolet wavelengths of sunlight. If exterior exposure to sunlight and rain is continued, southern pine wood will ultimately become gray in color—generally without sheen. Throughout most of the South, the presence of dark-colored spores and mycelia of fungi may cause weathered wood to have a dark gray, blotchy, and unsightly appearance. Weathered bare southern pine will usually attain a clean silvery appearance only if exposed in very dry climates or in coastal regions where salt atmospheres may inhibit the growth of micro-organisms.

Browne and Simonson (1957) measured the depths of the discolored layers in a number of western softwoods. They found the gray-colored layer in well weathered wood to be about 0.005 inch thick; it was comprised of loosely matted, largely delignified cellulose fibers. Underlying the gray layer they observed a well-browned layer measuring 0.02 to 0.1 inch thick; in this browned layer the orderly structure of wood was retained. The lignin-rich middle lamella was deeply browned. Throughout the brown layer, the content of water soluble extractives was greater than normal. Below the brown layer, the wood was essentially unchanged.

In their study, Browne and Simonson (1957) found that ultraviolet light penetrates no more than a few mils into wood. Visible light is intermediate in its ability to penetrate wood, and infrared light penetrates deepest of the three. Browning at the surface occurs more rapidly under ultraviolet light than under visible or infrared light. Under exposure to visible light it occurs to a depth much beyond the depth of penetration of ultraviolet light. As wood becomes browned, the depths to which visible light penetrates decreases. While the depth of the brown layer in western larch (*Larix occidentalis* Nutt.) exposed to visible light was often 0.1 inch, the authors observed that only about 0.016 percent of visible light penetrated to that depth. They concluded that the brown degradation products are formed in the thin surface layer penetrated by ultraviolet light and that these products are carried by rainwater into the wood as far as the observed depth of the browned layer.

Characteristically, high-yield pulps from groundwood tend to turn yellow

as they age. Kringstad (1969) concluded, from a review of the literature, that the absorption of light by lignin in the groundwood is responsible for at least a portion of the reactions causing the characteristic yellowing of exposed groundwood.

SURFACE DEGRADATION

Miniutti (1964, 1967) studied the effect of ultraviolet light on the surface structure of several softwoods. While his major work (1967) was with Douglas-fir and redwood (*Sequoia sempervirens* (D. Don) Endl.), he made some limited observations of southern pine (1964). His conclusions, in brief, were as follows.

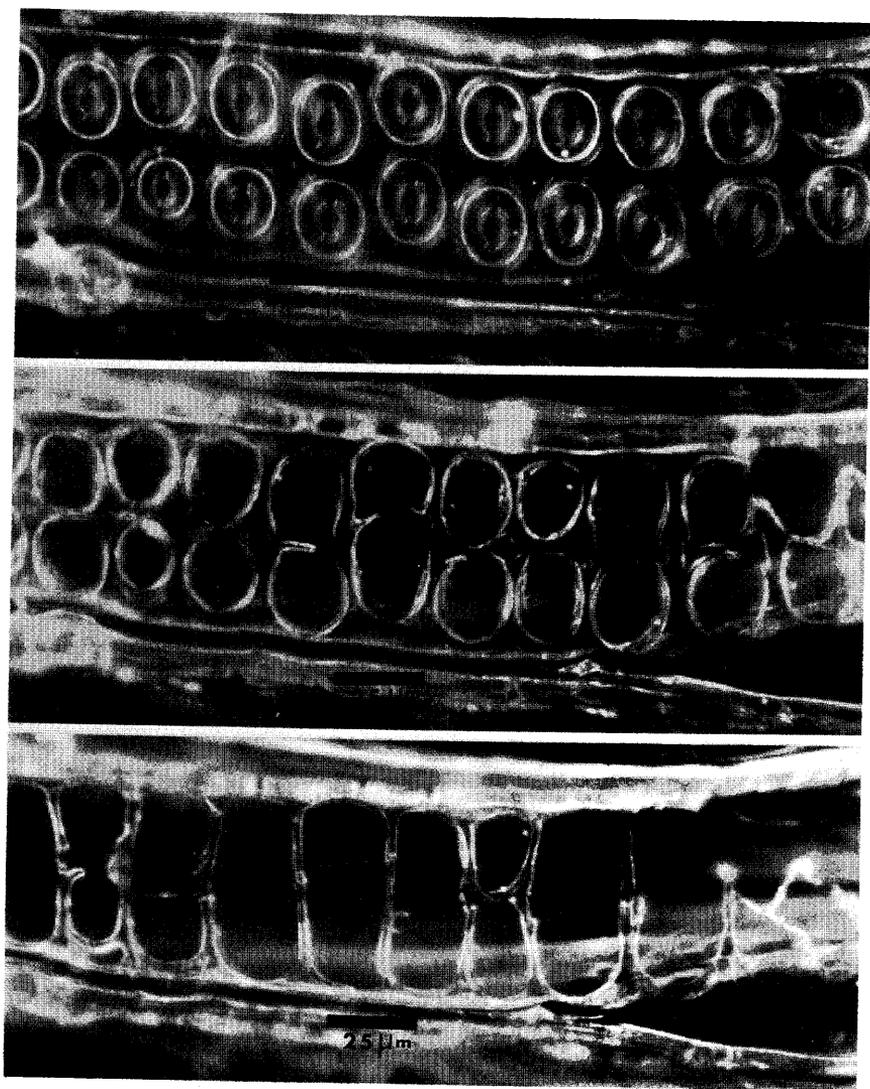
Ultraviolet light to wavelengths of about 2,537 Å. (shortwave ultraviolet) and 3,000 to 4,000 Å. (longwave ultraviolet) degraded wood substance; damage occurred much more rapidly during shortwave irradiation. Fortunately, the shortwave ultraviolet in solar radiation does not reach the surface of the earth. The first conspicuous evidence of deterioration was enlargement of the apertures of bordered pits in radial walls of first-formed earlywood tracheids (fig. 15-5). The pit borders and the surrounding walls were progressively destroyed. The crassulae were the most resistant portions of the earlywood walls in redwood.

In Douglas-fir, the most resistant portion of radial walls in first-formed earlywood tracheids were narrow rings consisting of the portions of pit borders most distant from the aperture. Neither crassulae, if present in the specimens irradiated, nor spiral thickenings were more resistant to photodegradation than the adjacent tracheid wall. Earlywood tracheid walls without pits were much more resistant to photodegradation, and developed less severe diagonal microchecks, than those with pits. Early tracheid walls were seriously embrittled by prolonged irradiation with longwave ultraviolet.

Longwave ultraviolet radiation caused stress concentrations and microchecks at (a) bordered pits, (b) the approximate zone of the compound middle lamellae between latewood tracheids, (c) feathered edges where the microtome knife cut through tracheid walls to open adjacent lumens, (d) the lines formed in radial earlywood surfaces where the adjacent corners of two tracheids contacted the radial wall of a third adjoining tracheid, and (e) the junction—in radial surfaces—of the last-formed row of latewood tracheids with the first-formed row of earlywood tracheids.

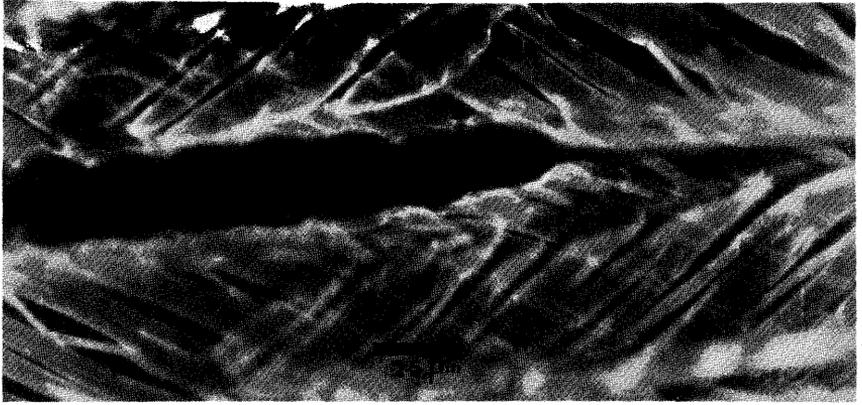
As in earlywood, diagonal microchecking in latewood was more severe when bordered pits were present than when absent.

Double tracheid walls in a tangential latewood surface were resistant to diagonal microchecking apparently because the exposed cell wall tended to be restrained by the less exposed layer beneath, whose microfibrils spiral in the opposite direction (fig. 15-6). Thus, diagonal microchecking was most severe when the knife-cut left a single latewood wall at the surface; it was less severe in a double wall consisting of earlywood over latewood,



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 Figure 15-5.—Views of the same cell wall segment of one of the first-formed earlywood tracheids in a radial surface of unfinished redwood after three periods of longwave ultraviolet irradiation (reflected-light photomicrographs). (A) After 4 weeks, pits appear unaltered. (B) After 19 weeks, borders of pit pairs have been destroyed. (C) After 27 weeks, most of the double tracheid wall has been destroyed, leaving only what appear to be crassulae and an occasional fragment of an annulus. (Photos from Miniutti 1967.)

and least severe when the surface was a double wall of latewood. This indicates that surface degradation could be minimized by a surfacing process designed to prevent exposure of single walls of latewood tracheids. This is difficult to accomplish since most surfacing processes usually cause latewood cells to separate near the intercellular layer, thereby exposing a single wall (figs. 23-7, 25-6, 25-7, and 25-8).



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Figure 15-6.—Tangential latewood surface of redwood compression wood after 27 weeks of longwave ultraviolet irradiation. Double tracheid walls with diagonal microchecks are shown at upper left and lower right, and single tracheid walls in the other two quadrants. Ray cells have been destroyed in the ray at left center. (Fluorescence photomicrograph from Miniutti 1967.)

Longwave ultraviolet produced longitudinal microditches in the compound middle lamellae between adjacent latewood tracheids in wood surfaces; they consisted of a longitudinal radiation microditch above a longitudinal microcheck (see fig. 15-7 for definition of terms). The microditch portion appeared to be caused by more rapid loss of wood

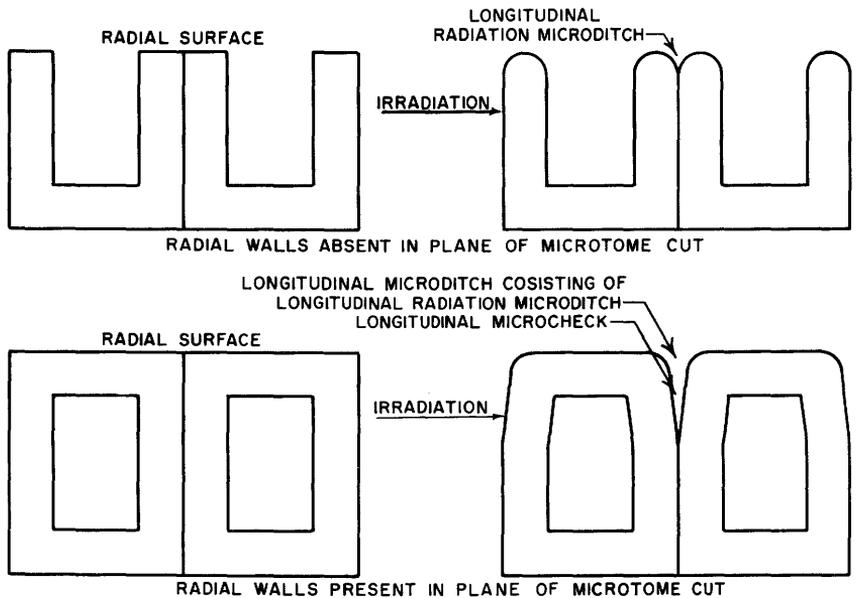


Figure 15-7.—Concept of transverse sections of latewood tracheids showing longitudinal voids that developed in two types of radial surfaces during ultraviolet irradiation. (Drawing after Miniutti 1967.)

substance in these zones of high lignin content than in the adjacent surface of lower lignin content. This indicated that the rate of photodegradation is faster for lignin than for cellulose. The apparent cause of the microcheck portion was loss of wood substance by photodegradation in the adjacent tracheid walls with accompanying shrinkage in the transverse direction and relief of stresses between tracheids.

A specimen of redwood wetted repeatedly during the early stages of longwave irradiation showed the same types of anatomical changes but developed more numerous and more severe microchecks than its unwetted companion, and the wetter surface was always more seriously disrupted. The general appearance of the wetted specimen resembled more closely that of wood in the early stages of weathering than the unwetted specimen did. This indicated that wetting by rain and dew, followed by drying, adds considerably to the general degradation of weathering wood surfaces.

In natural weathering, degradation proceeds fairly slowly; loss of surface cells occurs most rapidly in the earlywood and at a much lower rate in the latewood. From a century of full exposure to the weather, wood—including that of the southern pines—normally loses about $\frac{1}{4}$ inch in thickness. Only part of the loss is due to photodegradation.

Readers interested in scanning electron micrographs of weathered wood surfaces will find publications by Borgin (1970, 1971ab) useful.

CHEMICAL REACTIONS

Irradiation with ultraviolet light in the presence of oxygen causes significant chemical changes in whole wood—both ground and solid, in lignin-rich mechanical pulps, and in alpha-cellulose. For a review and survey of the present state of knowledge, the reader is referred to Kalnins (1966), Kringstad (1969), and Desai and Shields (1969).

Kalnins (1966) concluded, from his own work and that of others, that 11 main features of the photodegradation process are as follows.

(1) Wood is degraded by ultraviolet light. Some simple degradation products which have been identified are carbon monoxide, carbon dioxide, hydrogen, water, methanol, formaldehyde, organic acids, vanillin, and syringaldehyde.

(2) As a result of irradiation, the wood residue is chemically altered. The methoxyl and lignin content is reduced; the acidity and carbonyl concentration is increased, as is the ethanol solubility and especially the solubility in dilute base. Destruction of wood substance is visible on the surface under a microscope.

(3) Irradiation of wood, even by the visible portion of light, produces free radicals in wood.

(4) In the presence of oxygen, photo-oxidation of wood is the dominant process in the middle (about 2,500 to 3,200 Å.) as well as the near (3,200 to 3,800 Å.) ultraviolet region.

(5) In an inert atmosphere or in vacuum, volatile products are also

produced by middle ultraviolet but at a reduced rate. In the near ultraviolet range no volatile degradation products result.

(6) A post-irradiation effect exists in wood, as is shown by decreasing free radical concentration in the presence of oxygen and by the formation of volatile degradation products during storage in the presence of oxygen subsequent to irradiation in an inert atmosphere.

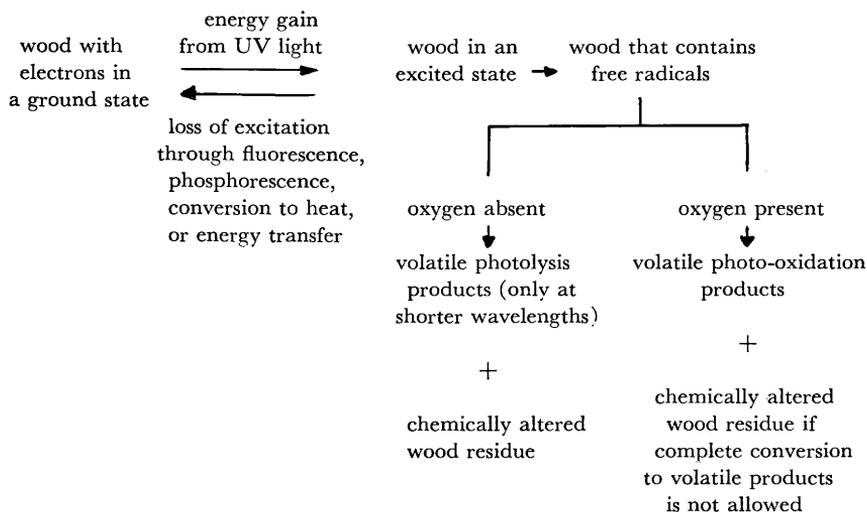
(7) Elevated temperature does not materially alter the rate of the degradation process. High humidity appears to accelerate degradation slightly. Constant rates as well as rates increasing with time of irradiation have been observed for the formation of volatile degradation products from wood.

(8) Variation in the rate of degradation of various species of wood has been observed. The extractives of wood also influence the process.

(9) The quantum yields of the volatile products that were formed from wood during irradiation were estimated to be slightly lower in an inert atmosphere, and slightly higher in an air atmosphere than the quantum yields of volatile products from cellulose.

(10) The quantitative determination of the degradation products of wood as well as the changes in the exposed wood are apparently useful tools for estimating the extent of degradation under various conditions, and may be of use in applied work.

(11) The photodegradation process may be illustrated by this scheme:



In connection with work on penetration of light into wood (Browne and Simonson 1957), Browne compiled some data on southern pine and eight other species of wood weathered outdoors for 30 years; these data were published by Kalnins (1966). Prior to analysis, half the wood was extracted with an alcohol-benzene mixture for 16 hours followed by 95-percent alcohol for 4 hours. The data for southern pine are as follows:

Analysis of weathered southern pine wood

Component and condition	Interior	Brown layer	Gray layer
	----- Percent -----		
Cellulose			
Unextracted	52.2	51.1	49.1
Extracted	50.5	52.2	51.0
Lignin			
Unextracted	30.5	20.0	7.4
Extracted	50.0	21.1	3.7

Weathering decomposed the lignin and made it soluble. Cellulose was less affected. In general, the water-soluble fraction—which appeared to consist of partly decomposed lignin and cellulose—was greatest in the gray layer and least in the interior.

Kalnins (1966) compared degradation products from earlywood and latewood obtained from a fast-grown green southern pine. The groundwood—18 g. of each type—was irradiated with ultraviolet light (wavelength of 2,537 Å.) for a period of 168 hours in an air atmosphere. Larger quantities of gaseous degradation products were obtained from earlywood than from latewood; yields were linear with time. Product yields after 168 hours were as follows:

Product	Earlywood	Latewood
	----- Millimoles -----	
CO ₂	5.90	3.90
CO	1.90	1.60
H ₂ .....	.85	.60
CH ₃ OH .....	.24	.30

Irradiation lowered groundwood pH, as follows:

Time	Earlywood	Latewood
	----- pH -----	
Before treatment	4.17	4.23
After treatment	3.40	3.48

As with solid wood, lignin-rich, high-yield pulps are chemically changed and darkened by exposure to light. Acetylation, benzylation, and methylation retard the darkening of woody material when exposed to light, whereas pretreatments with conventional "lignin-preserving" bleaching agents such as hydrosulfite, sulfite, borohydride, peroxide, and peracetic acid do not influence the rate of darkening. Slight sulfonation does not seem to influence the rate of formation of colored matter in high-yield pulp on exposure to light. The more rapid darkening of slightly sulfonated, high-yield pulps is due to the decrease in scattering coefficient caused by sulfonation. Higher degrees of sulfonation, however, do accelerate formation of colored matter in high-yield pulp when exposed to light. Certain antioxidants show minor retarding effects on the rate of degradation of

high-yield pulps but are of little commercial interest at present (Kringstad 1969).

Desai and Shields (1969) found that alpha-cellulose irradiated in air with ultraviolet light yielded degradation products including acetaldehyde, propionaldehyde, methyl formate, acetone, methanol, ethanol, methane, and ethane. They concluded that these compounds could result from further degradation of glucose and oligosaccharides formed during the primary degradation process—scission of the cellulose chain.

15-4 EXPOSURE TO IONIZING RADIATION

Location of **gamma rays**—an ionizing radiation—in the electromagnetic spectrum is shown in figure 15-4. These rays, which normally originate within a radioactive nucleus, affect not only living trees, but also the wood cut from them. Since a general review of the influences of ionizing radiation on the properties of wood and their evaluation is available (Youngs 1965), only brief observations pertinent to the utilization of southern pine are presented here.

Woodwell (1963) and Hamilton (1963) have indicated that ionizing radiation may kill pines, interfere significantly with normal growth, weaken the trees so they are more susceptible to parasites and natural forces, or produce pronounced changes in growth. Dosages required for significant development of such radiation effects are generally in the same order of magnitude as those causing severe damage to humans.

Trees growing in an environment containing higher than normal ionizing radiation characteristically produce anomalous tissues. When exposed to continuous irradiation entire increments will be affected but when irradiation occurs for a shorter period only portions of annual increments are affected. In shortleaf pine seedlings, exposed to gamma radiation from March to September for 20 of each 24 hours at a level of 1.5 equivalent roentgens³ per hour, J. R. Hamilton (unpublished) found that the number of xylem cambial derivatives was greatly reduced and their shape and size were altered (fig. 15-8).

Hamilton and Clark (1970) observed that pole-size shortleaf pine trees produced a zone of abnormal cells in both the earlywood and latewood when exposed to a mixed gamma and slow-neutron flux of 900 rads⁴ in June and 1,400 rads in August. The tracheids in the latewood zone were 6 percent shorter, 31 percent larger in diameter and had walls which were 16 percent thinner than those of the control. Micro tests revealed that tension parallel to the grain was reduced by 26 percent.

If wood cut from normal trees is subjected to ionizing radiation, it is

³ An equivalent roentgen is a measure of absorbed dose in soft tissue, i.e., 83 to 93 ergs per gram.

⁴ A rad is also a measure of absorbed dose (in any medium), i.e., 100 ergs per gram.

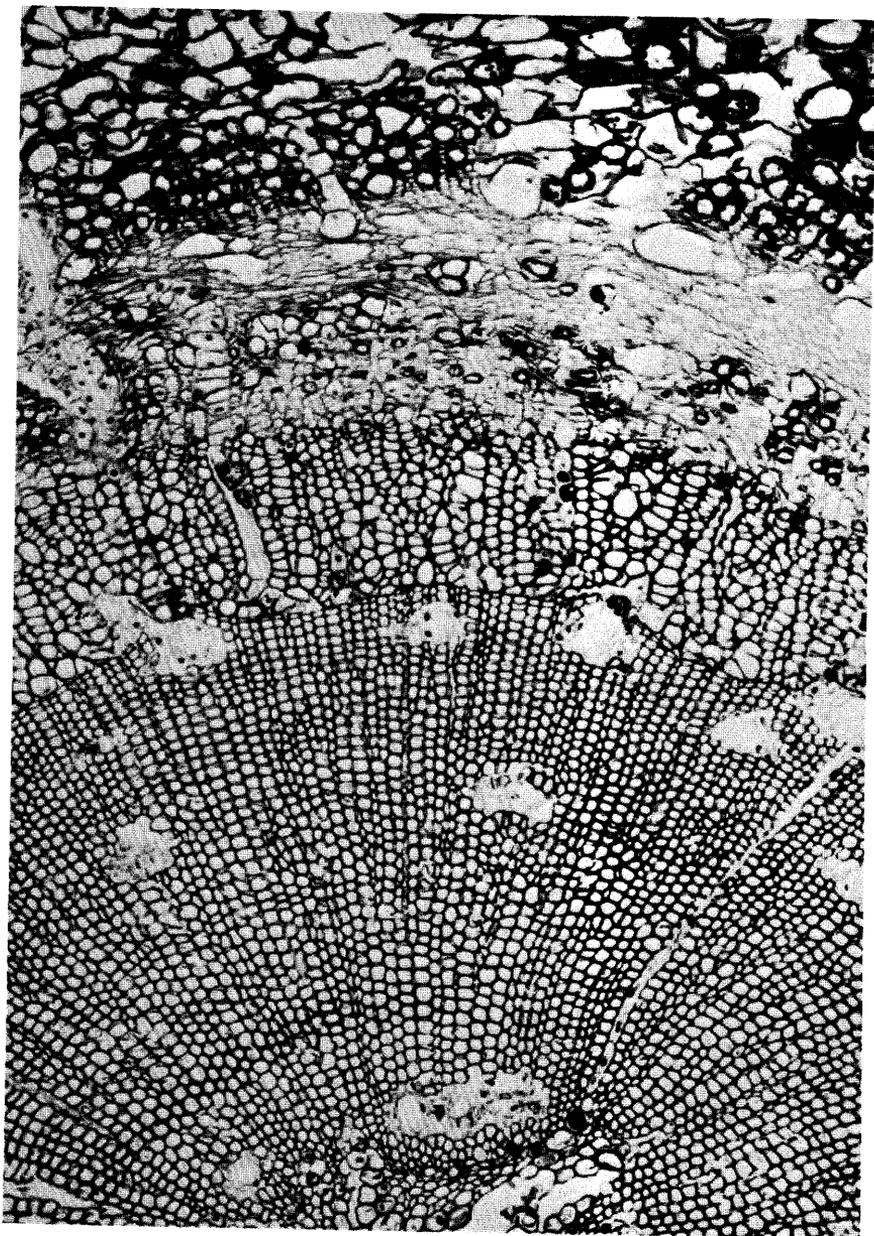


Figure 15-8.—Transverse section of a 2-year-old shortleaf pine seedling that, in its second year, was subjected to gamma radiation of 1.5 equivalent roentgens per hour for 20 hours out of each 24-hour day. Abnormal cellular structure in the second annual increment differs from the more orderly normal structure in the first annual increment. Continuity of ray cells in the abnormal tissue was disrupted. (Photo from J. R. Hamilton.)

changed both chemically and physically, although the changes may not be readily visible.

The chemical effects in wood resulting from high-energy radiation are not entirely clear. In general, chemical bonds in polymers are broken to produce an irreversible degradation and cross linking. Whether the result of bond cleavage is primarily cross linking or degradation depends upon the molecular structure and the part of the chain affected (Reinsmith 1958; Youngs 1965). The fact that gamma radiation has little effect on the shrinkage and swelling of wood may indicate that cross linking caused by radiation is not extensive.

Millett and Goedken (1965), in an effort to improve the hydrolysis rate of cellulose and yield of sugar in the saccharification of wood, combined thermal treatment with irradiation of nitration-grade sulfite pulp from slash pine. Their source of ionizing radiation was a high-voltage electron beam generated by a linear accelerator operating at 8 million electron volts. Irradiation at 10^6 equivalent roentgens followed by heat treatment at 200° C. for time periods of 0 to 16 hours raised the maximum sugar yield from 22.5 to 28.5 percent, an increase of about 30 percent. Irradiation alone at 10^6 equivalent roentgens provided an increase in sugar yield from 22.5 to 24.5 percent, an increase of approximately 9 percent. They concluded that the additional yield was not sufficient to be of potential commercial significance.

The generation of free radicals in wood by gamma rays has been reported (Ramalingam et al. 1963). It cannot be assumed, however, that the radicals created by gamma radiation are chemically the same as those caused by light (Kalnins 1966).

Various physical changes caused by gamma radiation have been observed. Pôlcin and Karhánek (1964) reported that when spruce (*Picea* sp.) wood, after radiation (5×10^7 rads), was disintegrated by grinding, a rapid decomposition of structure took place; loosened cell wall fractions of the irradiated wood were generally much deformed without showing excessive fibrillation, and they developed transverse fractures.

Choong and McIlhenny (1969) studied the effect of gamma radiation on the equilibrium moisture content, swelling characteristics, and bending strength of loblolly pine. Their data showed that gamma radiation applied to green wood at three dosage levels (1.8×10^6 , 8.6×10^6 , and 11.5×10^6 rads) did not significantly affect shrinkage and swelling or equilibrium moisture content. Irradiated specimens that were oven-dried and then brought to equilibrium moisture content at various humidities did have significantly lower equilibrium moisture contents than the untreated controls; when brought to equilibrium from the green condition, however, there was no significant effect. They found that gamma radiation did not significantly reduce modulus of elasticity of loblolly pine. Their green bending specimens, measuring $\frac{1}{3}$ - by $\frac{3}{4}$ -inch in cross section and 4 inches long, were subjected to a range of dosages (0 to 63.2×10^6 rads) and tested at 7-percent moisture content.

Modulus of rupture of these specimens was, however, substantially decreased by the gamma radiation as shown by the following tabulation of percentage reduction:

Dosage	Irradiated in air	Irradiated in nitrogen
10^6 rads	Percent	
0.00 (control)-----	0.0	0.0
.02-----	7.2	-----
.10-----	12.7	-----
.20-----	11.3	-----
.40-----	5.2	-----
.60-----	.9	.3
1.00-----	4.9	-.9
2.30-----	6.8	7.7
8.10-----	19.2	15.5
12.10-----	24.3	-----
16.10-----	28.4	28.6
33.30-----	36.3	-----
63.20-----	58.2	-----

15-5 LITERATURE CITED

- Alliott, E. A.
1926. The effect of acid on the mechanical strength of timber. *J. Soc. Chem. Ind. Trans.* 45: 463T-466T.
- American Wood Preservers' Association.
1969. Poles—preservative treatment by pressure processes. *AWPA Stand.* C4-69, 5 pp.
- Baechler, R. H.
1954. Wood in chemical engineering construction. *J. Forest Prod. Res. Soc.* 4: 332-336.
- Bell, W. A., and Gibson, J. M.
1957. Degradation of cellulose fibers in contact with rusting iron. *Nature* 180: 1065.
- Blew, O. J., Henriksson, S. T., and Hudson, M. S.
1961. Oscillating pressure treatment of 10 U.S. woods. *Forest Prod. J.* 11: 275-282.
- Borgin, K.
1970. The use of the scanning electron microscope for the study of weathered wood. *J. Micro.* 92(2): 47-55.
- Borgin, K.
1971a. The mechanism of the breakdown of the structure of wood due to environmental factors. *J. Inst. Wood Sci.* 5(4): 26-30.
- Borgin, K.
1971b. Why wood is durable. *New Sci. and Sci. J.* 50(748): 200-203.
- Breyer, M. B., and Banks, C. H.
1957. Effect of sulfuric acid on the properties of timber. I. Comparison of resistance of six timbers to sulfuric acid. *J. South. African Forest. Assoc.* 30: 7-36.
- Browne, F. L., and Simonson, H. C.
1957. The penetration of light into wood. *Forest Prod. J.* 7: 308-314.
- Buckman, S. J., and Rees, L. W.
1938. Effect of steaming on the strength of southern yellow pine. *Amer. Wood Preserv. Assoc. Proc.* 34: 264-300.
- Campbell, W. G., and Bamford, K. F.
1939. Factors affecting the relative resistance of certain woods to hydrolysis by dilute sulphuric acid. *J. Soc. Chem. Ind.* 58: 180-185. London.

- Choong, E. T., and McIlhenny, R. C.
1969. Effect of gamma radiation on hygroscopicity and bending strength of southern pine wood. *La. State Univ. LSU Wood Util. Notes* 17, 6 pp.
- Davis, W. H., and Thompson, W. S.
1964. Influence of thermal treatments of short duration on the toughness and chemical composition of wood. *Forest Prod. J.* 14: 350-356.
- Desai, R. L., and Shields, J. A.
1969. Photochemical degradation of cellulose material. *Die Makromol. Chemie* 122(2913): 134-144.
- Erickson, H. D., and Rees, L. W.
1940. The effect of several chemicals on the swelling and the crushing strength of wood. *J. Agr. Res.* 60: 593-603.
- Evans, U. R.
1960. The corrosion and oxidation of metals. 1094 pp. London: Edwards Arnold and Co.
- Farmer, R. H.
1962a. Corrosion of metals in association with wood. I. Corrosion from acidic vapors from wood. *Wood* 27: 326-328.
- Farmer, R. H.
1962b. Corrosion of metals in association with wood. II. Corrosion of metals in contact with wood. *Wood* 27: 443-446.
- Farmer, R. H.
1967. Chemistry in the utilization of wood. Vol. 9, 193 pp. N.Y.: Pergamon Press, Inc.
- Gobie, C. H.
1954. The chemical resistance of timber. *Wood* 19: 322-325.
- Goldstein, I. S.
1955. The impregnation of wood to impart resistance to alkali and acid. *Forest Prod. J.* 5: 265-267.
- Gray, V. R.
1958. The acidity of wood. *J. Inst. Wood Sci.* 1: 58-64.
- Guy, H. G.
1946. Use of treated wood under exposure to chemical attack. *Amer. Wood Preserv. Assoc. Proc.* 42: 256-262.
- Halliday, D., and Resnick, R.
1967. Physics. Parts I and II, 110 pp. N.Y.: John Wiley and Sons, Inc.
- Hamilton, J. R.
1963. Characteristics of tracheids produced in a gamma and gamma-neutron environment. *Forest Prod. J.* 13: 62-67.
- Hamilton, J. R., and Clark, A.
1970. The influence of ionizing radiation on tracheid morphology and tensile strength in shortleaf pine latewood. *Wood Sci.* 3: 59-61.
- Hatt, W. K.
1906. Experiments on the strength of treated timbers. *USDA Forest Serv. Circ.* 39, 31 pp.
- Hauser, S. J., and Bahlman, C.
1931. A study of the action of various chemicals upon different woods used for chemical tanks. *In The American bald cypress*, pp. 17-31. Jacksonville, Fla.: South. Cypress Manufacturers' Assoc.
- Ifju, G.
1964. Tensile strength behavior as a function of cellulose in wood. *Forest Prod. J.* 14: 366-372.
- Kalnins, M. A.
1966. Photochemical degradation of wood. II. *In Surface characteristics of wood as they affect durability of finishes*, pp. 23-60. *USDA Forest Serv. Res. Pap. FPL 57*. Forest Prod. Lab., Madison, Wis.
- Kass, A., Wangaard, F. F., and Schroeder, H. A.
1970. Chemical degradation of wood: the relationship between strength retention and pentosan content. *Wood and Fiber* 2: 31-39.
- Koch, P.
1971. Process for straightening and drying southern pine 2 by 4's in 24 hours. *Forest Prod. J.* 21(5): 17-24.
- Kringstad, K.
1969. Degradation of wood and high-yield pulps by light. *TAPPI* 52: 1070-1074.

- Leopold, B., and McIntosh, D. C.
1961. Chemical composition and physical properties of wood fibers. III. Tensile strength of individual fibers from alkali extracted loblolly pine holocellulose. *TAPPI* 44: 235-240.
- McBurney, L. F.
1954. Hydrolytic degradation. In *Cellulose and cellulose derivatives*. Vol. 5, Part 1, pp. 130-140. E. Ott, H. M. Spurlin, and M. Grafflin, eds. N.Y.: Interscience Publishers, Inc.
- McCool, M. M.
1948. Studies on pH values of sawdusts and soil-sawdust mixtures. *Boyce Thompson Inst. Contrib.* 15: 279-282.
- MacLean, J. D.
1930. Studies of heat conduction in wood—results of steaming green round southern pine timbers. *Amer. Wood Preserv. Assoc. Proc.* 26: 197-217.
- MacLean, J. D.
1932. Studies of heat conduction in wood. II. Results of steaming green sawed southern pine timbers. *Amer. Wood Preserv. Assoc. Proc.* 28: 303-329.
- MacLean, J. D.
1934. Temperatures in green southern pine timbers after various steaming periods. *Amer. Wood Preserv. Assoc. Proc.* 30: 355-374.
- MacLean, J. D.
1951. Rate of disintegration of wood under different heating conditions. *Amer. Wood Preserv. Assoc. Proc.* 47: 155-169.
- MacLean, J. D.
1952. Preservative treatment of wood by pressure methods. *USDA Agr. Handbook* 40, 160 pp.
- MacLean, J. D.
1953. Effect of steaming on the strength of wood. *Amer. Wood Preserv. Assoc. Proc.* 49: 88-112.
- MacLean, J. D.
1954. Effect of heating in water on the strength properties of wood. *Amer. Wood Preserv. Assoc. Proc.* 50: 253-281.
- Marian, J. E., and Wissing, A.
1960a. The chemical and mechanical deterioration of wood in contact with iron. I. Mechanical deterioration. *Svensk Papperstidn.* 63: 47-57.
- Marian, J. E., and Wissing, A.
1960b. The chemical and mechanical deterioration of wood in contact with iron. II. Chemical decomposition. *Svensk Papperstidn.* 63: 98-106.
- Marian, J. E., and Wissing, A.
1960c. The chemical and mechanical deterioration of wood in contact with iron. III. Effect of some wood preservatives. *Svensk Papperstidn.* 63: 130-132.
- Marian, J. E., and Wissing, A.
1960d. The chemical and mechanical deterioration of wood in contact with iron. IV. Prevention of deterioration. *Svensk Papperstidn.* 63: 174-183.
- Martin, G.
1954. The construction and maintenance of large wooden vessels. *Timber Technol.* 62(2176): 87-88; (2177): 126-128.
- Merriman, M. M., Choulett, H., and Brink, D. L.
1966. Oxidative degradation of wood. I. Analysis of products of oxygen oxidation by gas chromatography. *TAPPI* 49: 34-39.
- Millett, M. A., and Gerhards, C. C.
1972. Accelerated aging: Residual weight and flexural properties of wood heated in air at 115° to 175° C. *Wood Sci.* 4(4): April.
- Millett, M. A., and Goedken, V. L.
1965. Modification of cellulose fine structure—effect of thermal and electron irradiation pretreatments. *TAPPI* 48: 367-371.
- Miniutti, V. P.
1964. Preliminary observations—microscale changes in cell structure at softwood surfaces during weathering. *Forest Prod. J.* 14: 571-576.

- Miniutti, V. P.
1967. Microscopic observations of ultraviolet irradiated and weathered softwood surfaces and clear coatings. USDA Forest Serv. Res. Pap. FPL 74, 32 pp. Forest Prod. Lab., Madison, Wis.
- Narayanamurti, D., and Ranganathan, V.
1947. Resistance of wood to corrosion by hot chemicals. Indian Forest Leaflet. 101, 4 pp. Dehra Dun.
- Packman, D. F.
1960. The acidity of wood. *Holzforchung* 14: 178-183.
- Polčín, J., and Karáhnek, M.
1964. [Influence of ionizing irradiation on wood. Observation of the morphological structure by means of electron microscopy.] *Holzforchung* 18: 102-108.
- Kamalingam, K. V., Werezak, G. N., and Hodgins, J. W.
1963. Radiation-induced graft polymerization of styrene in wood. *J. Polymer Sci. (Part C, Polymer Symp.)* 2: 153-167.
- Reinsmith, G.
1958. Nuclear radiation effects on materials. *ASTM Bull.* 232, pp. 37-47. Amer. Soc. for Testing Mater.
- Ross, J. D.
1956. Chemical resistance of western woods. *Forest Prod. J.* 6: 34-37.
- Shreir, L. L., editor.
1963. *Corrosion*. Vol. 2. Corrosion control. 842 pp. N.Y.: John Wiley and Sons, Inc.
- Stamm, A. J.
1961. A comparison of three methods for determining the pH of wood and paper. *Forest Prod. J.* 11: 310-312.
- Stamm, A. J.
1964. *Wood and cellulose science*. 549 pp. N.Y.: Ronald Press Co.
- Stern, E. G.
1950. Deterioration of green wood along steel-nail shank and its influence on the nail-holding properties. *Va. J. Sci.* 1(3): 200-218.
- Thompson, W. S.
1964. Effect of preservative salts on properties of hardwood veneer. *Forest Prod. J.* 14: 124-128.
- Thompson, W. S.
1969. Effect of chemicals, chemical atmospheres, and contact with metals on southern pine wood: a review. *Miss. State Univ. Forest Prod. Util. Lab. Res. Rep.* 6, 33 pp.
- Uhlig, H. H.
1963. Corrosion and corrosion control: An introduction to corrosion science and engineering. 371 pp. N.Y.: John Wiley and Sons, Inc.
- Wangaard, F. F.
1966. Resistance of wood to chemical degradation. *Forest Prod. J.* 16(2): 53-64.
- Webb, D. A., and Sullivan, J. D.
1964. Surface effect of light and water on wood. *Forest Prod. J.* 14: 531-534.
- Welch, M. B.
1936. The effect of chemical solutions on some woods. *J. and Proc. Roy. Soc. New S. Wales* 3(5): 159-167.
- Wise, L. E., and Jahn, E. C., editors.
1952. *Wood chemistry*. Vol. 1, ed. 2, 688 pp. N.Y.: Reinhold Publishing Corporation.
- Wood, L. W., Erickson, E. C. O., and Dohr, A. W.
1960. Strength and related properties of wood poles. Amer. Soc. for Testing Mater. *Wood Pole Res. Program Final Rep.*, 83 pp.
- Woodwell, G. M.
1963. The ecological effects of radiation. *Sci. Amer.* 208(6): 40-49.
- Youngs, R. L.
1965. Influences of modern physics on the properties of wood and their evaluation. In *Application of advanced and nuclear physics to testing materials*, pp. 90-100. Amer. Soc. Testing and Mater. *Spec. Tech. Pub.* 373.

16

Attack by plant organisms

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16

Attack by plant organisms¹

Sapwood of all the southern pines is susceptible to damage by plant organisms after the tree is cut. Forseeable supplies will be second growth, with a large proportion of sapwood; any heartwood present, being close to the pith in young trees, will be little more resistant than sapwood. To protect it for longtime use, all southern pine wood must be kept dry, saturated in water, or impregnated with a chemical² toxic to damaging organisms.

Of limited practical importance is the fact that southern pine heartwood is somewhat more resistant to decay than sapwood, due presumably to the phenolic pinosylvin and its monoethyl ether, as proved for some other pines (Scheffer and Cowling 1966). Heartwood of longleaf and slash pines is considered moderately resistant (USDA Forest Products Laboratory 1967); that of other southern pines is listed as low in resistance, but experimental evidence is meager and inconsistent (Humphrey 1916, 1923; Buckman 1934; Clark 1957; Diller and Koch 1959). In tests of sapwood from three trees of each of the major southern pine species, Toole (1970) observed that sapwood of longleaf and slash pine was slightly more decay resistant than sapwood of shortleaf and loblolly. While decay rate of southern pine sapwood decreases with increased specific gravity (Buckman 1934; Garren 1939), available information for heartwood suggests no correlation (Diller and Koch 1959) or possibly an opposite trend (Buckman 1934).

The abnormal resin-infiltrated wood associated with tree wounds is very resistant to decay. While toxic material can be isolated from resin (Bateman 1924), the effectiveness of resin in preventing organism attack apparently is due largely to waterproofing (Zeller 1917; Verrall 1938). The amount of highly resistant fatwood or lighterwood is small, limiting it to local use as posts, stakes and fuelwood.

¹ With some changes and additions, ch. 16 is taken from Verrall (1969) by permission of Arthur F. Verrall and the Forest Products Research Society.

² Mention of a chemical in this chapter or elsewhere in this text does not constitute a recommendation; only those chemicals registered by the U.S. Environmental Protection Agency may be recommended, and then only for uses as prescribed in the registration—and in the manner and at the concentration prescribed. The list of registered chemicals varies from time to time; prospective users, therefore, should get current information on registration status from Pesticides Regulation Division, Environmental Protection Agency, Washington, D.C.

Inoculation of southern pine wood is by both wind- and insect-carried spores (Verrall 1941a). Pine bark beetles, especially the several species of *Ips*, carry spores of sap-stain fungi and are instrumental in inoculation of products while bark remains attached. Control of insects is often a necessary phase of fungus control.

16-1 NATURE OF ATTACKS

Plant organisms which may degrade wood by feeding on cell-wall substance or cell contents include fungi which cause rots, and others which produce molds and stains. Bacteria also attack and damage wood under some conditions. Storage techniques to protect roundwood against attack are described in chapter 18, and preservative treatments for southern pine wood products are discussed in chapter 22.

WOOD DESTROYING FUNGI

Wood destroying fungi are classified into those causing **white rot**, **brown rot**, and **soft rot**. A white rot, *Fomes pini* attacks heartwood, causing the most common decay in standing trees. Most brown-rot fungi, like most white and soft rots, generally decay southern pine after it has been cut. The initial decay fungus in harvested wood almost always is *Peniophora gigantea*, intermediate between white and brown rotters (Lindgren 1951; Lindgren and Eslin 1961). This fungus reduces toughness at a rate of 2 to 3 percent per week in summer, and one-third to one-half as fast in winter (Lindgren and Erickson 1957). Other decayers enter later, particularly the brown rotter, *Lenzites saepiaria*, which is especially destructive after 6 months. For the interested reader, Toole (1971) has related decay-caused reductions in weight and crushing strength of southern pine, to duration of exposure to both white- and brown-rot fungi.

White-rotted wood characteristically has a bleached appearance and nearly normal shrinkage. Brown-rotted wood develops a reddish-brown color, looks charred, and on drying shrinks excessively (especially longitudinally). In both white and brown rot, fungus hyphae produce local dissolution of the cell wall by enzymatic action, and penetrate the cell wall via bore holes; pits provide a second avenue of penetration (fig. 16-1). The cellulolytic enzymes of white-rot fungi first attack at the lumen wall and gradually work outward as the cellulose is removed from each successive wall layer. The cellulolytic enzymes of brown-rot fungi and the lignin-destroying enzymes of white-rot fungi penetrate and act within the cell wall (Wilcox 1965). Brown-rotted wood is low in holocellulose, has greatly reduced strength and toughness, and when pulped gives a low yield of poor-quality fiber. Figure 16-1 illustrates hyphae of a brown-rot fungus in southern pine.

In contrast to common decay fungi, soft rot attacks wood surfaces, the



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Figure 16-1.—Hyphae of the decay fungus *Lenzites saepiaria*, a brown rotter, in the lumina of pine wood tracheids. The tracheid walls are softened by extracellular enzymes secreted by the hyphae.

underlying wood remaining sound. Wood containing soft rot exhibits a spongy, cracked, charred-looking surface.

While brown-rot hyphae make bore holes transversely through the cell walls, hyphae of soft-rot fungi move longitudinally within the secondary wall parallel to the microfibrils of the S_2 layer (figs. 16-2 and 16-3). Soft-rot fungi deplete polysaccharides, but not lignin, in the cell wall.

SAP STAINS AND MOLDS

A bluish-gray (occasionally purple, pink, orange, or yellow) stain in sapwood of southern pine indicates the presence of wood-staining fungi that feed on the contents of parenchyma cells rather than on lignin and polysaccharides in the cell wall (fig. 16-4). Molds are characterized by variously colored downy growths and dusty spores on the surface. Because mold and stain fungi usually bore only minute holes through the cell wall (most frequently at pits), they do not seriously degrade bending and compression strength, but moderate to heavy attack significantly reduces toughness and slightly reduces surface hardness (Findlay and Pettifor 1937; Chapman and Scheffer 1940; and Chidester 1942). Stained wood may be significantly weakened, however, by incipient decay infections that thrive under the conditions favoring stain fungi.

To varying degrees, stain and mold fungi break down parenchyma (fig. 16-5) and thus increase permeability of southern pine wood to liquids



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Figure 16-2.—Cross section of southern pine sapwood showing growth of a soft-rot fungus in the S₂ layer of the tracheid walls. (Photo from Lindgren and Eslin 1961.)

(Saling 1930; Lindgren and Scheffer 1939; Chidester 1942; Lindgren 1952; Lindgren and Harvey 1952; Verrall 1965; Johnson 1969). Except as this increases wetting, stain apparently does not affect susceptibility of wood to decay (Chapman 1933; Verrall 1966). Attack by stain fungi is most prolific on green wood during seasoning; activity can continue at moisture contents as low as 24 percent, i.e., probably lower than that required for most decay (Colley and Rumbold 1930; Lindgren 1942).

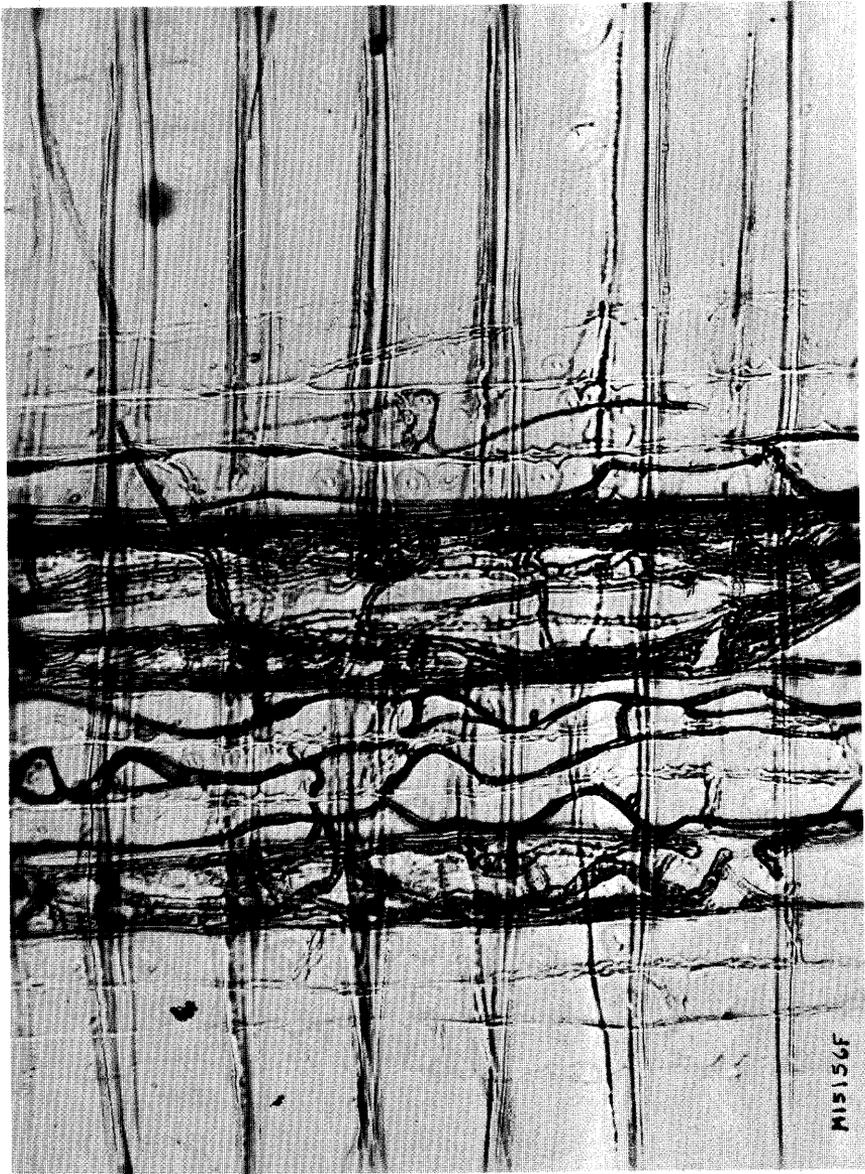
Of the many fungus species staining pine logs and lumber (Davidson



F-920963
Figure 16-3.—Longitudinal section of southern pine sapwood showing the spirally arranged channels of a soft-rot fungus in the S₂ layer. The hyphae apparently follow the fibrils of the cell wall. (Photo from Lindgren and Eslyn 1961.)

1935; Verrall 1939, 1941b), the most important are several species of *Ceratocystis* and *Diplodia natalensis*. The usual mold is *Trichoderma* (Lindgren 1952).

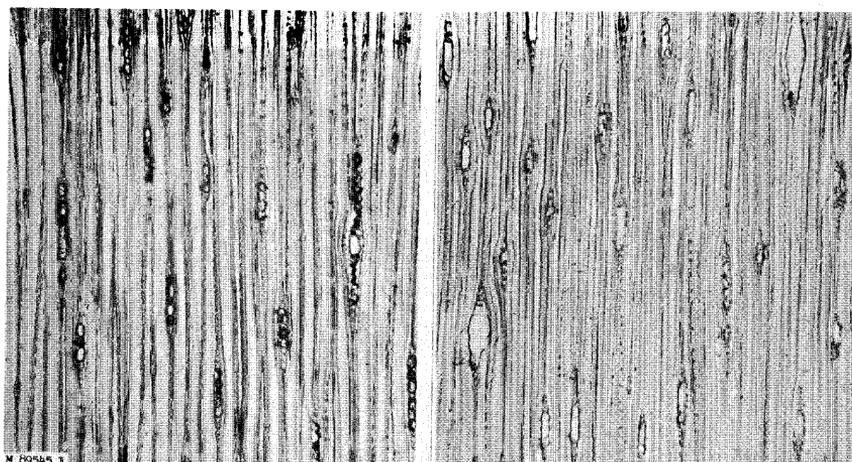
Within 12 to 24 hours after trees are felled, stain and mold fungi usually penetrate pine wood beyond the depth effectively reached by chemical protectants. Thus chemical treatment must be prompt if it is to be useful (Scheffer and Lindgren 1940; Verrall and Mook 1951; Kramer 1954).



M-15156F

Figure 16-4.—Hyphae of the blue-stain fungus *Ceratocystis pini* aggregated in the ray cells of pine wood. These fungi live mainly on materials stored in parenchyma cells. There is little attack on the tracheid walls.

Nelson (1934) and Bramble and Holst (1940) reported that the stain fungus carried by southern pine beetles reduced permeability when inoculated into living sapwood. Limited sampling of dead wood from beetle-killed southern pine suggests that the mold *Trichoderma*, which commonly



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Figure 16-5.—Tangential sections of southern pine sapwood showing the destruction of ray parenchyma by the mold *Trichoderma* (right). Section at left shows normal condition.

accompanies stain in nature, makes the stained wood more permeable than normal wood (Verrall 1965).

BACTERIAL ATTACK

When southern pine logs or veneer bolts are stored in water or under water sprays, anaerobic bacteria may attack the wood (Lutz et al. 1966). Gram-positive cocci and gram-negative rods attack epithelial and ray parenchyma and probably half-bordered pit membranes. Greaves and Barnacle (1970) have shown that bacteria in slash pine also attack tracheid bordered pits. The result is increased porosity but no discoloring and usually no measurable loss in specific gravity.

Scheld and De Groot (1971) observed a significant loss in sapwood toughness when longleaf pine logs were stored for 4 to 8 months under a continuous water sprinkling system. Extreme strength losses from bacterial attack appear to be uncommon, however. If loss occurs it develops slowly; the particular organisms and environmental conditions involved have not been ascertained.

16-2 PHYSIOLOGICAL REQUIREMENTS OF FUNGI

Temperatures between 75° F. and 85° F. are generally favorable to growth of fungi. Below 50° F. growth of wood-deteriorating fungi is negligible; elevated temperatures are lethal. Under moist conditions, the most heat-resistant fungi are killed in 75 minutes at 150° F., in 30 minutes at 180° F., and in 10 minutes at 200° F. (USDA Forest Products Laboratory 1956). Dry heat is a somewhat less effective sterilizing agent.

Growth of fungi can be retarded by submerging wood in water, thus limiting the oxygen supply. The wood moisture content optimum for growth of fungi appears to be considerably above fiber saturation point. Fungal growth stops when moisture content of wood falls below fiber saturation; in practice moisture contents of 20 percent or less are usually recommended to provide a margin of safety.

Studies on the vitamin requirements of wood-rotting *Basidiomycetes* (Robbins and Kavanagh 1942) led to the protection of wood by dethiamination (Gjovik and Baechler 1968). Experiments with white- and brown-rot fungi, however, suggest that the thiamine relationship to decay resistance is not entirely clear and that additional research is needed to explain variability in decay resistance of treated woods (Highley 1970).

Information is needed on concomitant associations and successions of organisms. A supposedly minor organism can prepare the way for a more destructive one. For example, molds may detoxify preservatives (Duncan and Deverall 1964; Unligil 1968), or increase decay rate (Verrall 1966). In contrast, certain molds may prevent or lessen decay (Lindgren and Harvey 1952).

16-3 THE STANDING TREE

Decay in standing pine trees is limited to heartwood or sapwood adjacent to wounds, since the moisture content of living sapwood is normally too high for growth of decay fungi. Southern pine stands are generally harvested before a large proportion of the wood becomes heartwood.

In live southern pines most heart rot is red heart or red ring rot caused by *Fomes pini* (Hepting and Chapman 1938; Gruschow and Trousdell 1958). It may continue to develop slightly in dead trees or logs (Boyce 1961), but there is no evidence of continued growth in converted products (Fritz and Atwell 1941; Wood 1955; Boyce 1961).

Less common is the red-brown butt rot caused by *Polyporus schweinitzii*. This brown rotter affects primarily the base of the bole. Unlike *F. pini*, *P. schweinitzii* probably can continue to cause important decay after the tree is cut. This assumption is based on reports of isolations of *P. schweinitzii* from southern pine test stakes (Duncan and Lombard 1965).

16-4 SAW LOGS AND VENEER BOLTS

In the southern region, pine saw logs and veneer bolts are rapidly attacked by stain, mold, and decay fungi during all seasons except for short periods in winter. There are few published data on their deterioration, and most information is based on commercial experience.

Prompt utilization is the only fully satisfactory means of preventing deterioration of saw logs and veneer bolts. Stain and decay can be prevented for at least a year by storage in ponds or under water sprays (Chesley et al. 1956; Mason 1961; Anonymous 1963; Mason et al. 1963; Volkman

1966; Lutz et al. 1966). These wetting methods, however, do not prevent attack by anaerobic bacteria (Lutz et al. 1966), which may increase permeability enough to affect preservative treatment (Knuth and McCoy 1962), veneer production (Lutz et al. 1966), and stability in use under conditions subjecting the wood to occasional wetting (Verrall 1966).

Chemicals are not extensively used to protect southern pine logs or veneer bolts. Research has indicated that the most effective spray contains the fungicide pentachlorophenol² plus the insecticide benzene hexachloride² (Johnston 1952; Kramer 1954; Smith 1959). Because only the surface is treated, application usually must be made within 1 to 2 days after felling, depending on season. Good protection is usually limited to 3 or 4 months. Aside from the economics of application, further information is needed on effectiveness before chemical protection can be unequivocally recommended.

16-5 PULPWOOD

There is an extensive literature on the deterioration of southern pine pulpwood and chips during storage; but much of it is of doubtful validity because of inadequate controls and atypical storage methods. The best reviews of this field are by Shema (1955), Lindgren and Eslyn (1961), and Hajny (1966).

In carefully designed studies (Lindgren 1951; Lindgren and Eslyn 1961), pine with bark in place lost from 2 to 4 percent in specific gravity in 2 months, 5 to 8 percent in 4 months, and 7 to 10 percent in 6 months of summer storage. During winter storage, losses usually were about one-third these amounts. Losses decreased with increased diameter and length of bolts. These results reflect the need for some drying of green pine sapwood before sufficient oxygen is available for fungus activity. The loss figures given may be somewhat high since the storage piles were relatively small and may have dried more rapidly—hence allowed decay to progress faster—than in large commercial piles.

In the same studies peeled bolts in test piles dried rapidly, creating a water-oxygen ratio favorable for decay early in the storage period. This, plus the exposure of more wood surface to infection, resulted in more rapid decay of peeled bolts than of rough bolts during short-storage periods. With storage periods beyond 2 to 3 months, specific gravity losses may be less in peeled bolts because they become too dry for rapid decay. Again, these results may not be typical of peeled bolts in large piles where drying is slower.

In general, the yield and quality of pulp decreases progressively with the proportion of decayed wood and the stage of decay (Lindgren and Eslyn 1961; Rhyne and Brinkley 1961; Saucier and Miller 1961; Mason et al. 1963; Hajny 1966; Volkman 1966). Loss may be small with light decay. With heavy decay, in addition to loss in specific gravity, there may be 10- to 20-percent reduction in yield and losses of 10 percent or more as fines

during chipping and screening. There also are important decreases in tear resistance, bursting strength, and folding endurance. Tensile strength is less affected. Decay reduces brightness in groundwood pulp; in the sulfate process, alkali consumption is increased if decay is present (McGovern et al. 1951).

Pulpwood can be stored in ponds up to 1 year without loss of yield or quality (Chesley et al. 1956). Under water sprays, yields and quality are unaffected for 6 months to 1 year (Mason et al. 1963; Volkman 1966).

Researchers have explored several methods of chemical control. A pentachlorophenol-benzene hexachloride² treatment can significantly reduce decay of pulpwood (Smith 1959) but was not economically feasible until the advent of the concentration yard where one or two cords of wood could be mechanically dipped at one time. The big obstacle to the effectiveness of this treatment is the difficulty of treating the day the trees are felled. A dip treatment, using fluorides² in 3- to 5-percent concentrations (Lindgren and Harvey 1952) is relatively effective even when applied a week after felling. At these concentrations the fluorides stimulate the mold *Trichoderma*, which is antagonistic to the early decayer *Peniophora gigantea*. This treatment is worthy of further trials.²

16-6 PULP CHIPS

There is an extensive literature on the outdoor storage of southern pine chips. Although based primarily on exploratory tests or commercial trials using small, noncompacted piles which have moisture, oxygen, and temperature conditions atypical of large commercial piles, reports tend to indicate that losses in specific gravity, yield, and strength of pulp are no greater than for dry roundwood storage.

The most complete study was reported by Rothrock et al. (1961) and more completely analyzed by Lindgren and Eslyn (1961). In compacted piles little deterioration occurred in 6 to 12 months except for the outer shell of the pile. Lindgren and Eslyn concluded that losses in specific gravity, yield, and strength of pulp are less in southern pine stored as chips than as rough roundwood. Losses should average even less for piles larger than those tested because the ratio of surface area to volume would decrease, and losses occur mainly in the outer shell. Very little stain, mold, and *Basidiomycete* decay occurred in the pile interior. Most decay was by the slower acting soft-rot fungi. Higher moisture contents, lower oxygen supply, and higher temperatures inside piles probably restrict the usual pine-deteriorating fungi. The common presence of bacteria also may be a restricting factor. The increased porosity caused by bacteria is not a defect in pulpwood; in fact, it tends to reduce cooking time.

Lindgren and Eslyn (1961) raise the possibility of further reducing chip deterioration by spray application of a fungicide since only the shell of a pile needs protection. Laboratory experiments and a large-scale experiment

on a simulated chip pile (Springer et al. 1969, 1971) have indicated that treatment of chips with green liquor from the kraft pulp process effectively reduces initial heating and subsequent weight loss due to microbial growth (Smith and Hatton 1971).

Djerf and Volkman (1969), after a controlled application of water spray to a chip pile, conclude that water spraying of chips during long-term storage offers no advantage over dry chip storage (see section 18-3).

Another biological problem in the pulp industry is slime in recirculated water, which in turn causes blemishes in the paper. The associated bacteria, yeasts, and moldlike fungi can be controlled with biocides. This problem was reviewed by Holmes (1941) and Zabel (1959).

16-7 BARK-FREE POLES AND TIMBERS

Posts, poles, piling, and large sawed timbers are more difficult to protect from fungi during storage or air-seasoning than items with the bark attached. Fungicidal sprays² commonly are used, but results often are unsatisfactory (Hunt and Garratt 1967). During the necessarily long seasoning periods, moderate internal stain and decay develop even when the surface remains bright. Recent research (Panek 1963) showed that a soak of at least 15 minutes in 30 percent ammonium bifluoride² afforded a high degree of protection to southern pine poles for 1 year during air-seasoning. At this concentration, the fluoride is toxic to all fungi, including the mold *Trichoderma* which is objectionable in items to be given a clean preservative treatment. The high-concentration fluoride² soak probably would be effective if applied several days after felling.

Even with satisfactory stain control, seasoning checks can permit entry of decay fungi, resulting in internal decay pockets. To avoid fungus degrade many southern pine poles now are dried in kilns or tunnels or otherwise specially handled instead of being air-seasoned (Hunt and Garratt 1967). (See secs. 20-2, 20-3, and 20-4.)

16-8 AIR-SEASONED LUMBER

Since temperatures reached under recommended kiln-drying schedules (Rasmussen 1961) and usual pressure-treating schedules (Hunt and Garratt 1967) effectively sterilize infected wood, deterioration of pine lumber during manufacture is a problem chiefly during air-seasoning. Mold, stain, and decay problems in air-seasoning of southern pine lumber were intensively studied during the 2 decades ending in 1950. The results were summarized by Scheffer and Lindgren (1940) and Verrall and Mook (1951). Other reviews of the field are by Verrall (1945) and Findlay (1959). Organisms associated with air-drying southern pine are described by Davidson (1935) and Verrall (1939, 1941b).

Green lumber is usually inoculated by spores of stain and mold fungi carried by wind, or by bark beetles and other insects which commonly visit freshly piled lumber (Verrall 1941a). Spores produced on log ends

apparently are scattered by saws, for spore populations are particularly high inside sawmills. Lumber piled on infected stickers frequently develops localized bands of stain at points of contact.

As pine wood dries below fiber saturation, fungi in it becomes inactive but may remain viable for extended periods. Stain fungi usually die within 1½ to 11 months in dry wood but sometimes survive for 7 years (Scheffer and Chidester 1948). Most decayers die within ¼ to 36 months. Exceptions include species of *Lenzites*, the most common decayers of pine products exposed to rainwetting, which can survive over 9 years in air-dried wood (Findlay 1950; Findlay and Badcock 1954). Incipient decay infections probably accompany much moderate to heavy stain. This is surmised since most serious decay in southern pine exterior woodwork of buildings is associated with air-dried and frequently stained lumber (Verrall 1966).

Since second growth with high sapwood content began to make up the bulk of the southern pine cut, fungus control in the seasoning yard has been essential because weather during much of the year favors stains and rots. Research has indicated that the most effective fungicidal protectants are dips or sprays of chlorinated phenols² and organic mercurials² (Verrall 1945; Verrall and Mook 1951). Particularly effective are mixtures of the two groups, with or without supplemental borax.² Almost universally used for several decades, fungicidal treatments are applied to decreasing proportions of the cut, now that much southern pine is kiln-dried green from the saw.

Studies by Scheffer and Lindgren (1940) and Verrall and Mook (1951) indicate that many of the commercial problems with stain, mold, and decay in air-seasoning lumber are associated with the following:

- Delayed fungicidal treatment. Since fungi frequently will penetrate pine sufficiently far in 12 hours during summer and 24 hours during winter to escape killing by chemicals, treatment must be prompt. Delayed treatment is a serious problem when the outputs of small mills are shipped to a concentration yard for dipping and seasoning. The closing of many small mills in recent years has reduced this problem.
- Exposing freshly dipped lumber to rainwash. Greatest danger occurs during the first hour after dipping, i.e., before the toxicants are adsorbed to the wood and resistant to leaching. Thus, protection from rainwash is particularly important at the green chain.
- Poor seasoning-yard practices. Fungicides are adjuncts to, not substitutes for, practices which protect seasoning lumber from rainwetting and slow drying.
- Bulk piling green lumber. Fungicides at regular concentrations may fail if green lumber is close piled for more than 2 to 3 days. If treated with fungicides at 1.5 to 2 times usual concentrations,² southern pine can be close piled for 2 weeks in the summer and 4 weeks in winter without serious attack.

16-9 GREEN VENEER

Southern pine core veneer commonly is stored green in close piles for periods of a few days up to 5 weeks or more. Such veneer quickly begins to mold and, after 3 to 4 weeks, begins to blue stain. Material stored more than 2 to 4 weeks, depending on weather conditions, has a general coating of mold mycelium and spores, plus a pattern of denser, discolored patches of mold.

Among the molds attacking pine veneer are *Trichoderma*, *Penicillium*, and *Aspergillus*, the common green and black molds on green pine lumber. In addition, there is conspicuous development of the salmon-orange mold, *Monilia sitophila*, which seldom is found except on steamed wood.

There is little doubt that, with the longer storage periods, the molds importantly increase porosity of the veneer. This could result in starved glue joints due to excessive penetration. Dried mycelium and spores on the surface can also reduce bond quality by impairing contact between the glue and wood fibers (Haskell et al. 1966).

The use of fungicides on veneer to prevent mold is questionable, although such treatment could be effective. For example, hardwood veneer treated with sodium pentachlorophenate² has been observed to release toxic fumes in the dryer. A better solution is to grade logs to produce the needed proportions of face and core veneer, and balance lathe and dryer capacity so that green veneer is not stored more than a few days.

16-10 WOOD IN USE

Fungus damage to wood in use is mainly decay. Most wood in use has been seasoned, though not always adequately. While stain and mold fungi occur on such wood when it is rewetted, they grow there less prolifically than on green wood. All decayers of southern pine require free water in the wood (i.e., moisture content above fiber saturation); the species is determined by the amount and consistency of wetting and the type of exposure (Duncan and Lombard 1965). Studies of fungus deterioration of wood in use therefore are concerned mainly with the problems of keeping wood dry and with the use of preservatives.

CONTACT WITH SOIL

Southern pine in contact with the soil or fully exposed to the weather has a short service life unless adequately protected by wood preservatives. Both *Basidiomycetes* and soft rotters are involved (Duncan 1960; Duncan and Lombard 1965). Premature decay of treated wood usually is associated with low retentions and poor penetration, exposure under conditions too severe for a particular preservative, or exposure of interior wood by cutting after treatment (Hunt and Garratt 1967). The last is less important in southern pine than in many other species because pine is mostly

sapwood, which is fully penetrated by preservative. Fungi vary in their tolerance of preservatives (Cowling 1957), but that probably is not a major cause of preservative failure.

CONDENSATION

Winter condensation in buildings is primarily a northern problem (USDA Forest Products Laboratory 1949). However, in damp crawl spaces sufficient winter condensation to promote heavy staining and molding, and sometimes appreciable decay, occurs as far south as the Mississippi Gulf Coast. Control of such condensation by soil covers, drainage, and ventilation (USDA Forest Products Laboratory 1949) is even more effective in the South than in the North.

Condensation associated with air conditioning by refrigeration occurs in hot, humid climates (Verrall 1962). Most decay is in damp crawl spaces, although it can occur in walls between cooled rooms and noncooled kitchens, laundries, or shower rooms. Control consists of reducing the humidity of the crawl space and moderating cooling. Subfloor vapor barriers plus thermal insulation also are effective but difficult to install and maintain.

The third type of condensation, i.e., due to heat radiation on clear still nights, leads mainly to paint molding but may cause some decay in screen and door frames.

There are few, if any, published data on the specific stain, mold, decay fungi, and bacteria associated with the various types of condensation. Decayers in screen frames wetted by condensation due to heat radiation presumably are the high-temperature *Lenzites saepiaria*, *L. trabea*, and *Daedalea berkeleyi* that are resistant to drying. These also are important rotters in siding, trim, and other exterior woodwork wetted by rain seepage (Verrall 1966). The mold *Trichoderma* also commonly inhabits wet woodwork. Undoubtedly, bacteria and many miscellaneous fungi grow in rainwetted woodwork, but information on this is lacking. *Trichoderma* is compatible with the high-temperature, desiccation-resistant decayers (Verrall 1966), but the effects of other organisms on decay in pine woodwork are unknown.

RAIN SEEPAGE

Good structural designs and the use of water repellents can minimize rain seepage and its resultant decay (Verrall 1966). The effectiveness and limitations of water repellents are fairly well known (Verrall 1959, 1965, 1966). Pressure treatments of wall plates on groundline slabs is recommended (USDA Forest Service 1960) as a precautionary measure in view of limited knowledge about movement of moisture through, and condensation on, the slab. Recent information suggests that danger is restricted to peripheral plates wetted by rain splash; possibly in colder climates there

is also danger from condensation. Rate of deterioration is, to some extent, determined by the interaction of species of fungi, moisture content, and temperature.

PORIA INCRASSATA

Southern pine (like other woods, including heartwood of redwood and cypress) is occasionally destroyed in buildings by a water-conducting fungus, primarily *Poria incrassata* (Verrall 1968). This fungus develops large, tough, water-conducting strands which can take water from the soil or other constant source and wet normally dry wood many feet up in a building. Fortunately, the fungus is extremely sensitive to drying (Scheffer and Chidester 1943; Findlay and Badcock 1954), which obviates any need to remove decayed wood, except for strength reasons, after the source of water is removed (Verrall 1968). Observations (Verrall 1968) and research data³ show that under almost all building conditions, conducted water is vital to survival of *P. incrassata*; previous suggestions that the fungus frequently maintains itself on water-of-metabolism are unfounded. Most attacks occur in new buildings or those with recent structural changes. This, coupled with a higher incidence in lumber-storage sheds than in other buildings, suggests that most infections arise from the use of infected lumber.

16-11 BENEFICIAL USES OF FUNGI IN WOOD

A large amount of carbohydrate material in wood and spent sulfite liquor is being wasted. Pentose and hexose sugars can be isolated from spent liquor or, by acid hydrolysis, from wood waste. These sugars can be used to cultivate food yeasts (Harris 1949; Holderby and Moggio 1959). Processes have been developed for fermenting wood sugars by yeasts and bacteria to produce alcohols (ethyl, butyl, isopropyl, and others), acetone, and organic acids—lactic, acetic, butyric (Hajny 1959). Currently these processes are used primarily to reduce stream pollution. For economical production of chemicals, uses must be found for other wood components, i.e., lignins and hemicelluloses.

Southern pine sawdust, when applied with suitable amounts of fertilizer, is an excellent mulch or soil amendment for southern pine nurseries (Wakeley 1954). The most beneficial effects, however, occur only after soil micro-organisms have decomposed the cellulosic components, leaving the lignins which give the desired physical and physical-chemical properties to the soil for plant growth.

Sawdust and wood waste can be used without the addition of extra fertilizers if first composted (Wilde 1958; Bollen and Glennie 1961). For composting, Wilde artificially inoculated sawdust with the agaric *Coprinus ephemerus*.

³ Scheffer, T. C. 1941. Importance of conducted water and "autohumidification" in decay by the "dry rot" fungus *Poria incrassata*. USDA Forest Serv. Forest Prod. Lab. unpublished report, 69 pp.

16-12 LITERATURE CITED

- Anonymous.
1963. Sprinkler storage for pine logs. *Pulpwood Prod.* 11(10): 8, 10, 12.
- Bateman, E.
1924. What makes a pine stump last? *Southern Lumberman* 115 (1501): 51.
- Bollen, W. B., and Glennie, D. W.
1961. Sawdust, bark and other wood wastes for soil conditioning and mulching. *Forest Prod. J.* 11: 38-46.
- Boyce, J. S.
1961. *Forest pathology*. 600 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Bramble, W. C., and Holst, E. C.
1940. Fungi associated with *Dendroctonus frontalis* in killing shortleaf pines and their effect on conduction. *Phytopathology* 30: 881-899.
- Buckman, S.
1934. What is the relationship between durability and specific gravity of wood? *J. Forest.* 32: 725-728.
- Chapman, A. D.
1933. Effect of steam sterilization on susceptibility of wood to blue-staining and wood-destroying fungi. *J. Agr. Res.* 47: 369-374.
- Chapman, A. D., and Scheffer, T. C.
1940. Effect of blue stain on specific gravity and strength of southern pine. *J. Agr. Res.* 61: 125-133.
- Chesley, K. G., Hair, J. C., and Swartz, J. N.
1956. Underwater storage of southern pine pulpwood. *TAPPI* 39: 609-614.
- Chidester, M. S.
1942. The effect of a mold, *Trichoderma lignorum*, on loblolly pine sapwood. *Amer. Wood Preserv. Assoc. Proc.* 38: 134-139.
- Clark, J. W.
1957. Comparative decay resistance of some common pines, hemlock, spruce, and true fir. *Forest Sci.* 3: 314-320.
- Colley, R. H., and Rumbold, C. T.
1930. Relation between moisture content of the wood and blue stain in loblolly pine. *J. Agr. Res.* 41: 389-399.
- Cowling, E. B.
1957. The relative preservative tolerances of 18 wood-destroying fungi. *Forest Prod. J.* 7: 355-359.
- Davidson, R. W.
1935. Fungi causing stain in logs and lumber in the southern States, including five new species. *J. Agr. Res.* 50: 789-807.
- Diller, J. D., and Koch, E. J.
1959. Weight losses of 40 wood species exposed to *Poria incrassata* and *Merulius lacrymans*. *Forest Prod. J.* 9: 298-302.
- Djerf, A. C., and Volkman, D. A.
1969. Experiences with water spray wood storage. *TAPPI* 52: 1861-1864.
- Duncan, C. G.
1960. Wood-attacking capacities and physiology of soft-rot fungi. *USDA Forest Serv. Forest Prod. Lab. Rep.* 2173, 70 pp.
- Duncan, C. G., and Deverall, F. J.
1964. Degradation of wood preservatives by fungi. *Appl. Microbiol.* 12: 57-62.
- Duncan, C. G., and Lombard, F. F.
1965. Fungi associated with principal decays in wood products in the United States. *USDA Forest Serv. Res. Pap. WO-4*, 31 pp. Wash., D.C.
- Findlay, W. P. K.
1950. The resistance of wood-rotting fungi to desiccation. *Forestry* 23: 112-115.
- Findlay, W. P. K.
1959. Sap-stain of timber. Parts I and II. *Forest. Abstr.* 20: 1-7; 167-174.
- Findlay, W. P. K., and Badcock, E. C.
1954. Survival of dry rot fungi in air-dry wood. *Timber Technol.* 62: 137-138.
- Findlay, W. P. K., and Pettifor, C. B.
1937. The effect of sap-stain on the properties of timber. I. Effect of sap-stain on the strength of Scots pine sapwood. *Forestry* 11: 40-52.
- Fritz, C. W., and Atwell, E. A.
1941. Decay in red-stained jack pine ties under service conditions. *Can. Forest Serv. Forest Prod. Lab. Circ.* 58, 26 pp.

- Garren, K. H.
1939. Studies on *Polyporus abietinus*. III. The influence of certain factors on the rate of decay of loblolly pine sapwood. J. Forest. 37: 319-323.
- Gjovik, L. R., and Baechler, R. H.
1968. Field tests on wood dethia-minized for protection against decay. Forest Prod. J. 18(1): 25-27.
- Greaves, H., and Barnacle, J. E.
1970. A note on the effect of microorganisms on creosote penetration in *Pinus elliotii* sapwood and *Eucalyptus diversicolor* heartwood. Forest Prod. J. 20(8): 47-51.
- Gruschow, G. F., and Trousdell, K. B.
1958. Incidence of heart rot in mature loblolly pine in coastal North Carolina. J. Forest. 56: 220-221.
- Hajny, G. J.
1959. A technical review of developments in microbiological utilization of wood sugars. Forest Prod. J. 9: 153-157.
- Hajny, G. J.
1966. Outside storage of pulpwood chips. A review and bibliography. TAPPI 49(10): 97A-105A.
- Harris, E. E.
1949. Food-yeast production from wood-processing byproducts. USDA Forest Serv. Forest Prod. Lab. Rep. 1754, 34 pp.
- Haskell, H. H., Bair, W. M., and Donaldson, W.
1966. Progress and problems in the southern pine plywood industry. Forest Prod. J. 16(4): 19-24.
- Hepting, G. H., and Chapman, A. D.
1938. Losses from heart rot in two shortleaf and loblolly pine stands. J. Forest. 36: 1193-2001.
- Highley, T. L.
1970. Decay resistance of four wood species treated to destroy thiamine. Phytopathology 60: 1660-1661.
- Holderby, J. M., and Moggio, W. A.
1959. The production of nutritional yeast from spent sulfite liquor. Forest Prod. J. 9(6): 21A-24A.
- Holmes, J. A.
1941. Slime control in paper mills. Pap. Trade J. 113(13): 104-106.
- Humphrey, C. J.
1916. Laboratory tests on the durability of American woods. I. Flask tests on conifers. Mycologia 8(2): 80-92.
- Humphrey, C. J.
1923. Decay of lumber and building timbers due to *Poria incrassata* (B.&C.) Burt. Mycologia 15(6): 258-277.
- Hunt, G. M., and Garratt, G. A.
1967. Wood preservation. Ed. 3, 433 pp. N.Y.: McGraw-Hill Book Co., Inc.
- Johnson, B. R.
1969. Permeability and microstructure of loblolly pine and Rocky Mountain Douglas-fir as influenced by *Trichoderma viride* Mold. MS Thesis. Univ. Wisconsin, Madison, Wis. 107 pp.
- Johnston, H. R.
1952. Insect control: Practical methods for the control of insects attacking green logs and lumber. Southern Lumberman 184 (2307): 37-39.
- Knuth, D. T., and McCoy, E.
1962. Bacterial deterioration of pine logs in pond storage. Forest Prod. J. 12: 437-442.
- Kramer, P. R.
1954. Results of spraying pine and hardwood logs for control of insects and stain. Tex. Forest Serv. Tech. Rep. 9, 18 pp.
- Lindgren, R. M.
1942. Temperature, moisture, and penetration studies of wood-staining *Ceratostomella* in relation to their control. USDA Tech. Bull. 807, 35 pp.
- Lindgren, R. M.
1951. Deterioration of southern pine plywood during storage. Forest Prod. Res. Soc. Proc. 5: 169-181.
- Lindgren, R. M.
1952. Permeability of southern pine as affected by mold and other fungus infection. Amer. Wood Preserv. Assoc. Proc. 48: 158-168.

- Lindgren, R. M., and Erickson, E. C. O.
1957. Decay and toughness losses in southern pine infected by *Peniophera*. Forest Prod. J. 7: 201-204.
- Lindgren, R. M., and Eslyn, W. E.
1961. Biological deterioration of pulpwood and pulp chips during storage. TAPPI 44: 419-429.
- Lindgren, R. M., and Harvey, G. M.
1952. Decay control and increased permeability in southern pine sprayed with fluoride solutions. J. Forest Prod. Res. Soc. 2(5): 250-256.
- Lindgren, R. M., and Scheffer, T. C.
1939. Effect of blue stain on the penetration of liquids into air-dry southern pine wood. Amer. Wood Preserv. Assoc. Proc. 35: 325-336.
- Lutz, J. F., Duncan, C. G., and Scheffer, T. C.
1966. Some effects of bacterial action on rotary-cut southern pine veneer. Forest Prod. J. 16(8): 23-28.
- McGovern, J. N., Martin, J. S., and Hyttinen, A.
1951. Effect of storage of slash pine pulpwood on sulfate and groundwood pulp quality. Forest Prod. Res. Soc. Proc. 5: 162-168.
- Mason, R. R.
1961. Sprinkling pine pulpwood in storage to prevent deterioration losses. Hiwassee Land Co. Forest Res. Note 7, 13 pp.
- Mason, R. R., Muhonen, J. M., and Swartz, J. N.
1963. Water sprayed storage of southern pine pulpwood. TAPPI 46: 233-240.
- Nelson, R. M.
1934. Effect of bluestain fungi on southern pines attacked by bark beetles. Phytopathol. Z. 7: 327-353.
- Panek, E.
1963. Pretreatments for the protection of southern yellow pine poles during air-seasoning. Amer. Wood Preserv. Assoc. Proc. 59: 189-195.
- Rasmussen, E. F.
1961. Dry kiln operator's manual. USDA Handbook 188, 197 pp.
- Rhyne, J. B., and Brinkley, A. W., Jr.
1961. Seven months outside storage of pine and hardwood chips at the Panama City Mill of International Paper Company. Southern Pulp and Pap. Manufacturer 24(2): 86, 88, 116-117.
- Robbins, W. J., and Kavanagh, V.
1942. Vitamin deficiencies of the filamentous fungi. Bot. Rev. 8: 411-471.
- Rothrock, C. W., Jr., Smith, W. T., and Lindgren, R. M.
1961. The effects of outside storage on slash pine chips in the South. TAPPI 44: 65-73.
- Saling, W. M.
1930. The effect of blue stain on the penetration and absorption of preservatives. Amer. Wood Preserv. Assoc. Proc. 26: 183-196.
- Saucier, J. R., and Miller, R. L.
1961. Deterioration of southern pine chips during summer and winter storage. Forest Prod. J. 11: 371-379.
- Scheffer, T. C., and Chidester, M. S.
1943. Significance of air-dry wood in controlling rot caused by *Poria incrassata*. Southern Lumberman 166(2091): 53-55.
- Scheffer, T. C., and Chidester, M. S.
1948. Survival of decay and blue-stain fungi in air-dry wood. Southern Lumberman 177(2225): 110-112.
- Scheffer, T. C., and Cowling, E. B.
1966. Natural resistance of wood in microbial deterioration. Annu. Rev. Phytopathol. 4: 147-170.
- Scheffer, T. C., and Lindgren, R. M.
1940. Stains of sapwood and sapwood products and their control. USDA Tech. Bull. 714, 124 pp.
- Scheld, H. W., and De Groot, R. C.
1971. Toughness of sapwood in water-sprayed longleaf pine logs. Forest Prod. J. 21(4): 33-34.
- Shema, B. F.
1955. The microbiology of pulpwood. TAPPI Monogr. Ser. 15: 28-54.
- Smith, R. S., and Hatton, J. V.
1971. Economic feasibility of chemical protection for outside chip storage. TAPPI 54: 1638-1640.

- Smith, V. K., Jr.
1959. Treating stored wood: Decay in pulpwood inventories can be reduced. *Pulpwood Prod.* 7(2): 10, 12.
- Springer, E. L., Eslyn, W. E., Zoch, L. L., and Hajny, G. J.
1969. Control of pulp chip deterioration with kraft green liquor. USDA Forest Serv. Res. Pap. FPL-110, 4 pp. Forest Prod. Lab., Madison, Wis.
- Springer, E. L., Haslerud, E. J., Fries, D. M., Clark, I. T., Hajny, G. J., and Zoch, L. L.
1971. An evaluation of four chemicals for preserving wood chips stored outdoors. *TAPPI* 54: 555-560.
- Toole, E. R.
1970. Variation in decay resistance of southern pine sapwood. *Forest Prod. J.* 20(5): 49-50.
- Toole, E. R.
1971. Reduction in crushing strength and weight associated with decay by rot fungi. *Wood Sci.* 3: 172-178.
- USDA Forest Products Laboratory.
1949. Condensation control in dwelling construction. Housing and Home Finance Agency, 100 pp. Wash., D.C.
- USDA Forest Products Laboratory.
1956. Temperatures necessary to kill fungi in wood. USDA Forest Serv. Forest Prod. Lab. Tech. Note 259, 3 pp.
- USDA Forest Products Laboratory.
1967. Comparative decay resistance of heartwood of native species. USDA Forest Serv. Res. Note FPL-0153, 2 pp. Forest Prod. Lab., Madison, Wis.
- USDA Forest Service.
1960. Wood decay in houses: How to prevent and control it. USDA Home and Gard. Bull. 73, 17 pp.
- Unligil, H. H.
1968. Depletion of pentachlorophenol by fungi. *Forest Prod. J.* 18(2): 45-50.
- Verrall, A. F.
1938. The probable mechanism of the protective action of resin in fire wounds on red pine. *J. Forest.* 36: 1231-1233.
- Verrall, A. F.
1939. Relative importance and seasonal prevalence of wood-staining fungi in the southern States. *Phytopathology* 29: 1031-1051.
- Verrall, A. F.
1941a. Dissemination of fungi that stain logs and lumber. *J. Agr. Res.* 63: 549-558.
- Verrall, A. F.
1941b. Fungi associated with stain in chemically treated green lumber. *Phytopathology* 31:270-274.
- Verrall, A. F.
1945. The control of fungi in lumber during air-seasoning. *Bot. Rev.* 11: 398-415.
- Verrall, A. F.
1959. Preservative moisture-repellent treatments for wooden packing boxes. *Forest Prod. J.* 9: 1-22.
- Verrall, A. F.
1962. Condensation in air-cooled buildings. *Forest Prod. J.* 12: 531-536.
- Verrall, A. F.
1965. Preserving wood by brush, dip, and short-soak methods. *USDA Tech. Bull.* 1334, 50 pp.
- Verrall, A. F.
1966. Building decay associated with rain seepage. *USDA Tech. Bull.* 1356, 58 pp.
- Verrall, A. F.
1968. *Poria incrassata* rot: Prevention and control in buildings. *USDA Tech. Bull.* 1385, 27 pp.
- Verrall, A. F.
1969. Attack by plant organisms on southern pine wood—a review. *Forest Prod. J.* 19(7): 40-46.
- Verrall, A. F., and Mook, P. V.
1951. Research on chemical control of fungi in green lumber, 1940-51. *USDA Tech. Bull.* 1046, 60 pp.
- Volkman, D.
1966. Water spray storage of southern pine pulpwood. *TAPPI* 49(7): 48A-53A.
- Wakeley, P. C.
1954. Planting the southern pines. *USDA Agr. Monogr.* 18, 233 pp.
- Wilcox, W. W.
1965. Fundamental characteristics of wood decay indicated by a sequential microscopical analysis. *Forest Prod. J.* 15: 255-259.

Wilde, S. A.

1958. Marketable sawdust com-
posts: Their preparation
and fertilizing value. For-
est Prod. J. 8: 323-326.

Wood, L. W.

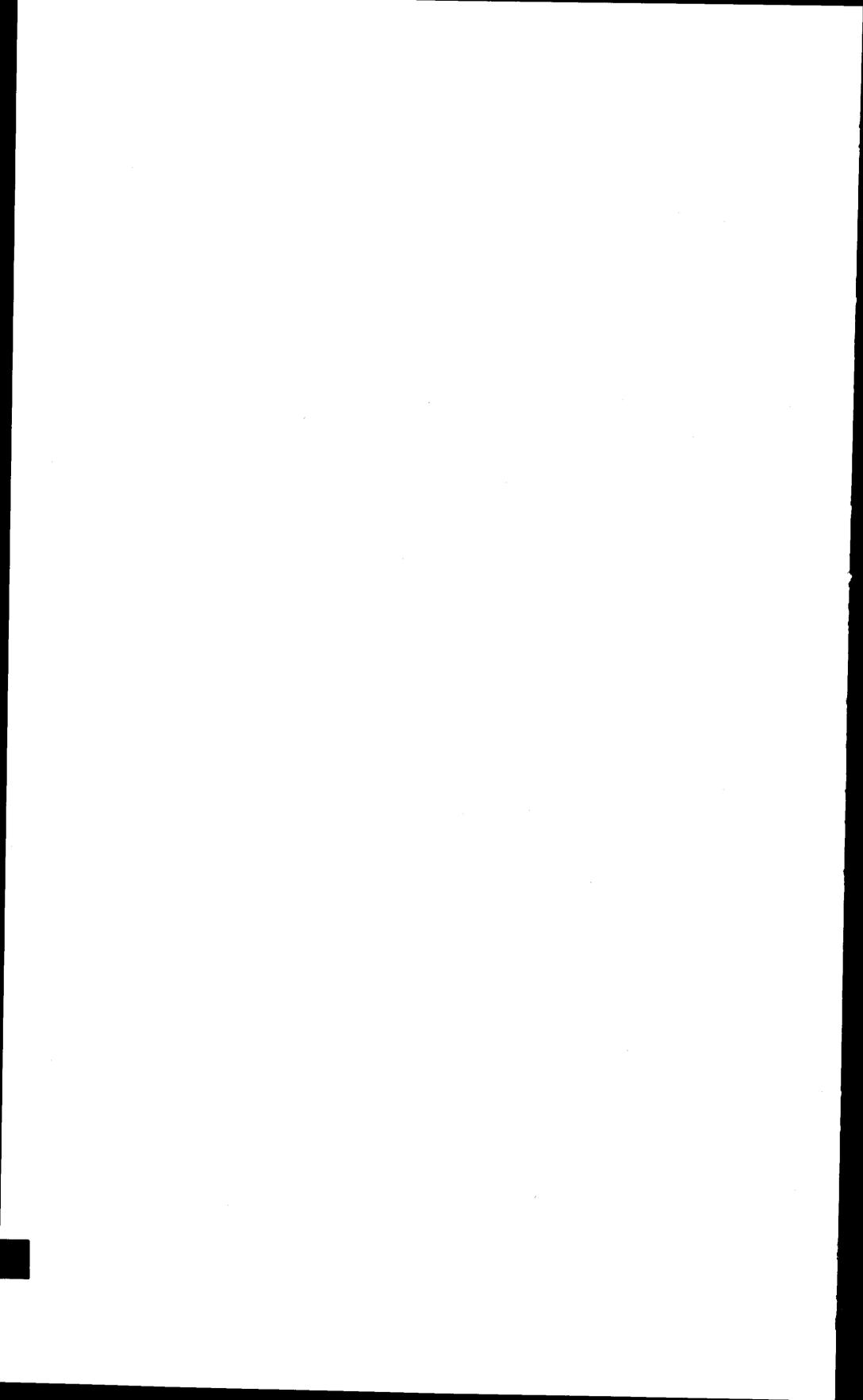
1955. Properties of white-pocket
Douglas-fir lumber.
USDA Forest Serv. For-
est Prod. Lab. Rep. 2017,
44 pp.

Zabel, R. A.

1959. Fungus losses in the paper
industry and related re-
search needs. TAPPI
42(5): 28A, 30A, 32A,
34A.

Zeller, S. M.

1917. Studies in the physiology of
the fungi. III. Physical
properties of wood in re-
lation to decay induced
by *Lenzites saepiaria*
Fries. Ann. Mo. Bot.
Gard. 4: 93-164.



17

Attacks by insects, marine borers, and birds

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17

Attack by insects, marine borers, and birds

This chapter describes the principal insects, marine borers, and birds that damage southern pine products; also discussed are research results pertinent to damage prevention by mechanical or chemical¹ methods.

17-1 TERMITES

Termites are wood-destroying, soft-bodied social insects having two similar pairs of wings. The world population of termites includes about 2,300 species classified as: **subterranean termites**, which mostly nest in the ground and require ground contact; **drywood termites**, which live in wood of low moisture content and do not maintain contact with the ground; **dampwood termites**, which locate colonies in damp (and hence often decayed) wood and sometimes extend their attacks into relatively sound dry wood; and **harvester termites**, many of which forage over wide areas for grass and other nonwoody cellulosic materials.

Discussed here are those species of economic importance in the geographic areas comprising the major U.S. markets for southern pine lumber, i.e., the Southern, Eastern, and Central States. Because dampwood termites are found in North America only on the west coast, and harvester termites are not found in North America, these species are not further discussed.

Readers desiring information on all termite species are referred to the two-volume text of Krishna and Weesner (1969, 1970) and to Snyder's (1956, 1961, 1968) abstracts of the world literature on termites.

¹ Mention of a chemical in this chapter or elsewhere in this text does not constitute a recommendation; only those chemicals registered by the U.S. Environmental Protection Agency may be recommended, and then only for use as prescribed in the registration—and in the manner and at the concentration prescribed. The list of registered chemicals varies from time to time; prospective users, therefore, should get current information on registration status from Pesticides Regulation Division, Environmental Protection Agency, Washington, D.C.

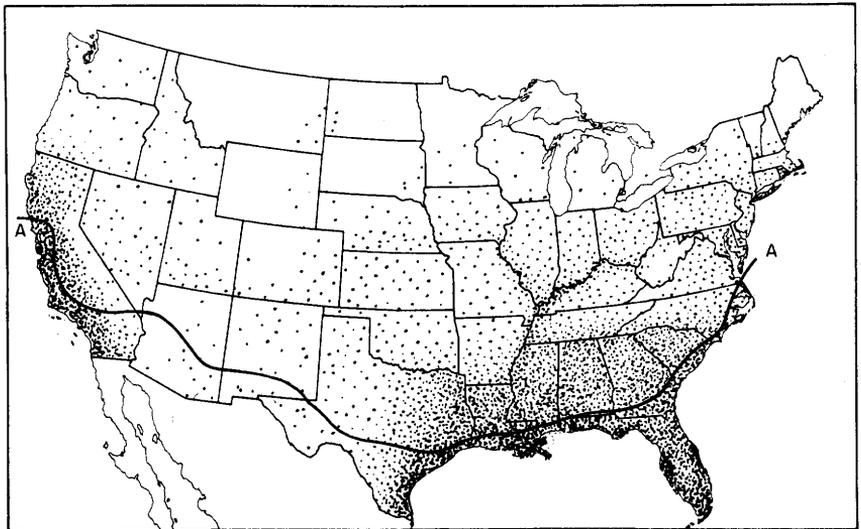
ECONOMIC IMPACT

Among insects that destroy southern pine products, termites are by far the most destructive. They attack and destroy buildings and other wood products in all States of the Union except Alaska. Subterranean termites, the most destructive type, are most common and aggressive in those parts of the United States comprising the major market for southern pine (fig. 17-1).

There are no termite epidemics; wherever termites occur, they vary their activities with the supply of available dead wood. Since they create a problem only where the wood they attack is in use or has value for future use, economic damage is most severe in densely populated areas.

The National Pest Control Association estimates that the United States now has about 46 million dwelling units subject to termite attack, and the net annual increase in such dwelling units is about 750,000. Less than 1 percent of the total houses (330,000) receive treatment for control of termites. The Association also estimates that its members are paid about \$115 million per year for termite control, and that the total for all pest control operators is \$170 million. Private individuals spend an additional estimated \$15 million on termite control and on repairs and replacements resulting from termite damage. The Defense Department spends \$70 million annually on termite control.

Thus, the total cost of termite control is estimated at not less than \$250 million per year. One-third of this cost is believed to be for damage repairs, the other two-thirds for chemical treatment. The total does not,



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Figure 17-1.—Relative hazard of native subterranean termite infestation in the United States is indicated by density of stippling. The northern limit of damage by drywood, or nonsubterranean, termites is indicated by line A. (Drawing adapted from St. George et al. 1969, and Anderson 1970, p. 196.)

however, represent the entire impact of termites on wood in use. In many instances, termite damage goes undetected, and in numerous others the owner either will not or cannot do anything to stop the damage. The losses in these categories probably far exceed the amount expended for control. Furthermore, termites do considerable damage to utility poles, fenceposts, and other wood that is not in structures. All things considered, the annual cost of termites probably exceeds \$500 million.

Losses attributable to termites in the United States are expected to increase in the future for two reasons. One is the expected population increase—more houses mean more opportunity for economic losses to termites. The second is the recent establishment here of the Formosan termite (*Coptotermes formosanus* Shiraki), a species that is somewhat more aggressive than our native species and that may eventually extend its range into most coastal areas of the United States.

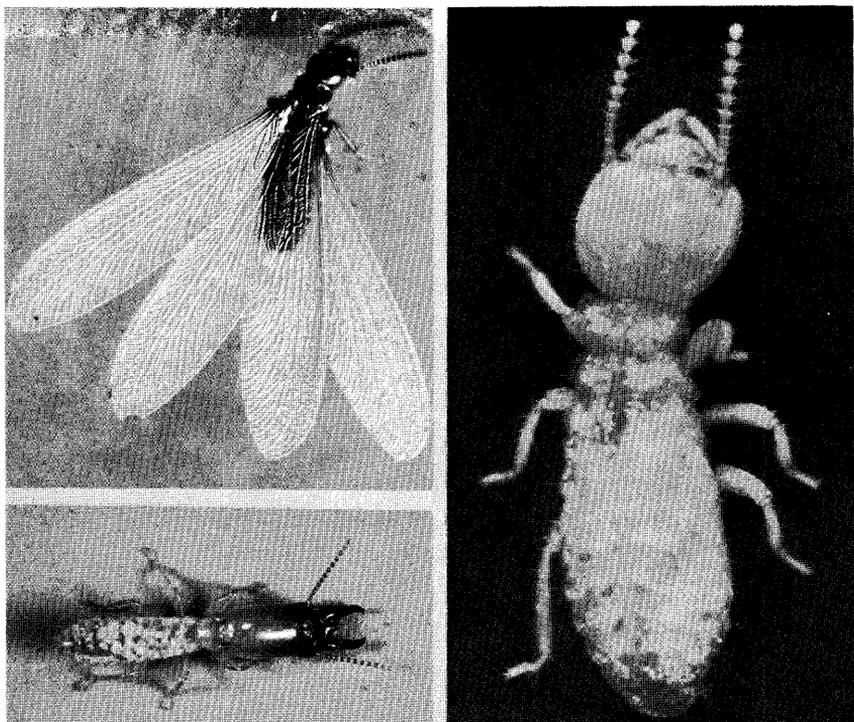
SUBTERRANEAN TERMITES

The four subterranean termite species particularly damaging to southern pine products all belong to the family Rhinotermitidae. Three are in the genus *Reticulitermes*, *R. flavipes* (Kollar), *R. virginicus* (Banks), and *R. tibialis* Banks; and one—the Formosan termite—is of the genus *Coptotermes*, i.e., *C. formosanus* Shiraki.

Description and life cycle.—This text only briefly describes salient points in the life cycle of termites; for discussions in greater depth, the reader should consult Krishna and Weesner (1969, 1970).

Subterranean termites are social insects that live in nests or colonies in the ground. Each colony is made up of three forms or castes—workers, soldiers, and reproductives (fig. 17-2). During their lifetimes, the individuals of each caste pass through three stages—egg, nymph or immature form, and adult. The adult workers are wingless and grayish white. The soldiers have much larger heads and longer mandibles, or jaws, than the workers. The worker is the wood destroyer and the one usually seen in damaged wood. The soldier guards the colony. Adult winged reproductives (**alates**) have yellow-brown to black bodies and two pairs of long, whitish, opaque wings of about equal size and shape. They differ from the reproductive forms of ants (fig. 17-3), which have two pairs of transparent wings of unequal size. Termites have thick waistlines. In contrast, ants, which are often mistaken for termites, have thin waistlines (St. George et al. 1969).

At certain times of the year—most frequently after the first warm days of spring, often following a warm rain—the winged reproductives swarm from established colonies, leave, and fly to new locations. Nutting (1969, p. 237) notes that the percentage of winged reproductives in a colony is difficult to obtain and cites observations ranging from less than 3 percent to about 40 percent of total colony population. After they alight and shed their wings (figs. 17-3 Bottom, 17-4), a male (king) and female



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Figure 17-2.—Eastern subterranean termite (*Reticulitermes flavipes* (Kollar)). (Top left) Winged sexual adult or reproductive measures nearly 1 cm. from head to tip of folded wings. (Right) Adult worker is slightly less than $\frac{1}{2}$ cm. in length. (Bottom left) Adult soldier is slightly more than $\frac{1}{2}$ -cm. long.

(queen)—finding wood on the ground—crawl under it or into its crevices to initiate a new nest and colony.

According to Snyder's (1915) description of *Reticulitermes flavipes* (Kollar), a nuptial chamber is formed, and within a few days or weeks the first eggs are laid; there are normally 6 to 12 eggs in the first clutch. Recent work at the USDA Forest Service Southern Forest Experiment Station indicates that from 25 to 60 days are normally required for hatching. The young termites are fed initially by the adults. After several weeks the young termites are able to feed themselves on wood.

For the first 6 months most of the termites are small, i.e., 2 to 5 mm. in length. In a colony large enough to supply ample food through fraternal feedings, full-size adults of the reproductive caste (fig. 17-2) require about 2 years to develop from hatching; the other castes probably require less than 1 year. Of the adults, workers are shortest (slightly less than $\frac{1}{2}$ -cm. in length), soldiers are intermediate (slightly more than $\frac{1}{2}$ -cm. in length), and alates are longest (nearly 1 cm. from head to tip of folded wings). Workers not falling victim to cannibalism may live 1 to 5 years;

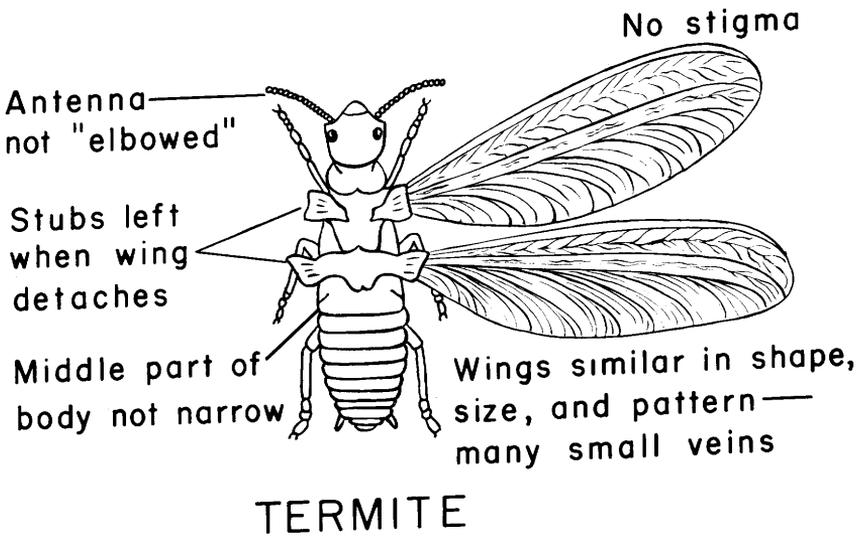
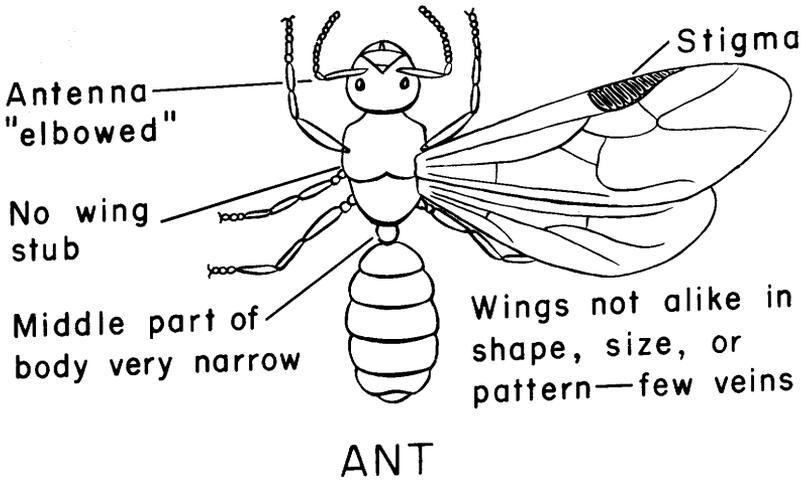


Figure 17-3.—Differences between winged adult ants and termites. (Drawing after Johnston, H. R., Smith, V. K., and Beal, R. H. *Subterranean termites, their prevention and control in buildings*. USDA Home and Garden Bull. (in press).)

queens probably live much longer—perhaps as long as 25 years (Snyder 1948).

A colony-founding queen may lay 20 to 40 eggs during her first year of fertility; in later years her egg-laying rate may increase to at least a dozen per day. Reproductives supplementary to the founding queen are required for rapid population increase in a colony. Ebeling (1968, p. 16) states that a supplementary queen can produce more eggs (60 to 80) in a day than the founding queen during the first 2 years of the colony's development.



Figure 17-4.—Winged adult termites and discarded wings—proof of the presence of a colony nearby. (Photo from Johnston, H. R., Smith, V. K., and Beal, R. H. Subterranean termites, their prevention and control in buildings. USDA Home and Garden Bull. (in press).)

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Snyder (1915) found it hard to estimate the size and extent of old, well-established colonies of *R. flavipes* (Kollar), since they may branch over several acres of ground as the increasing population seeks fresh supplies of dead wood. Based on observations of 5,000 to 10,000 eggs in a well-established colony of *R. virginicus* (Banks), he estimated the colony population as tens of thousands. Scientists at Gulfport, Miss. have found colonies of *R. virginicus* that almost certainly number 100,000.

Feeding and food selection.²—Central to termite behavior is their aversion to exposure and need to maintain contact with the ground or other source of moisture while they search for cellulose, their principal food. Generally they forage widely both underground by subterranean galleries and aboveground by covered runways or tubes constructed of earth.

There are several possibilities for explaining the food-finding behavior of subterranean termites. Much of it is probably random; in other words, a gallery or runway is extended until it either produces food or is abandoned as unproductive. Some aboveground food-finding may be accomplished by a combination of random exploration and trail laying, since most, if not all, termites can generate an odor trail from one or more abdominal sternal glands. However a new wood supply is located, it is not attacked effectively unless it can be reached by a subsurface gallery, or until it is connected to the colony by a constructed runway.

Termites commonly exhibit some feeding selectivity. Extractive-rich heartwood of old-growth longleaf pine lumber is virtually immune to termite attack in the United States. All southern pine sapwood and most heartwood in southern pine lumber now available, however, is promptly attacked when exposed. Termites appear to favor earlywood of southern pine over the denser latewood (fig. 17-5). They also prefer pine that is wet, i.e., from fiber saturation point (roughly 25 to 30 percent) up to 150 percent or more. They attack wood of much lower moisture content, however, by building covered runways to connect it to soil or other moisture source.

Stems and roots of living southern pine trees are seldom if ever attacked by native subterranean termites. Perhaps the oleoresin that flows into any wound in a living pine is a physical deterrent to attack, or a chemical repellent.

Termites can attack sound wood but favor wood that is partly decayed. As termites extend their excavations into sound wood, they carry with them decay and mold fungi which thrive in the moist atmosphere of their excavations. The advantage conferred by fungi to the termite presumably results from an enrichment of the cellulosic food in carbohydrate, nitrogen, and possibly vitamin content.

As noted previously, there is ample evidence that termites preferentially

² The text under this heading is condensed from Smythe, R. V. Feeding and food selection of subterranean termites. An oral review of the literature presented at the 1968 Meeting of the Entomological Society of America, Dallas, Tex. Dec. 2-5, 1968.

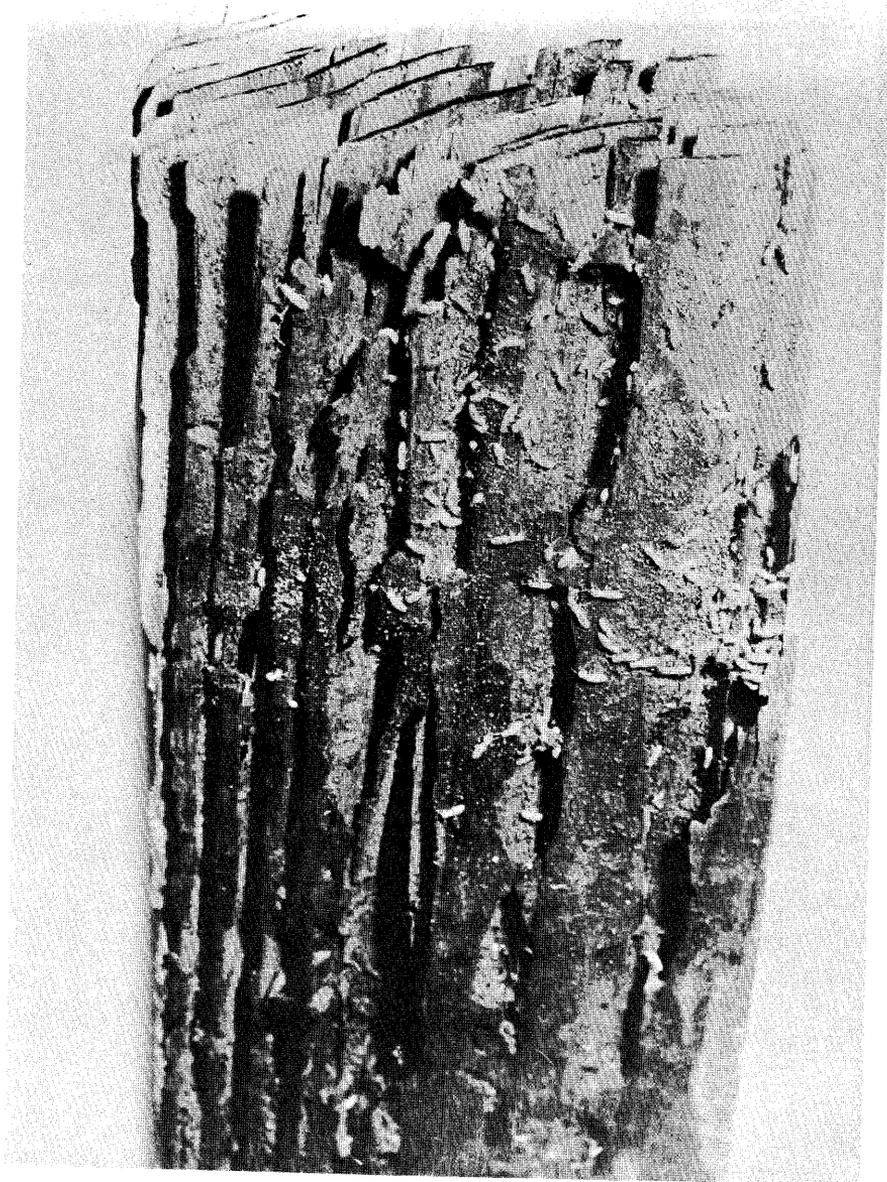
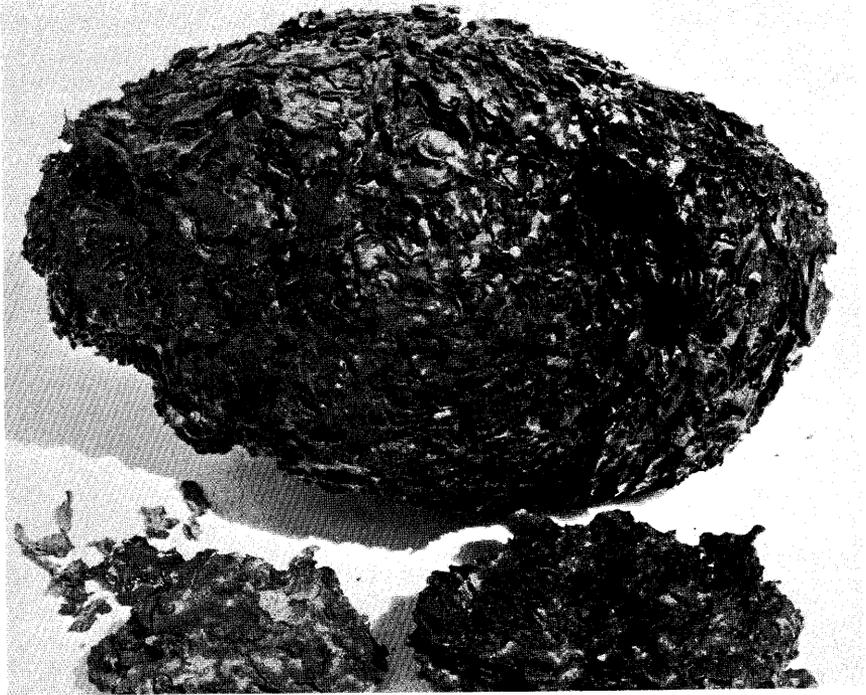


Figure 17-5.—Southern pine 2 by 4 destroyed by subterranean termites. Excavations are in earlywood; latewood is largely intact. (Photo from Smith and Johnston 1962.)

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seek out decayed wood. Certain fungi, especially *Lenzites trabea*, elicit attractant responses. The attractant compound from *L. trabea*-decayed quaking aspen (*Populus tremuloides* Michx.) has been identified as a 12-carbon unsaturated primary alcohol. Interestingly, this attractant is identical to the trail-laying compound produced by *R. flavipes* (Kollar).



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Figure 17-6.—A primary nest of the Formosan termite constructed of a substance called carton. Nests are generally constructed below ground at the bases of trees, stumps, or posts, or near buildings; they are also, however, often constructed above ground between studs in buildings or in hollow trees or poles. This one was unearthed from the soil around the base of a tree in New Orleans. (Photo from Beal and Stauffer 1967.)

Recent work suggests that *R. flavipes* (Kollar) can detect *L. trabea*-decayed wood in the soil at a distance of 2 feet, but only if no duff layer on the soil is present; possibly, microbial degradation activity in leaf mold masks the attractant from decayed wood.

The four species of subterranean termites that most heavily damage southern pine products all normally harbor flagellate protozoa in their intestines; these symbiotic protozoa enable termites to metabolize cellulose. Evidence to date suggests that termites comminute the wood and transport it to their hind gut where the protozoa digest it and metabolize it anaerobically to carbon dioxide, hydrogen, and acetic acid via glucose; acetic acid may then be oxidized by the termite to satisfy its energy needs.

Food exchange.—An additional aspect of termite feeding habits is of importance to possible methods of colony eradication; among the chief regulatory and integrative mechanisms of termite colonies is the mutual exchange of nutrients between colony members, i.e., **trophallaxis**. Grassé (1949) and Grassé and Noirot (1945) have described the two methods by which termites exchange food.

In the **stomodeal** method the soliciting termite caresses with its antennae the head of the prospective donor, or taps with its mandibles against the mouth parts of the donor. The donor reflexively disgorges a droplet of fluid which is passed from the donor's mouth to that of the recipient.

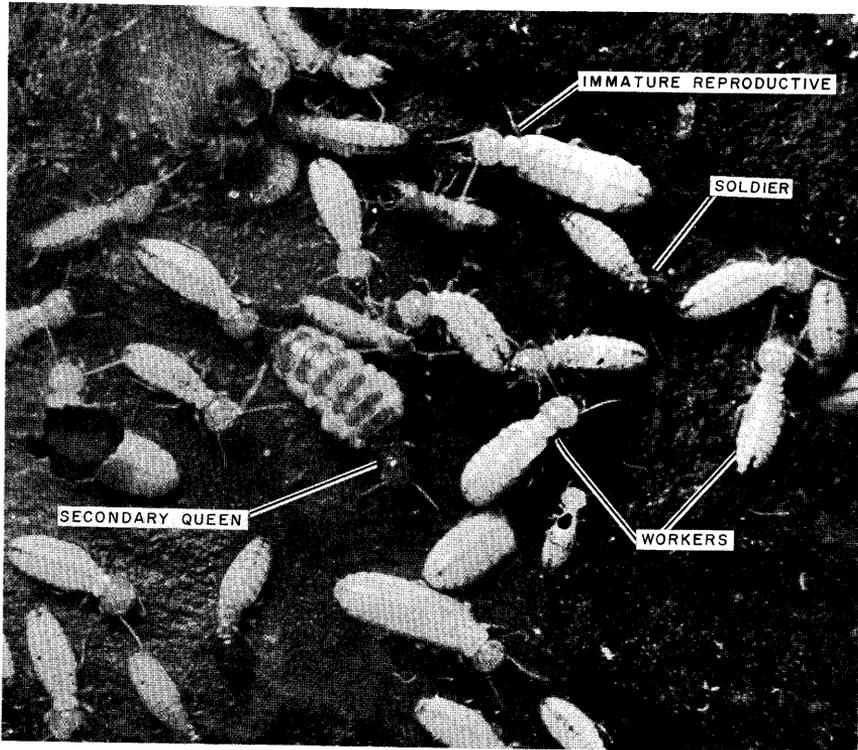
In the **proctodeal** method, one termite solicites by tactile stimulation from the donor a part of the fluid content of the hind gut; a droplet of liquid from the rectal pouch is then voided by the donor and ingested by the recipient. This proctodeal food consists of hind-gut fluid containing flagellate protozoa, products of digestion, and also fragments of wood.

Formosan termite.—The Formosan termite (*Coptotermes formosanus* Shiraki), a species not found in the continental United States prior to 1965, was first identified in Houston, Tex. in a waterside warehouse. Beal and Stauffer (1967), in tracing the spread of the insect in this country, noted that during 1966 isolated infestations were discovered in Galveston, Tex. and in New Orleans, Lake Charles, and West Lake, La.; later in the year two other infestations were discovered in New Orleans and by mid-June 1967, entomologists had uncovered an infested area in Charleston, S.C. In 1968 Formosan termites were found at three new locations: Beaumont, Tex., Port Allen, La., and Raceland, La. (Johnston and Beal 1969). Beal and Stauffer (1967) concluded that, judging from climates abroad in which *C. formosanus* has thrived, the unopposed range in this country would probably include most coastal areas and perhaps some interior areas.

Formosan termites typically construct subterranean nests that may attain several cubic feet in size; they are usually located at the base of trees, stumps, or posts, or near buildings. The nests, constructed of **carton** (a mixture of masticated wood, termite saliva, and excrement), are distinct (fig. 17-6) from the less elaborate structures built by native termites. Radiating from the nest are hard-walled tunnels, composed of essentially the same material as the nests and almost impervious to water. Some tunnels go 10 feet into the earth and horizontally from 150 to 200 feet from the primary nest. Many long tunnels lead to secondary nests, composed also of carton (Beal and Stauffer 1967). Where necessary to reach wood, the Formosan termite will build covered runways above ground.

Beal and Stauffer (1967) state that a mature primary queen, often measuring close to $1\frac{1}{2}$ inches long, may lay up to 1,000 eggs a day and build up a huge population in a short time; a single centralized colony may contain several hundred thousand individuals.

C. formosanus alates and soldiers can be readily distinguished from the native species of subterranean termites; Formosan termite workers are almost identical in appearance to native workers (fig. 17-7). The bodies of the Formosan winged reproductives are 30 to 50 percent longer than the less than 0.4-inch length of the natives, and their wings are decidedly longer than the wings of the natives (fig. 17-8). Formosan alates have pale-yellow bodies; alates of the native species of subterranean termites



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Figure 17-7.—Secondary nest of Formosan termite, showing workers, soldiers, immature reproductives, and a secondary queen. The king, usually found close to the queen, escaped into the debris as this was taken. (Photo from Beal and Stauffer 1967.)

have black bodies. Formosan soldiers are more aggressive than natives; when a Formosan nest is broken into, the soldiers remain visible while the others hide. When excited, the Formosan soldiers exude an easily seen white substance from the external opening of the frontal gland, the fontanelle, located on the top of the head. The fontanelle on soldiers of native termites is undeveloped. Formosan soldiers (figs. 17-8, 17-9) have more oval-shaped and shorter heads than soldiers of the native species, whose heads tend to be oblong (Beal 1967; Beal and Stauffer 1967).

While Formosan termites are known to attack some living trees, there is no evidence that they attack living southern pines. Some creosoted utility poles have been attacked; most activity was in sapwood that contained little or no creosote. The termites reached the untreated wood through checks and cracks below the ground line (Johnston and Beal 1969).

DETECTION OF SUBTERRANEAN TERMITES

Large numbers of winged reproductive termites emerging or swarming from the soil or wood may be the first indication of the presence of a ter-

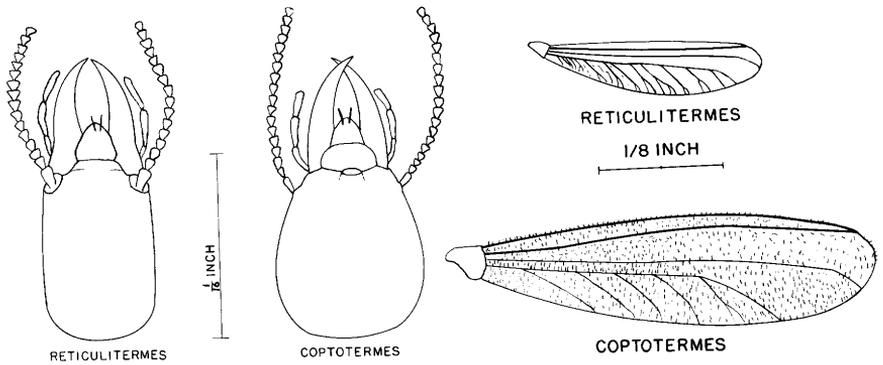


Figure 17-8.—(Left) Heads of soldiers of the two subterranean termite genera are easy to distinguish. (Right) The forewing on the *Coptotermes* (Formosan) alate is hairy and larger than that on *Reticulitermes*, the native genus. (Drawings after Beal 1967.)

mite colony. Even though the actual flight of these adults is not observed, the presence of their discarded wings (fig. 17-4) is very good evidence of a well-established colony nearby. These discarded wings often are found on the floor beneath doors or windows where termites have emerged within a building and been unable to escape.

In order to see the extent of termite damage, exterior wood must usually be stripped away. The excavations of subterranean termites are free of

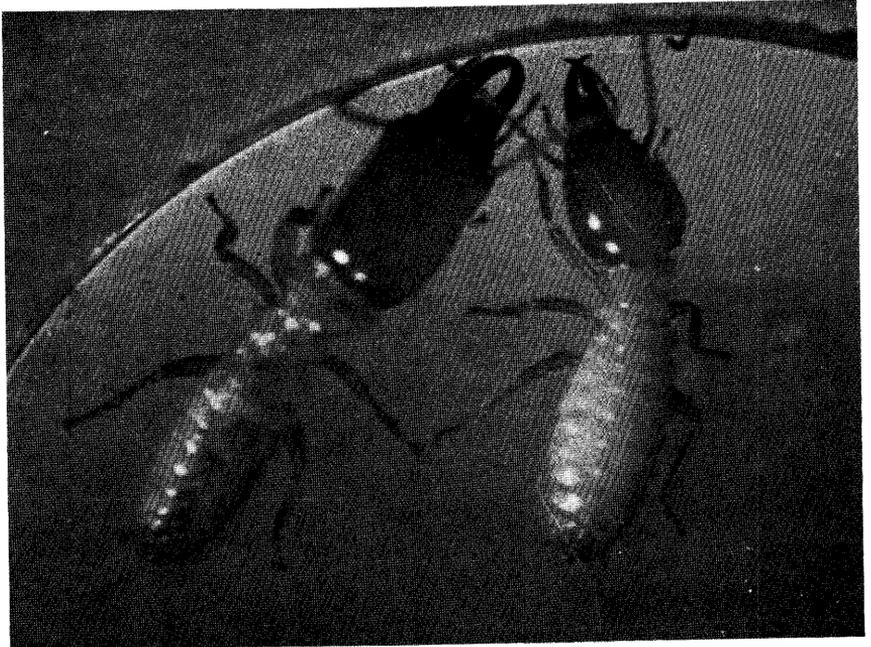


Figure 17-9.—On the left, native subterranean termite soldier; a Formosan soldier on the right. The chief distinguishing feature is the oblong shape of the native soldier's head. (Photo from Beal and Stauffer 1967.)

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frass, but may show grayish specks of excrement and earth. Wood particles are not pushed out of their workings, as is the case with drywood termites and some other wood-boring insects (see sec. 17-2).

The presence of covered runways, the flattened, $\frac{1}{4}$ - to $\frac{1}{2}$ -inch-wide shelter tubes which subterranean termites construct over the surface of foundation walls, is another sign of termite infestation (fig. 17-10).

PROTECTIVE TREATMENT—SUBTERRANEAN TERMITES

Protection against termites is not generally synonymous with eradication; while it may be desirable to eradicate termites in certain situations and in densely populated areas, there are numerous beneficial aspects of termite life in rural and forested areas. Most of the widely used termite control measures are designed to exclude the insects rather than kill them.

Pressure impregnation of wood with preservatives.—Section 22-1 describes treatment for preservation, and tables 22-3 and 22-4 summarize the performance of various preservatives in stakes and round southern pine posts in soil contact.¹ In brief, treatments that research indicates should protect southern pine in contact with the ground against both termites and decay for an average life exceeding 40 years under south Mississippi conditions include pressure treatments with coal tar creosote and used crankcase oil (50-50), pentachlorophenol (3 to 5 percent) in used crankcase



Figure 17-10.—Subterranean termite shelter tubes on foundation.

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oil, water-gas tar, and zinc meta arsenite, as well as double diffusion treatment with copper sulfate and sodium arsenate.¹

Indicated by research to be slightly less effective (25- to 40-year average life) are pressure treatments with acid copper chromate (Celcure), chromated zinc chloride, coal tar, coal tar creosote, fluor chrome arsenate phenol (Tanalith), lignite coal tar creosote, tetrachlorophenol (3 to 5 percent) in used crankcase oil, and zinc chloride; steeping in mercuric chloride and full-length Osmose (diffusion) treatments should also result in average lives of more than 25 years.¹

Beal (1969) has shown that subterranean termites may extend tubes across wood treated with pentachlorophenol or Wolman salts to attack adjacent untreated southern pine.¹ Addition of chlorinated hydrocarbon insecticides¹ to the preservatives deterred such tubing. While the length of Beal's experiment and number of treatments were insufficient to recommend specific concentrations of insecticide, he found that no test units treated with more than $\frac{1}{16}$ -percent of aldrin, dieldrin, chlordane, or heptachlor were tubed over.¹

Soil-treatment chemicals.¹—Evaluations of insecticides to control subterranean termites are based on long-term studies by the USDA Forest Service at the Wood Products Insect Laboratory in southern Mississippi (Johnston et al.³). The insecticides are primarily evaluated for their effectiveness as contact poisons or repellents by two methods.

The **ground-board method** simulates treatment of soil before a concrete slab foundation is poured. In this test all vegetation and duff is removed from a 17-inch square of soil; then a known amount of chemical, as a water emulsion, is spread evenly over the exposed soil. After the chemical soaks into the soil, a 1- by 6- by 6-inch untreated, sapwood, southern pine board is laid flat in the center of the treated area. To reach the untreated board, termites must penetrate the treated soil.

The **standard stake method** simulates treatment of soil in trenches around foundation walls, piers, piling, water and sewer lines, and other ground-to-building connections. In this test, soil is removed to make a cylindrical hole 15 inches in diameter and 19 inches deep (reduced to 14 $\frac{3}{4}$ inches in some studies); the removed soil is treated with 4 gallons of insecticide emulsion in water per 10 cubic feet of soil and then replaced in the hole. A 2- by 4-inch untreated, sapwood, southern pine stake measuring 18 or 12 inches in length (depending on depth of hole) is then driven into the center of the treated soil.

With both test methods, the wood is examined annually for termite damage, and severely decayed specimens are replaced. In 1970, certain concentrations of aldrin, chlordane, dieldrin, and heptachlor were still giving 100 percent control after 17 to 21 years.¹

³ Johnston, H. R., Smith, V. K., and Beal, R. H. 1971. Chemicals for subterranean termite control: Results of long-term tests. *J. Econ. Entomol.* 64(3): 745-748.

Based on research data from these tests, concentrations (by weight in water) of 1/2-percent aldrin, 1 percent chlordane, 1/2-percent dieldrin, or 1/2-percent heptachlor, when applied at a rate of 1 gallon per 10 sq. ft. of soil (or 4 gallons per 10 linear feet of foundation wall), should provide protection (USDA Forest Service 1968) from native termite species for many years. Research on these treatments indicates duration of protection to be at least 22 years for chlordane, 21 for aldrin and dieldrin, and 18 for heptachlor.¹ When Formosan termites (*Coptotermes formosanus* Shiraki) are present, research indicates that concentrations should be increased.¹

Effectiveness of the insecticides is not greatly altered by the amount of water carrier used, but is more closely related to the actual amount of insecticide placed in the soil (Johnston et al.³).

Analysis of soil adjacent to treated plots shows that these insecticides moved only a few inches through sandy loam soil after 2 decades of heavy rainfall and weathering (Smith 1968, 1969); since in practice they are placed on the soil under buildings where there is a minimum of weathering, erosion, or other disturbance, the treatment presents a minimal hazard to man.

There is risk of contamination if the insecticides are applied near a water well on soil that contains layers of gravel or that tends to crack severely during periods of drought. In such cases a soil chemical should not be applied; instead, mechanical barriers should be used, as later described.

Building practices to exclude termites.—Because subterranean termites virtually always must enter buildings through connections to earth, certain construction practices will deter their attacks. Removal of tree roots, stumps, and other wood debris from the building site before construction starts; and removal of grade stakes, form boards, and lumber scraps as building proceeds will reduce available food supply in the soil and hence danger of termite infestation.

St. George et al. (1969) and Ebeling (1968) discuss structural details of foundations that deter access by termites. Their recommendations may be briefly summarized as follows.

Prevent moisture from accumulating in the soil under a building, and slope the soil surface so that moisture will drain away from it.

Choose carefully the kind of foundation. Poured concrete foundations, properly reinforced, are best. If hollow blocks or brick foundations or piers are used, cap them with at least 4 inches of reinforced poured concrete or fill the top course of blocks and all joints completely with concrete to prevent attack through poor mortar and through hollows in blocks. Along perimeter and interior foundations, 4 gallons of the previously described water emulsion should be applied per 10 linear feet. Additional protection will be obtained by applying 1 gallon per 10 sq. ft. of soil around pipes or conduits that extend from the ground up to the woodwork of the building.

In buildings with crawl spaces, beams and girders should be at least 12

inches and floor joists at least 18 inches above the ground. Make the outside gradeline at least 6 inches below all exterior woodwork.

In places where the termite hazard is extreme, the use of pressure-treated sills, joists, and headers is an additional safeguard.

Provide good ventilation underneath buildings with crawl space. In general, the net area of ventilation openings should be $\frac{1}{160}$ th of the ground area beneath the building. Distribute the vents so that no dead-air pockets are formed.

Concrete slab-on-ground construction is susceptible to termite attack, and infestations are difficult to control. Slabs vary in susceptibility to penetration by termites.

The monolithic type is best, because the floor and the footings are poured in one operation, and there are no joints to permit entry.

The floating slab is the most hazardous. It may rest on a ledge of the foundation or be independent of it. Termites can enter at the joint between the slab and the foundation.

Because settlement cracks occur almost always in any type of slab, and termites can enter through them, the underlying soil should be treated with chemicals¹ (1 gallon of the previously described water emulsion per 10 sq. ft.) before pouring the concrete of any slab. Also, 4 gallons of the water emulsion per 10 linear feet should be applied to the soil along the inside and outside of perimeter foundations, along interior foundations, and around the places where plumbing comes through the slab (Johnston 1965).

Suppression through ingested stomach poisons.—The previously discussed protective measures, i.e., preservative treatment of wood, soil treatment with contact poisons, and mechanical blocking are all ways of deterring termite attack by creating chemical or physical barriers.

An alternative approach is to incorporate a stomach poison into food attractive to the termite. As previously noted, the food exchange and social habits of termites are such that a slow-acting poison may be transferred throughout a colony even though only a limited number of individuals ingest it originally.

Promising research with this approach was reported by Esenther and Gray (1968). They applied Mirex¹—a slow-acting stomach poison effective on several other social insects—to wood blocks partially decayed by a fungus which attracts termites. Foraging by termites ceased promptly after the poisoned blocks were exposed. Observations are continuing, and being extended, to determine whether the method is effective in eliminating localized pockets of infection.

DRYWOOD TERMITES

Drywood termites are members of the family *Kalotermitidae*. They are distinguished from subterranean termites not only by their larger size but also by their ability to establish colonies and live in undecayed wood having

little moisture; they require no contact with the ground. In the South, drywood termites cause much less damage than subterranean termites, but economic losses attributable to them are substantial.

Since drywood termites remain in the wood and build no shelter tubes to the ground, the most common evidence of their presence is a pile of fecal pellets immediately below holes or cracks in the infested wood. Drywood termites burrow radially across the grain as well as along the grain so that they destroy both latewood and earlywood by excavating broad chambers which may be connected by tunnels. Because drywood termites require no connection to the ground, they may survive movement from one region to another, and therefore may be dispersed readily. Figure 17-1 indicates the portion of the United States in which infestation by drywood termites is a hazard.

In the areas in which southern pine is utilized, the most important species of drywood termite is probably *Incisitermes snyderi* (Light). This termite (fig. 17-11) is light in color and has a range from South Carolina to Florida, west to eastern Texas. It causes damage to woodwork of buildings, furniture, and utility poles. It flies in the early evening after dark in May and June. A flight, which may be attracted to lights, is usually comprised of a dozen or more individuals (Snyder 1954).

A second drywood termite of substantial economic importance in southern coastal areas—particularly southern Florida—is *Cryptotermes brevis* (Walker). Members of this species are usually smaller than those of *I. snyderi*, and their fecal pellets are also smaller. Galleries of *Cryptotermes* are full of debris while those of *Incisitermes* are free of debris.

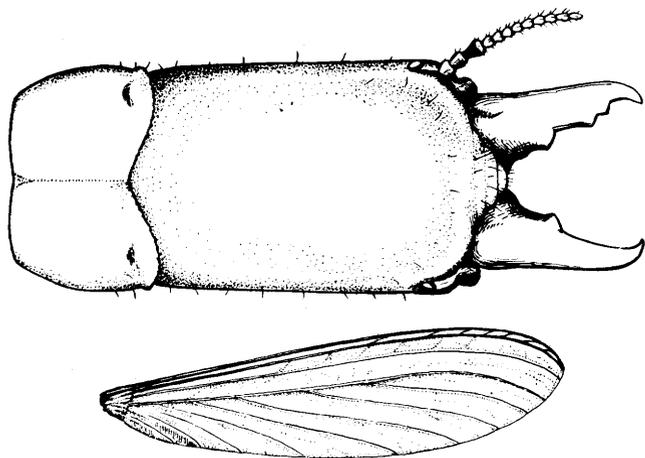


Figure 17-11.—Keys to identification of drywood termite *Incisitermes snyderi* Light. (Top) Dorsal view of head and prothorax of soldier, showing serrate margin of prothorax at anterior; enlarged 15 times. (Bottom) Venation of forewing; enlarged six times. (Drawing after Snyder 1954, p. 33; reprinted by permission of the National Pest Control Association, New York ©.)

There are no well-illustrated published accounts of the life cycle of *I. snyderi* (Light), or *C. brevis* (Walker); however, the interested reader can consult Harvey (1934) for biological information on the closely related species *I. minor* (Hagen), which is common in coastal California and peripheral desert areas of southern California and Arizona; Ebeling (1968, pp. 21, 22, 23) illustrates the adult members of each caste, eggs, fecal pellets, and patterns of damage of this western species.

In brief, following flight from the previously occupied colony and divestiture of wings, the newly paired alates burrow about $\frac{3}{8}$ -inch into dry or green earlywood above ground level, seal the entry, enlarge the cavity until they can turn about in a pear-shaped chamber, and then become inactive for about 9 months. The queen then lays the first eggs—two to five in number—and here the colony starts.

The young nymphs which hatch from the first eggs enlarge the burrow so that after 15 months the amount of wood removed is 0.5 to 2.5 cc. Toward the end of the second year after the colonizing pair entered the wood, about 3 cc. of wood has been destroyed by the securely established young colony, which now consists of a king and queen, one soldier, and a dozen or more nymphs (Harvey 1934).

The egg-laying period of an active, prolific queen begins in late spring and ends in late fall, during which time she alternately lays one to 12 eggs each 24 hours for periods of a week or 10 days and then ceases egg laying for a month or more. The incubation period in 1- and 2-year-old colonies is 77 days when the temperature is kept at 80° F. and the relative humidity at 83 percent.

During her second year, the primary queen usually produces about eight eggs with a maximum of 12 to 15; with each succeeding year her fecundity increases and probably reaches a maximum when she is 10 to 12 years old. After this time, secondary queens may begin to produce eggs. Probably more than a year is required for a nymph to develop from egg to alate or soldier. After 15 years, the colony—without ever leaving its food source above ground—may number about 2,600 individuals, of which nearly all are nymphs, with only 120 soldiers, the original royal pair, and one or more supplementary reproductives. If the colony is in a pole, the passages are usually most numerous in the sapwood, which may become a mere shell or skeleton framework; a protective shell is always left around passageways, however, so that from the exterior the wood under attack appears intact (Harvey 1934).

PROTECTIVE TREATMENT—DRYWOOD TERMITES

Drywood termites are seldom seen. They remain hidden within the wood except during dispersal flights.

Detection.—Drywood termites seal all openings in wood with a brownish or blackish substance which they secrete. This secretion soon hardens into

cementlike plugs, usually paper thin, and often containing pellets of excreta (Snyder 1950).

Drywood termites excrete pellets of partly digested wood; subterranean termites do not. The pellets, which vary in size, may be found in the tunnels and in piles on the floor where they have been ejected from the infested wood. When the termites are eating southern pine, the pellets normally have the coloration of southern pine wood. Termite pellets can be distinguished by concavities in their surfaces. Excreted pellets of the anobiid beetle *Nicobium hirtum* Illiger resemble those of drywood termites in size and coloration, but have completely convex surfaces—as do frass pellets of all the wood-feeding anobiids.

Drywood termites may also construct thick, flat, short tubes of secreted substances and excreted pellets to shelter them as they pass from one piece of wood to another. In their excavations they may form chambers so close to the surface that it appears blistered; when tapped with the finger, attacked wood may sound hollow or emit a papery rustle, indicating tunnels just below the surface (Snyder 1950).

Materials to deter infestation.—Lumber, whether new or secondhand, should be carefully inspected for evidences of infestation. Infested lumber should never be used in construction unless the termites are first killed by heating in a kiln to 150° F. for 1.5 hours or to 140° F. for 4 hours.

In completed structures, ventilation openings should be screened with noncorrodible wire cloth, preferably having 20 meshes to the inch, to prevent entrance of winged termites. Several coats of heavy paint will give the exterior woodwork of buildings considerable protection against termite entry; all cracks, crevices, and joints should first be caulked.

Pitchy heartwood of old-growth longleaf pine (lightwood) is resistant to attack by drywood termites—particularly if painted. Most southern pine lumber currently available, however, is no more resistant than most other coniferous woods in common use in the United States (Snyder 1950).

Control with insecticides.¹—Because the drywood termite enters wood via cracks (usual) or even directly into wood, it is not possible to isolate buildings from attack. Vent screens of sufficiently fine mesh to deny access to drywood termites are unsatisfactory because they become clogged with cobwebs, dust, and debris. Paint, while it provides considerable protection, still leaves many areas open for attack, e.g., keyholes and lower edges of doors.

To forestall attack, a few methods of treatment have been found reasonably successful. Use of lumber properly pressure treated with preservatives¹—as described in connection with subterranean termite control—will prevent attack. Providing substantially less protection are brush or spray coats of some of the preservatives, e.g., 5 percent pentachlorophenol solution, copper naphthenate solution, and zinc naphthenate.¹ Chlordane, or other effective insecticide,¹ incorporated in plywood glue lines is also reported to deter attack by drywood termites (Ebeling 1968). Fiber or wood-

pulp products treated with white arsenic or pentachlorophenol during manufacture will resist attack (Snyder 1950).¹

Ebeling (1968) describes the use of certain silica areogels that possess a monomolecular layer of ammonium or magnesium fluosilicate as a deterrent to drywood termite attack. The dust is blown at high velocity into attic spaces or other areas to be protected. To be effective as an insecticide, enough silica gel must be deposited on a surface so that an insect crawling over it will pick up a considerable quantity on its lower body surfaces.¹

Where damage is discovered in existing structures, research indicates that three treatments may arrest or delay further damage. None of them leave residual protection against reinfestation. In the first of these, termite galleries are located by probing with a sharp instrument, and ¼-inch holes are bored into the infested timbers at about 1-foot intervals. An insecticidal dust, e.g., one containing about 50 percent calcium arsenate, is then blown into the galleries at the rate of 1 ounce of dust per 20 access holes. Alternatively, a third of a teaspoon of a liquid mixture of ethylene dibromide and DDT¹ in a petroleum solvent of high flash point can be injected per hole; this latter treatment should be applied only by experienced pest-control operators (Ebeling 1968).¹

Ebeling (1968) also describes application of a proprietary mayonnaise-type emulsion of pentachlorophenol.¹ The emulsion is brushed over all wood surfaces and joints in the suspected area, and is most effective when applied to bare wood.

Researchers at the USDA Forest Service Wood Products Insect Laboratory in Gulfport, Miss. found that small easy-to-reach infestations of drywood termites were controlled by thoroughly brushing or spraying infested wood with 0.5 percent dieldrin, 0.5 percent lindane, or 2.0 percent chlor-dane in a solvent such as mineral spirits or kerosene.¹ In large timbers with deep-seated infections, more than one application may be necessary.

The third method—fumigation—is the only control measure suggested (as of 1970) by the USDA; the three registered fumigants and their application rates are as follows:¹

<u>Fumigant</u>	<u>Application rate</u> <i>Pounds/1,000 cu. ft.</i> <i>enclosed</i>	<u>Maximum</u> <u>temperature</u> <i>°F.</i>	<u>Time</u> <i>Hours</i>
Hydrogen cyanide.....	2	65	48
Methyl bromide.....	3	60	24
Sulfuryl fluoride.....	1	70	24
Sulfuryl fluoride.....	2	55-69	24

In this method, structures are covered with a gas-tight tarpaulin, or sealed with gas-tight paper, and the fumigating gas released in the enclosure. Hydrogen cyanide, methyl bromide, and sulfuryl fluoride are highly toxic and must be used only by licensed operators.¹ A fumigated building must not be entered until it has aired for at least 48 hours.

17-2 OTHER CHEWING INSECTS

Numerous nonmarine chewing insects other than termites make damaging excavations in southern pine trees, logs, and lumber. In addition to creating mechanical damage, some of these insects introduce stain and decay fungi that cause serious degrade in southern pine products.

STANDING PINES

The principal insects that attack living pine trees in a manner that directly or indirectly causes degrade in lumber sawn from the attacked tree are the turpentine borer (*Buprestis apricans* Herbst), the southern pine beetle (*Dendrotonus frontalis* Zimm.), and three species of *Ips* engraver beetles (*Ips avulsus* (Eichhoff), *Ips grandicollis* (Eichhoff), and *Ips calligraphus* (Germar)). The turpentine borer damages wood by boring holes in it. Southern pine beetles and the three species of *Ips* indirectly cause degrade by infecting trees with blue stain.

While the black turpentine beetle (*Dendroctonus terebrans* (Olivier)) attacks living pines—especially trees weakened by turpentine, fires, heavy cutting, droughts, windstorms, and other disturbances—it does not burrow into the wood. Broods of its larvae, developing beneath the bark of a tree, destroy the cambial layer—thus girdling and killing it. Stain fungi have been isolated from adult bodies and from tunnels of the black turpentine beetle, but there is no evidence of stain spreading into the wood from their attack.

Turpentine borer.⁴—Beal (1932) described the life history of the turpentine borer (*Buprestis apricans* Herbst). Larvae of this beetle attack the basal portion of southern pines that have been turpentine, fire scarred, or injured mechanically. Larval boring may weaken the trees so that they break off in windstorms. When infestations are severe, 3 to 6 feet of the butt log may become unfit for lumber. Sound, healthy trees are seldom attacked.

The legless larvae are elongated white grubs up to 1½ inches long. They appear flat headed because the thoracic or front segments of the body are distinctly wider than the abdominal segments. The beetle is grayish bronze with a greenish metallic luster, and 1¼ inches long (fig. 17-12).

The female lays eggs in checks in drywood of turpentine trees or trees that have been fire scarred or otherwise injured. The larvae mine extensively in the sapwood and heartwood. The life cycle is completed in approximately 3½ years.

Often the earliest signs of this beetle are ¼-inch-wide elliptical emergence holes in dry turpentine faces or fire scars, or tunnels in trees broken off by wind. Infested wood sawn into lumber reveals larval tunnels filled with fine, tightly-packed boring dust and resin.

⁴ This description is taken with minor editorial changes from Bennett et al. (1958).

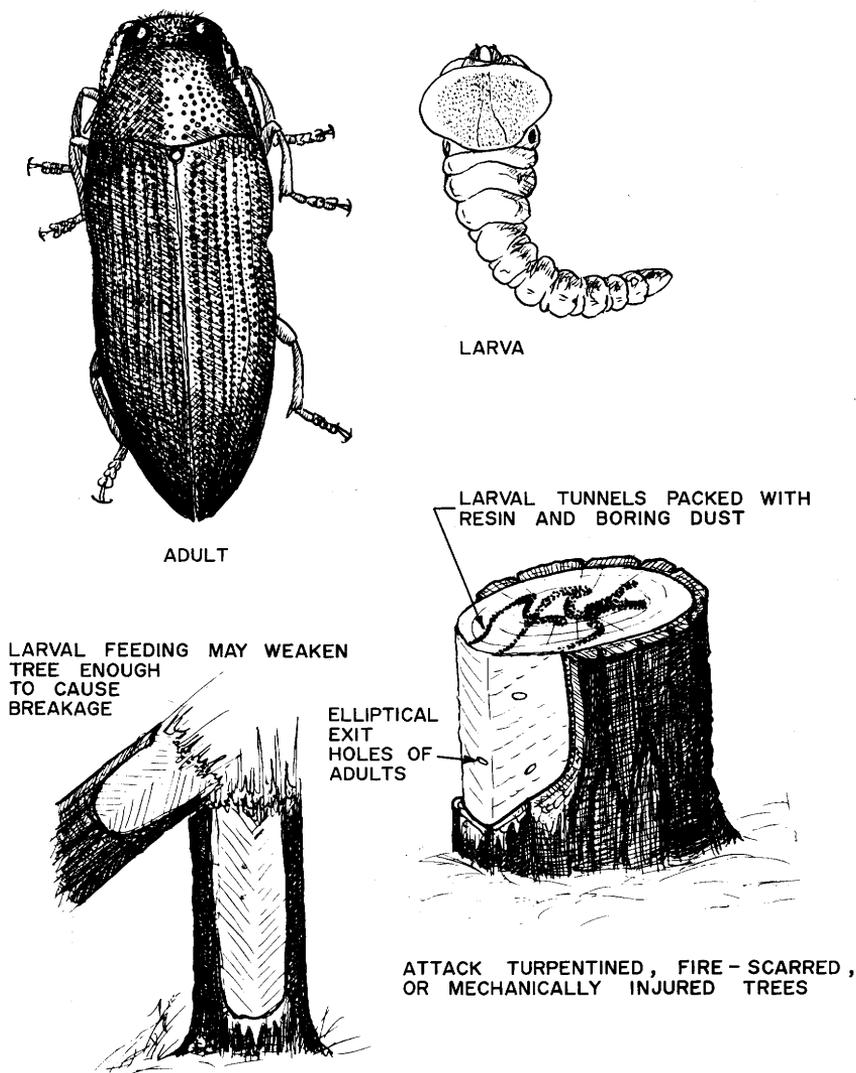


Figure 17-12.—Turpentine borer. (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

The turpentine borer has been a major pest in the naval stores region. Modern naval stores practices, however, together with prompt harvest of worked-out trees, have virtually eliminated severe infestations. Prescribed burning to decrease wildfire hazards and to reduce the number of charred, cracked faces on trees worked for naval stores has also helped.

Removal of brood trees from the forest, avoidance of mechanical injury to trees during logging, salvage of susceptible trees following windstorms, and prescribed burning to reduce wildfire hazards are all measures that help control losses from the turpentine borer.

Eggs, larvae and pupae in lumber cut from infested trees are killed by the usual kiln schedules for southern pine.

Southern pine beetle.—The southern pine beetle (*Dendroctonus frontalis* Zimm.) is important to pine utilization for two reasons—the economic impact on the southern pine industry of beetle-killed trees, and the propensity of the beetle to introduce stain and decay fungi into attacked trees.

In the United States, the beetle ranges from New Jersey throughout the Southeastern States, New Mexico, and Arizona; its range also extends into Mexico and southward to the Republic of Honduras (fig. 17-13).

Bennett⁵ noted that within its range the insect has a greater potential for destroying the raw materials of the southern pine pulp, plywood, and lumber industries than any other destructive agent. Severe epidemics occur almost every year, and annual losses in the Southeastern United States are estimated to exceed 100 million bd. ft. of sawtimber and 20 million cu. ft. of growing stock. Roughly \$1 million is spent annually in suppressing the insect by chemical or other direct measures. For one reason or another, only about half of the beetle-killed timber is salvaged. Bennett⁵ estimated that blue-stain fungi carried by the insect cause a degrade loss of about \$10 per M b.f. in lumber salvaged from attacked trees.

Literature on the southern pine beetle prior to 1960 has been thoroughly

⁵ Bennett, W. H. The southern pine beetle. USDA Forest Serv., Southern Forest Exp. Sta. Problem Analysis FS-SO-2203-1.10, dated July 25, 1966. 16 pp.

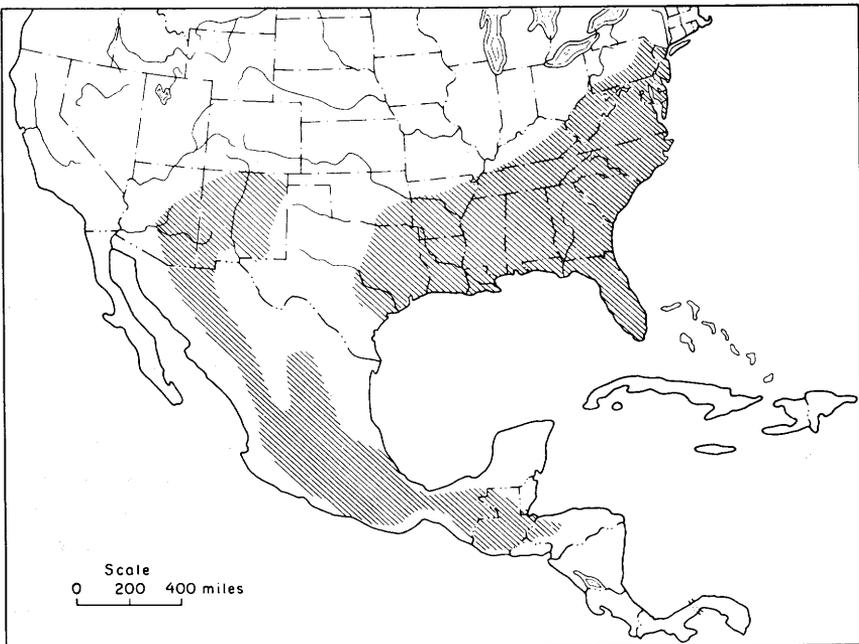


Figure 17-13.—Distribution of the southern pine beetle in North and Central America. (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

reviewed by Osgood (1957), Thatcher (1957, 1960), and Dixon and Osgood (1961). Wood (1963) provided a more recent review and included information on *D. mexicanus* Hopkins and *D. arizona* Hopkins, both of which he concluded were the same species as the southern pine beetle. Miller and Keen (1960) summarized 50 years of research on the related western pine beetle. (*D. brevicornis* Lec.), many facets of which are applicable to the southern pine beetle. Reports of current research on the southern pine beetle are obtainable periodically from the USDA Forest Service Southern Forest Experiment Station, New Orleans, La.

The following is slightly condensed from Kowal (1960)—as revised by Bennett and Ciesla (1971).

As its name implies, the southern pine bark beetle attacks all species of southern pine within its range (fig. 17-13); it prefers loblolly, shortleaf, Virginia, and pitch pines over slash and longleaf pines. Overstocked stands in poor vigor are prone to attack, especially if they have recently gone through several years of suddenly reduced radial growth. Beetles often attack such stands at times of stress, such as that caused by drought or severe flooding, or frequent and severe stand disturbances from intermittent partial cutting, mechanized logging, or road construction.

The presence of a southern pine beetle outbreak is usually first indicated by discoloration of the crowns of infested trees. Yellowing of needles begins in the upper crown, with the fading needles soon turning to a reddish brown. Frequently, large groups of trees, sometimes encompassing several hundred acres, are killed; seldom as few as one or two. The trunks of discolored trees usually show small yellowish-white masses of pitch called **pitch tubes**, $\frac{1}{4}$ - to $\frac{1}{2}$ -inch in diameter, marking the points of beetle attack. In unusually dry weather, however, there may be little or no pitch, and the chief evidence of attack may be reddish-brown boring dust lodged in bark crevices.

Beneath the bark of infested pines are winding S-shaped galleries, etched on the inner bark and the wood surface. The curved shape clearly distinguishes the galleries of the southern pine beetle from those of any other pine bark beetle in the South (fig. 17-14). If the attack is recent, there may be some adults in the egg galleries or very tiny, whitish larvae near the galleries. In older attacks, most of the brood will be within the bark.

The egg (fig. 17-15) is pearly white and barely visible to the naked eye. It hatches into a tiny, whitish, legless larva with a glossy, reddish-brown head; the body is wrinkled and curved (fig. 17-15). The larva transforms to the resting stage or pupa (fig. 17-15), which is pure white and very fragile, then into the adult stage. The young adult beetle is soft and amber in color, but soon hardens and darkens. Older beetles are a dull, dark brown, and their wings are a lighter shade than the foreparts of their bodies. The beetle is short legged, stout, and about $\frac{1}{8}$ -inch long. The forepart of its head is notched, and the hind end of its body is rounded (fig. 17-15).



F-486342

Figure 17-14.—Winding egg galleries made by the southern pine beetle in inner bark.
(Photo from Kowal 1960.)

The insect overwinters in the bark in the egg, larval, pupal, and adult stages, to emerge and attack trees in the spring (March–May) about the time flowering dogwood is in full bloom. The life cycle from egg to adult

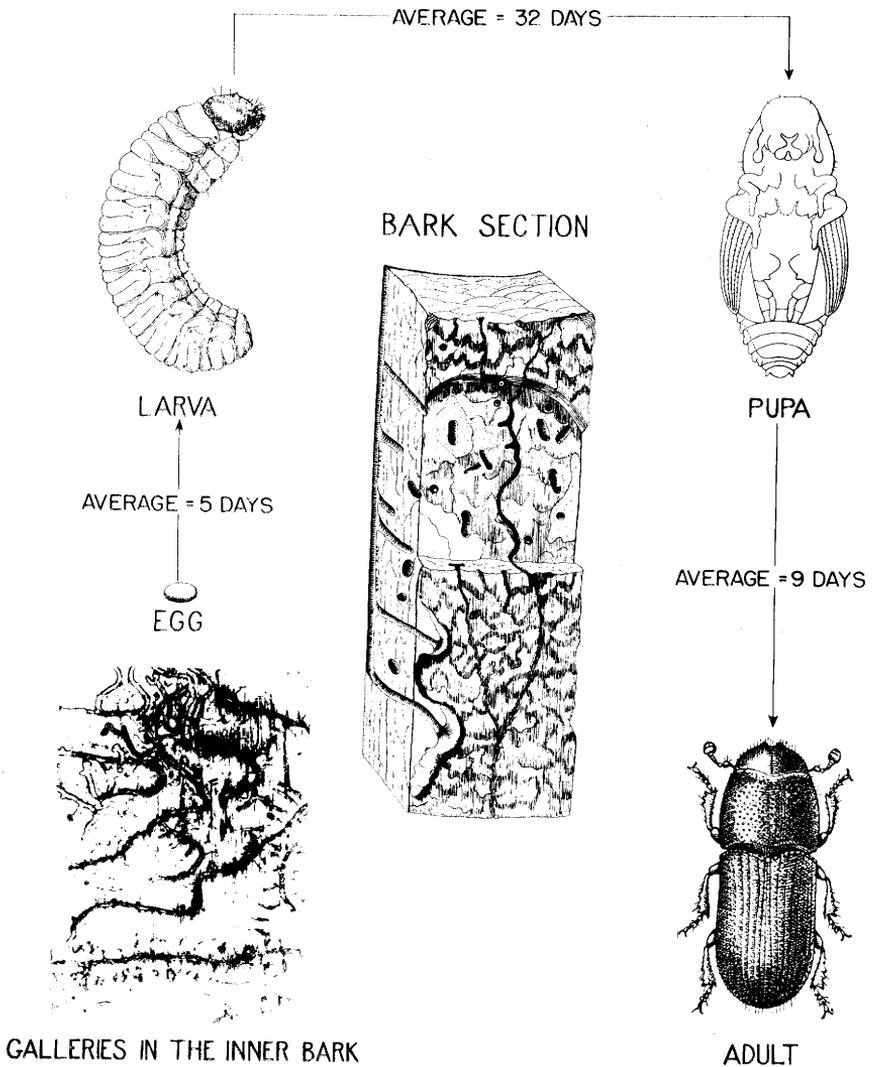


Figure 17-15.—Life history of the southern pine beetle. Mature beetle measures about $\frac{1}{8}$ -inch in length. (Drawings adapted from Kowal 1960.)

F-486344

requires 30 to 40 days; 4 to 7 generations are produced in a year (several more in Honduras) with a considerable overlapping. Populations usually peak in early summer in the Gulf States and in late summer and early fall further north. Activity usually ceases by November, but beetles may emerge and attack trees in winter during prolonged warm spells. Under ideal conditions, the number of beetles may increase fivefold to tenfold in a single generation.

Excavations by thousands of pairs of beetles and their larvae in the cambium and inner bark crisscross one another and girdle the tree.



F-520998

Figure 17-16.—Emergence holes of southern pine beetle adults in the outer bark. The holes measure about 1/16-inch in diameter.

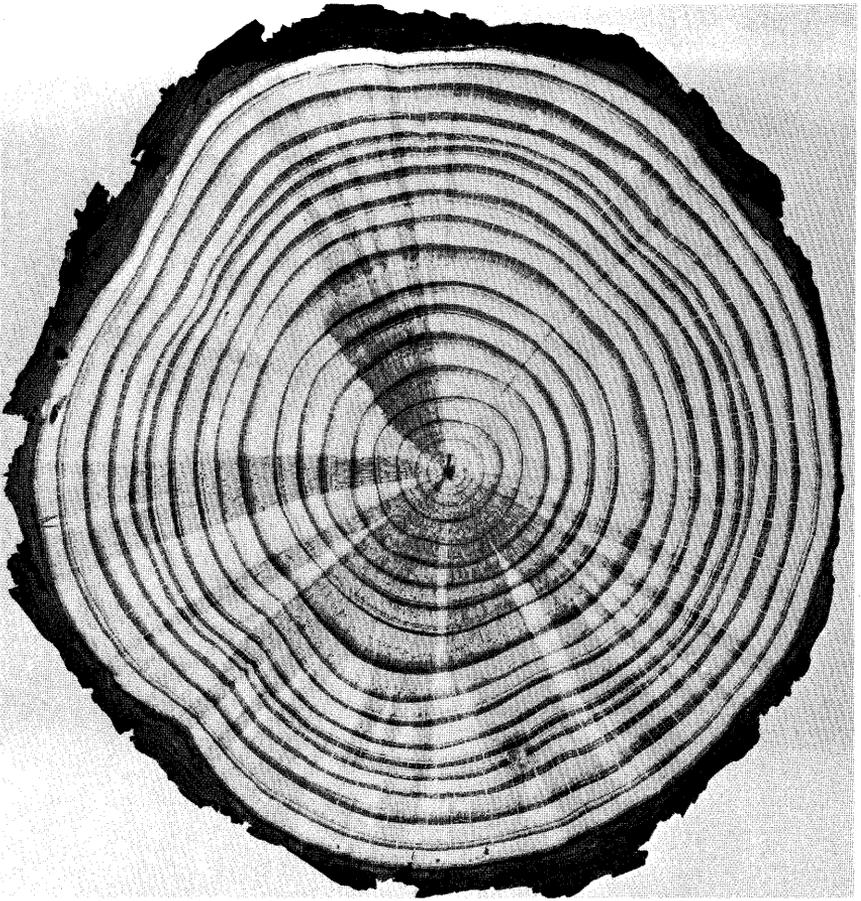
Blue-stain fungi, carried by the beetle, plug the tree's conductive tissue and hasten its death. When fully grown, the larvae pupate in cells near the bark surface, from which they emerge as young adults. Their multiple emergence holes make the bark look as though it had been hit by birdshot (fig. 17-16). Under favorable conditions, 600 or more beetles may emerge per square foot of bark.

Beetle broods are attacked by many parasites and predators, including woodpeckers, but these rarely have notable effect on severe outbreaks. In the northern part of the beetle's range, heavy brood mortality results when temperatures are around 0° F. over several successive days. Temperatures over 100° F. will also kill many larvae in the Gulf South.

Blue-stain fungi introduced by the beetle rapidly penetrate wood rays in pine stems (fig. 17-17). To deter fungal growth, logs or pulpwood freshly cut from trees attacked by bark beetles should be immediately placed under water sprays. Growth in lumber sawn from stained logs can be arrested by an appropriate dip (see table 22-6)¹; fungi remaining in the lumber are killed by most kiln schedules used for southern pine.

In the forest, the primary objective of control measures is to prevent infestation spread and to reduce the beetle population to a low level as rapidly as possible.

Infestations can best be detected by aerial observation of red-topped and fading pines from an altitude of about 1,000 feet. Presence of the southern



F-520969
Figure 17-17.—Cross section of loblolly pine showing blue stain after attack by southern pine beetle (*Dendroctonus frontalis*).

pine beetle must be confirmed by examination on the ground. Surveys should be made over outbreak areas at 3- to 4-week intervals from April to October.

The cheapest and most practical method of control is to remove infested trees by commercial sales. Trees containing beetle broods should be removed first and promptly. Removal of a ring of uninfested trees along the periphery of an infestation is believed to reduce the hazard of reinfestations and may make a salvage program economically feasible. Infested trees should be processed immediately at the mill and bark slabs and infested bark destroyed by burning or chipping. Barron (1971) reported that specific gravity of standing trees was reduced 5 to 16 percent within 6 months after attack by southern pine beetles. Moisture content of beetle-killed trees was reduced by 22 to 53 percent within the first month following attack; thereafter the change was slow.

Where removal is not feasible, beetle broods may be killed by application of Lindane in No. 2 fuel oil; research indicates that an effective Lindane spray may be prepared by adding 1 gallon of 20-percent emulsifiable concentrate to 27 gallons of No. 2 fuel oil.¹ All infested trees must be cut and bucked into workable lengths. The entire bark surface should be sprayed to the point of runoff with a coarse spray using a low-pressure sprayer. This may necessitate turning larger infested logs two or three times. Never apply spray to wet bark. Caution: Care should be taken to avoid prolonged contact of Lindane with the skin. This chemical may be absorbed by the skin and produce harmful effects.¹

Piling infested trees in windrows and thoroughly burning the bark also gives good control of beetle broods.

Most important to successful control of this insect is reexamination of treated areas. Recently infested trees are often difficult to detect and are sometimes overlooked during initial treatment. These may serve as a source of continuing infestation. Areas treated from April through October should be checked at 2- to 3-week intervals for 9 weeks following initial treatment, and all additional infested trees should be removed or sprayed.¹ Bimonthly examinations are usually sufficient for areas treated during the winter.

The most logical approach to the southern pine beetle problem is through preventive action to remove the underlying causes of infestations. This can best be accomplished by growing and managing timber stands that are unfavorable to beetle development and that will require a minimum of direct control. Managing stands with an eye to tree vigor and to sustained good growth, quickly removing lightning-struck trees and other high-risk trees by sanitation salvage, and using common sense in avoiding undue stand disturbances are possibilities for silvicultural control that are waiting to be put to use.

***Ips* engraver beetles.**⁴—The three common species of *Ips* beetles kill sapling and larger pines that have been weakened by drought, fire, hail, hurricanes, ice storms, or other causes. They can be found in most lightning-struck trees. Logging slash, fresh-cut logs, and fire-scorched trees are especially attractive to them. Infested trees are typically scattered through the forest, but the beetles may kill clumps of trees when conditions are in their favor. Although these beetles do not bore into the wood, their entrance holes through the bark allow rapid entry of decay organisms which hasten deterioration. Moreover, they carry stain fungi on their bodies into the inner bark where it spreads rapidly through the xylem. Since *Ips*-caused tree mortality and decay and stain in logs and pulpwood are widespread, losses in the southern pine industry attributable to engraver beetles are substantial.

The interested reader can find a description of the life cycle of *Ips* beetle in Thatcher (1960). All three species girdle the cambial region, but they are unlike in size, and they sometimes show a preference for different parts of the tree (fig. 17-18). They are distinguished from the southern pine

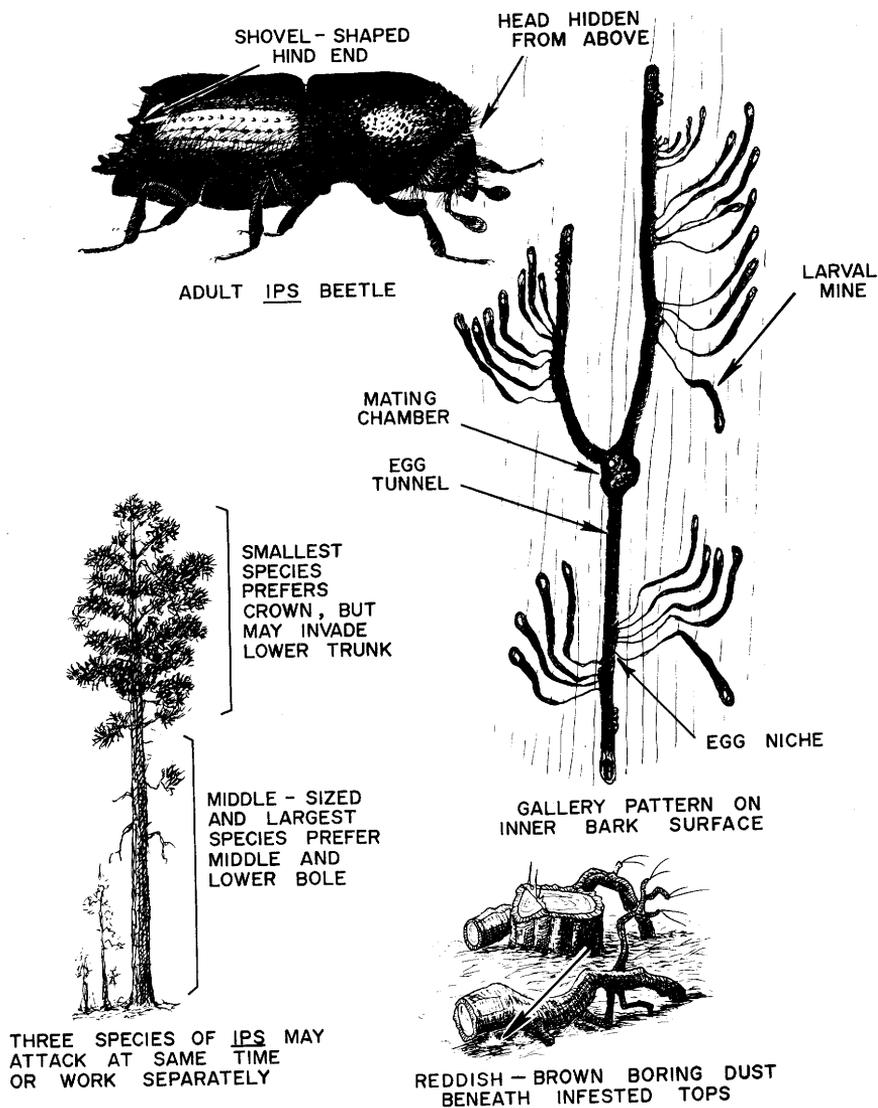


Figure 17-18.—*Ips* engraver beetle. The beetles normally live in logging tops, stumps, and lightning- or fire-scorched trees; during dry periods they attack and kill standing southern pines. (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

beetle by their posterior profile when viewed from the side (fig. 17-19). Brief descriptions of each species follow.

The smallest, *Ips avulsus* (Eichhoff), is not quite $\frac{1}{8}$ -inch long. It attacks the crowns and frequently the trunks of trees of all sizes. Populations build up in most fresh logging slash; the beetles spread to crowns of nearby timber when logging ceases or when the standing trees have been weakened by drought or some other disturbance. They sometimes kill one branch at a time, but when abundant may suddenly attack the entire crown. When they are particularly active, they may make stands more susceptible

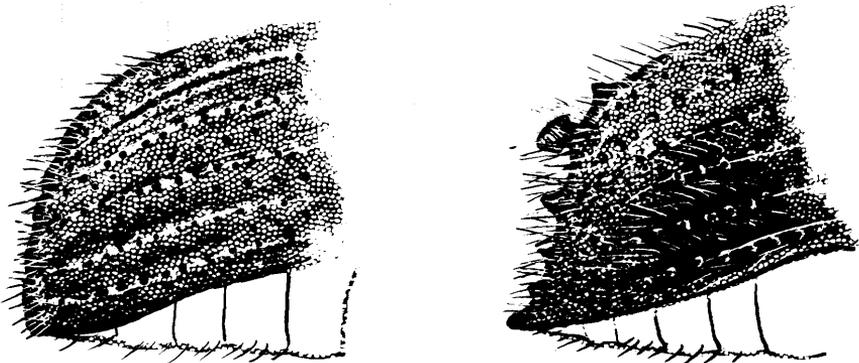


Figure 17-19.—Greatly enlarged views of hind end of southern pine beetle (left), and *Ips* beetle (right). (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

to other *Ips* beetles and the southern pine beetle. Presence of *I. avulsus* in the crowns may not be noticeable except to an experienced spotter or with the aid of binoculars.

The largest, *Ips calligraphus* (Germar), is almost $\frac{1}{4}$ -inch long; it generally prefers the lower trunk. Intermediate in size (about $\frac{3}{16}$ -inch long), *Ips grandicollis* (Eichhoff) commonly attacks the middle and upper trunk. Both species, however, may be found on any part of the trunk and the larger branches.

The three species may work together in the same tree, their tunnels overlapping, or they may work independently or in succession. They may also become associated with southern pine beetles and the black turpentine beetle. There may be four or more generations per year.

Trees infested with *Ips* will usually have numerous pink or red-brown (sometimes whitish) pitch tubes, about the size of a wad of gum, on the bark of the branches or trunk. In trees of low vigor, however, pitch tubes may be lacking, and the earliest signs of attack will be reddish boring dust in bark crevices at the base of the tree.

If the crowns alone are infested, pitch tubes will be difficult to see and the foliage may be only a trifle faded when the broods are ready to leave. Sometimes the crowns turn yellow or red, limb by limb.

The egg tunnels, engraved on the inner bark and the surface of the wood, are more or less straight. They are typically Y- or H-shaped and run parallel to the grain of the wood. The egg tunnels are generally free of boring dust. Larval feeding mines—wavy, somewhat indistinct, and filled with boring dust—lead from the egg tunnels.

Since *Ips* generally attack overdense or overmature stands during or following drought, stands should be kept thrifty. When beetle trees are widely scattered, control is generally too expensive to be practical. However, if the attacks are numerous, or if beetles are spreading to nearby trees, currently infested trees should be salvaged before the beetles have left and the slash burned; slabs should be burned at the sawmill. Where early salvage is impossible, the trees should be felled and the tops, trunks,

and stumps sprayed with the Lindane formulation¹ recommended for southern pine beetle. When logging in a drought year or on poor sites, it is generally a good precaution to avoid intermittent cutting and to burn or spray recent tops and slash immediately if cutting must be interrupted.

The general strategy in control is to treat trees that have broods in them. Usually crowns are still green or faded when broods are ready to leave. By the time the foliage has turned red, beetles have usually, though not always, left. Do not make the mistake of treating vacated red tops and overlooking nearby infested green tops.

When drought is the primary cause of unusual *Ips* beetle activity, soaking rains will generally stop the infestation.

Beetle activity in stored logs and pulpwood is probably best suppressed by water spray (see secs. 18-1, 18-2).

LOGS AND PULPWOOD

In addition to infestations by the southern pine beetle and *Ips* engraver beetles, southern pine logs and pulpwood may be attacked by ambrosia beetles (*Platypus flavicornis* F.) and pine sawyers (*Monochamus titillator* (F.))—also termed long-horned wood borers. In contrast to the cambial-region activity of the bark beetles, these insects bore deep into the sapwood and heartwood of southern pine.

Ambrosia beetles.—The family Platypodae is represented in the United States by seven species of the genus *Platypus* (Arnett 1963). Of these, only *P. flavicornis* F. is known to attack southern pines; this ambrosia beetle is found from Texas east to Florida and New Jersey (Chamberlin 1939; Coster 1969).

Ambrosia beetles attack weakened, dying, or freshly cut pines and unseasoned pine lumber. The adults are reddish-brown, elongated beetles approximately ¼-inch in length. They bore into the sapwood and heartwood of logs or lumber, making pin-size holes—dust-free and 0.8 to 1.3 mm. in diameter—darkly stained by an ambrosia fungus upon which the adults and larvae feed. The female lays eggs in small clusters in the tunnel, and the developing larvae excavate small cells extending from the tunnel parallel with the grain of the wood (fig. 17-20). There are several generations each year. Small piles of yellowish-white fluffy boring dust accumulate around the base or in bark crevices of infested trees, stumps, and logs. In lumber the characteristic pin-size holes surrounded by black stain may be observed extending into the wood (Bennett et al. 1958).

Coster (1969) found that ambrosia beetles attack standing southern pines in increasing numbers from about the 5th to the 10th day after attack by the southern pine beetle; thereafter, ambrosia beetle attacks declined.

Prompt utilization of dead and dying trees and rapid seasoning of lumber will reduce or eliminate losses from ambrosia beetles. Where these courses are impractical, green logs may be protected for several months by spraying

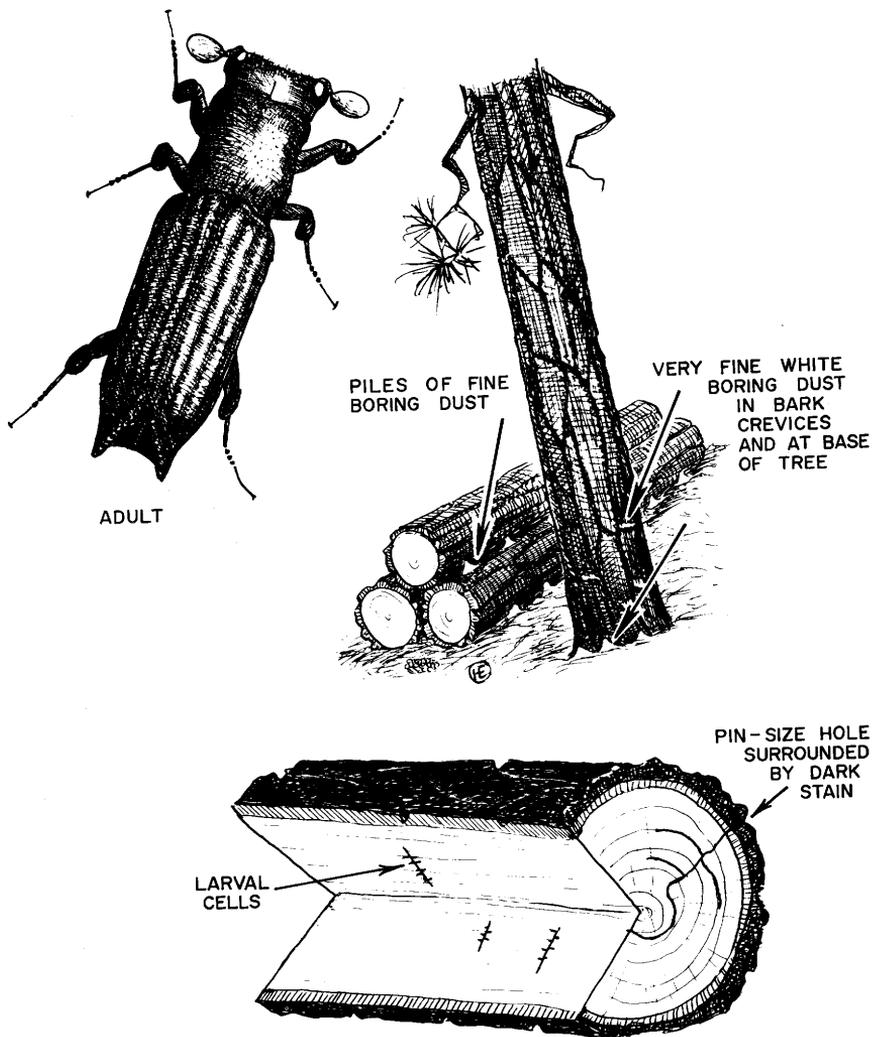


Figure 17-20.—Ambrosia beetle. (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

with Lindane in No. 2 fuel oil¹, mixed in the same proportion found effective for the southern pine beetle (Johnston 1952; Bennett et al. 1958). To be effective the spraying should be accomplished immediately after felling. It is perhaps more practical to control ambrosia beetles in decks of logs and pulpwood by water spraying them copiously and continuously until used. Kiln schedules commonly used for lumber and veneer kill ambrosia beetles; kiln-dried pine is safe from further attack.

Research indicates that green lumber may be protected while air-drying by dipping it in a water emulsion prepared by mixing 2 quarts of benzene hexachloride emulsifiable concentrate (containing 1 pound of

the gamma isomer per gallon) with 50 gallons of water (Bennett et al. 1958)¹.

Pine sawyers.⁶—Larvae of the pine sawyer (*Monochamus titillator* (F.)) cut $\frac{1}{3}$ - to $\frac{1}{2}$ -inch tunnels through the sapwood and heartwood of green southern pine logs and dead or dying pines, degrading lumber cut from them and opening the way for decay fungi (fig. 17-21). The sawyers—sometimes called long-horned wood borers—never attack and kill vigorous green pines, but confine their work to windthrown and fire-killed trees, or trees killed by primary insects such as the southern pine beetle.

Green pines felled during the summer months are immediately attacked by the adult sawyers; during midsummer it is possible for sawyers to attack unprotected logs and destroy them within a period of 3 weeks.

The larvae are legless, somewhat flattened white grubs up to 2 inches long. The thoracic or front segments of the body are slightly wider than the abdominal segments. The adult is a beetle, mottled grayish brown, $\frac{3}{4}$ to $1\frac{1}{4}$ inches long. The antennae are sometimes two or three times as long as the body (fig. 17-21).

The first evidence of the presence of sawyers is the pits or egg scars on the bark; the egg niches, which are often mistaken for woodpecker work, measure $\frac{1}{4}$ - to $\frac{1}{2}$ -inch across and are funnel shaped. From 2 to 3 weeks after appearance of the egg scars, the borers can be heard gnawing deep in the wood. Beneath the bark, dense, brownish frass and coarse-shredded, excelsior-like wood shavings are present. The larvae bore close to the surface to pupate. Circular, pencil-size holes in the wood and bark are a sign that adults have emerged. There are two or three generations per year in the South.

Rapid salvage and utilization of dead and dying trees and prompt conversion of green logs will reduce losses; these are the most effective control measures. If bark is immediately peeled from felled green trees, damage by sawyers will be prevented.

If southern pine logs and pulpwood are placed in storage decks promptly after felling, sawyer damage can be controlled by spraying them continuously and copiously with water until utilized.

If prompt storage under water spray is not possible, chemical control is an alternative; i.e., damage can be prevented by promptly spraying the bark with Lindane¹ in No. 2 fuel oil mixed in the same proportion found effective for the southern pine beetle. One gallon of the finished spray will treat 100 sq. ft. of bark surface. All surfaces should be covered thoroughly—until drops begin to form and run off. Logs should be turned so that all surfaces can be sprayed.

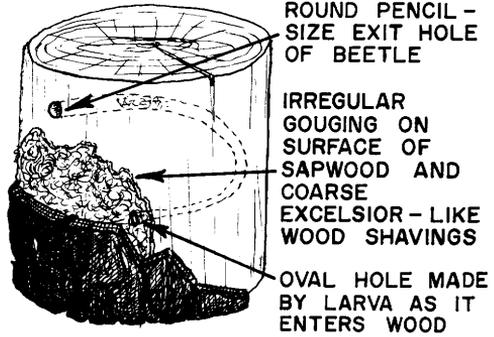
DRY PINE LUMBER

The most expensive form of insect damage to wood is that to material

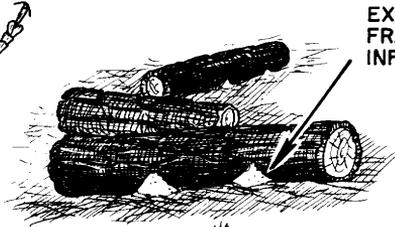
⁶ This description is taken from Beal (1928) and Bennett et al. (1958).



ADULT



LARVA



EXCELSIOR-LIKE FRASS UNDER INFESTED LOGS



ATTACK DEAD OR DYING TREES AND GREEN LOGS

Figure 17-21.—Southern pine sawyer. Trees under attack show funnel-shaped egg niches in the outer bark. (Drawing after the Bennett and Ostmark revision of Bennett et al. 1958.)

in use, because the entire investment in manufacturing and installation is threatened. Chief among the insects that cause such damage are termites (see sec. 17-1). Other troublesome insects that damage dry southern pine include several beetle species often collectively termed powder post beetles, the carpenter ant (*Camptonotus* spp.), and the great carpenter bee (*Xylocopa virginica* Dru.).

Of the powder post beetles, the most damaging to pine are the old-house borer (*Hylotrupes bajulus* L.), and three anobiid species—*Xyletinus peltatus* (Harris), *Nicobium hirtum* Illiger, and *Anobium punctatum* (DeGeer).

Old-house borer⁷.—The old-house borer (*Hylotrupes bajulus* L.) prefers sapwood of pine and spruce to other woods, and its tunneling can cause severe damage to buildings in the Eastern United States. Serious infestations of this insect have occurred in the Atlantic Coastal States from Florida northward through Massachusetts. Adult beetles have also been found in Mississippi, Louisiana, and Texas; except for the latter State, the borer has not been found west of the Mississippi River. Despite its name, it most frequently damages new buildings in the United States.

Nearly all of the lifetime of the old-house borer is spent as a larva (borer). The adult stage lasts from 8 to 16 days; the egg stage, about 2 weeks; the larval stage, several years; and the pupal stage, about 2 weeks.

In many areas the majority of the adults fly in June and July; in Texas adults have been found in early May. They are active as late as September in the Northeast.

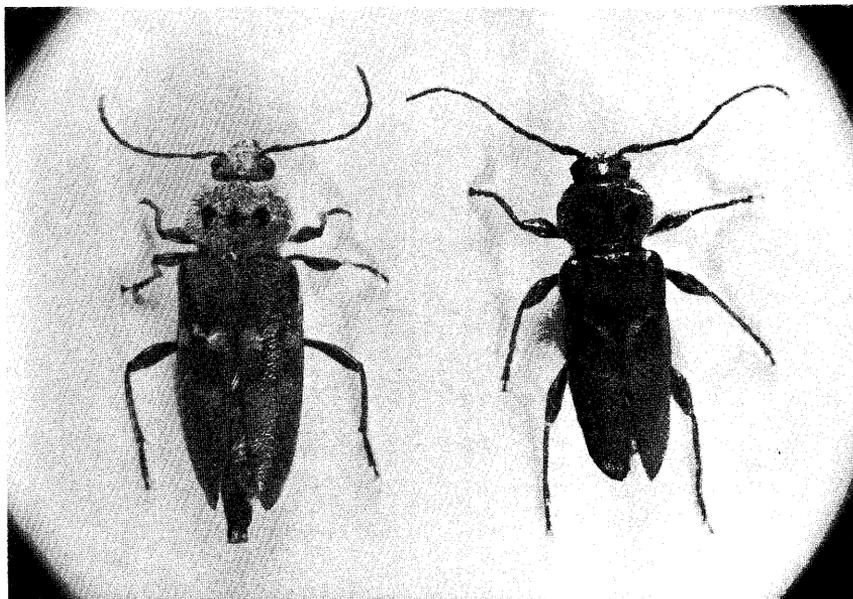
The adult beetle is ½- to ¾-inch long and slightly flattened in shape. It is brownish black. Many gray hairs appear on the head and the forward part of the body. Each hard-shelled wing cover has two patches of gray; when fused they form either two transverse bands or two downy-white spots (fig. 17-22).

The eggs are white to grayish white, spindle shaped, and about ¼-inch long. They are deposited in clusters in cracks or checks in boards. The larva is flesh colored, straight bodied, wedge shaped, and segmented; its length varies up to about 1¼ inches (fig. 17-23). The larva has small legs. Three tiny ocelli (black eye spots) can usually be seen on each side of the head at the base of the antennae.

The pupa is about the size of the beetle and is flesh colored when first formed. Later, as the pupa matures, it darkens and develops antennae, eyes, wings, and legs.

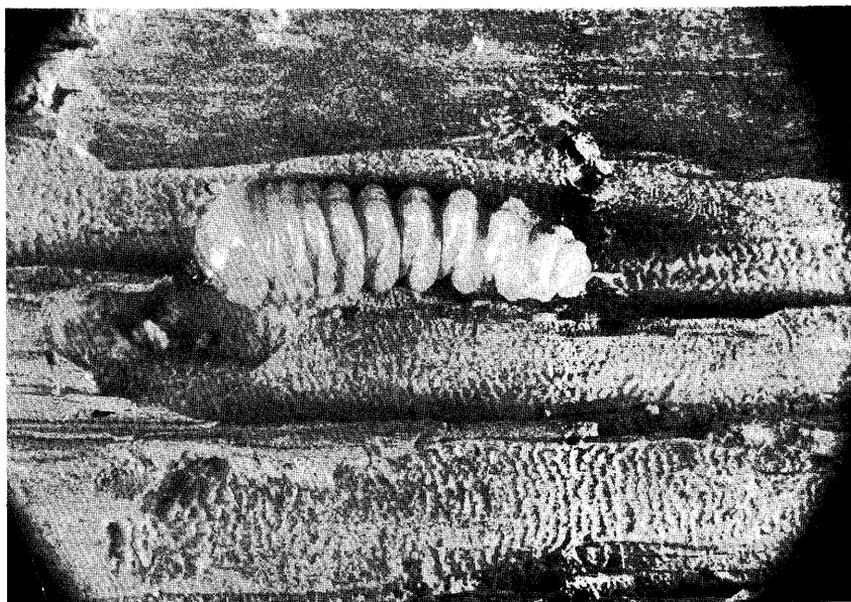
Newly hatched larvae feed near the surface of the wood. Later they penetrate deeper and may continue their tunneling until they have completely mined the sapwood (fig. 17-24). Ordinarily, heartwood is not attacked. During their feeding, larvae seldom break through the wood

⁷ Descriptive text under this heading is taken from McIntyre and St. George (1961).



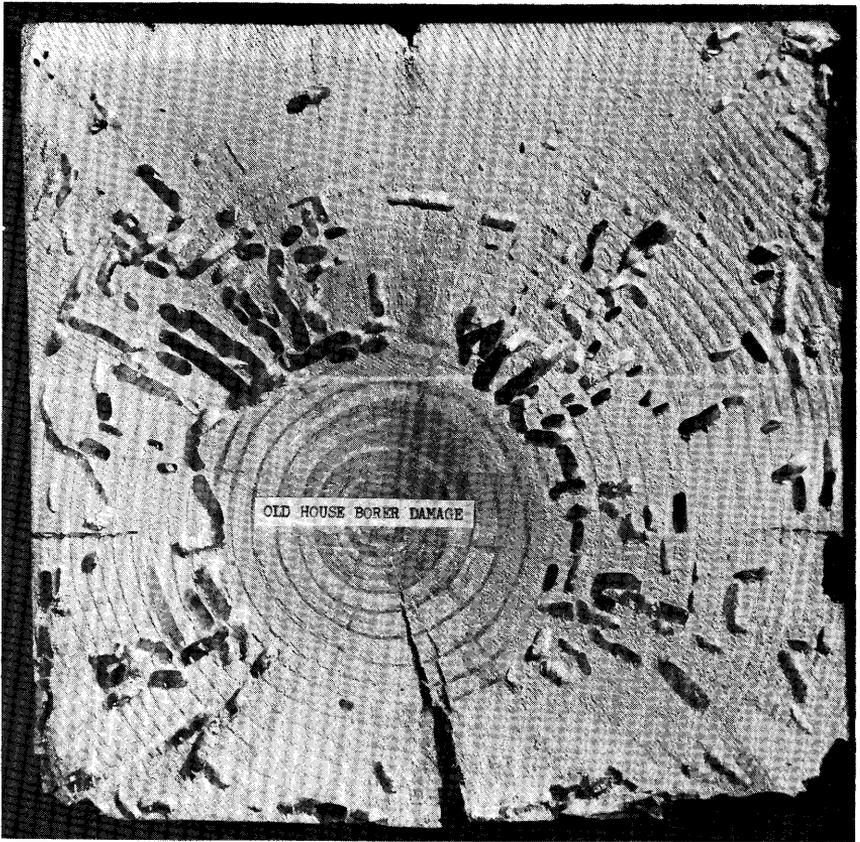
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Figure 17-22.—Old-house borer adults, enlarged about 3X. Female (left); male (right). (Photo from McIntyre and St. George 1961.)



F-494431

Figure 17-23.—Nearly mature larva of old-house borer; it may measure up to $1\frac{1}{4}$ inches in length. Powdery borings have been removed from the tunnels. (Photo from McIntyre and St. George 1961.)



F-494432

Figure 17-24.—Moderate damage from old-house borer in an 8- by 8-inch pine beam removed from a warehouse and cut to expose the borer tunnels. (Photo from McIntyre and St. George 1961.)

surface. Borer activity may not produce any visible surface changes. Thus, a timber so heavily mined that it is near collapse may appear from the outside to be perfectly sound.

Ordinarily the old-house borer will not be discovered until damage is extensive. Following are some possible indications that old-house borers are active in a building.

- A rasping or ticking sound made by larvae while boring or feeding.
- Blistering of the wood where the larva has worked close to the surface.
- Powdery boring in sapwood or the larva in its tunnel, made visible by cutting through the surface where tunneling is suspected.
- Boring dust on surfaces below infested timbers.
- Surface holes made by adult beetles emerging. Broadly oval shape; size $\frac{1}{4}$ -inch.
- Beetles in the building.

Individual timbers in buildings may be severely damaged in 4 to 7 years. Other timbers in buildings may be only lightly infested. Air-dried pine floor joists, plates or sills, and subflooring are apt to be damaged most severely. Other framing such as studs, stair carriages, furring strips, and roof rafters are sometimes attacked. Occasionally, new buildings of brick or stone construction have the borer in furring strips and wooden wall members.

Lumber that has been kiln-dried is also subject to attack.

When infestation by the old-house borer is discovered, two types of remedial action are necessary. These are: (1) correcting or repairing any serious structural defects caused by extensive borer feeding; and (2) controlling the remaining insects present in the wood left in place. Either or both remedies may be expensive.

From the life cycle of the old-house borer, it is evident that infected lumber should never be used in construction. If joints are caulked and surfaces painted, borers will find few places to deposit eggs.

Chemical controls have not been extensively evaluated, but standard wood preservatives and liquid insecticides (e.g., 4 pounds of Lindane dissolved in 100 gallons of light oil), and fumigants (see sec. 17-1 under heading *Control with insecticides*) should be effective—particularly if applied during the months April through September¹. Injection of silica dust or poisonous dust into tunnels of the old-house borer is not recommended.

Annual inspection of untreated wood exposed in crawl spaces or attics should permit detection of old-house borer attacks before structural damage becomes serious.

In Europe, heat treatment of buildings with specially built machines is used to control the borer.

Known insect enemies of the old-house borer include two parasitic braconid wasps and one predaceous clerid beetle. In buildings, small numbers of old-house borer adults are captured by spiders. How much influence these natural enemies have on borer populations has never been determined.

Common furniture beetle⁸.—Of the several anobiid species that attack southern pine wood, *Xyletinus peltatus* (Harris) causes the most economic damage in the South. The smaller and less destructive common furniture beetle (*Anobium punctatum* (DeGeer)) has been more thoroughly described in the literature, however; its description is therefore placed ahead of the other anobiids.

In southern pine wood, attack by the common furniture beetle is mainly confined to sapwood, in which tunneling by larvae may be extensive. Most types of chipboard, hardboard, and insulating board appear to be immune.

⁸ Descriptive text under this heading is condensed from Bletchly (1967, pp. 16-18) by permission of Her Majesty's Stationery Office, London.

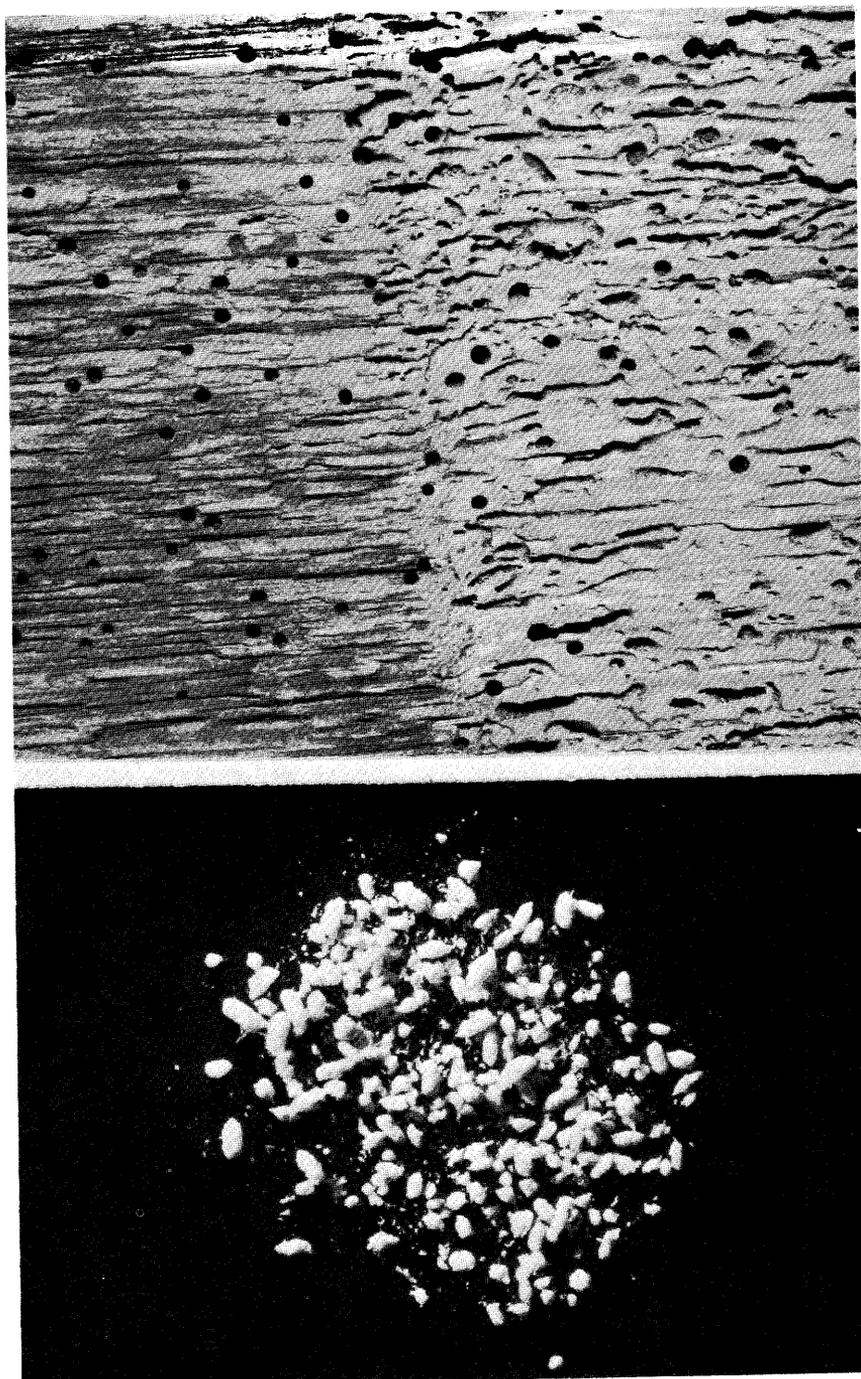


Figure 17-25.—(Top) Damage by the common furniture beetle, *Anobium punctatum* (DeGeer) in softwood flooring partly planed to expose tunnels. Exit holes on left measure about 1/16-inch in diameter. (Bottom) Bore dust, 11X. (Photos from Bletchly 1967.)

Infestations normally increase slowly over the years, and a building may be 20 years old before damage becomes obvious.

Presence of the beetle can be recognized by the $\frac{1}{16}$ -inch round exit holes and the network of short, dust-filled tunnels; the bore dust or frass contains pellets of ellipsoid or lemon shape (fig. 17-25). As the beetles continue their activity, fresh exit holes appear and piles of bore dust are ejected.

Females lay up to 80 eggs on end-grain, rough surfaces, cracks, crevices, and joints or in old flight holes. Eggs hatch in 4 to 5 weeks, and the larvae bore into the wood immediately; they are unable to crawl over the surface to seek alternative sites to commence boring. The larvae feed on the wood substance and cell contents for three or more years before pupating; they fill their tunnels with bore dust. Adult beetles emerge through exit holes between May and August (in England) and do not feed. They are often sluggish in cold weather, but can fly actively on warm sunny days to attack new wood. Damp, cool conditions in cellars and outbuildings are particularly suitable to the beetle, and the presence of soft rot facilitates their establishment and subsequent larval development. Prolonged temperatures over 77° F., or dry conditions, may prove fatal.

The white ellipsoidal eggs, about $\frac{1}{80}$ -inch in diameter, are only just visible to the naked eye (fig. 17-26).

The larva is curved, white, and covered with hairs and small hooklike structures (spinules) visible under a microscope (fig. 17-26). It possesses three pairs of legs and has two dark jaws. When fully grown, it is about $\frac{1}{5}$ -inch long.

When first formed, the pupa is white but generally darkens as it develops into an adult; females can be distinguished from males (fig. 17-26) by the possession of two teat-like projections at the tail end.

The beetles (fig. 17-26) are brownish black, and about $\frac{1}{10}$ - to $\frac{1}{5}$ -inch long; females are usually larger than males. The head projects downwards from the thorax so that it cannot be seen from above, although the antennae (with three swollen terminal joints) are clearly visible. The prothorax has a median hump and forms a hood over the head. The elytra are distinctly and regularly pitted (hence the name *A. punctatum*). For the characters used in distinguishing the sexes, reference should be made to a paper by Kelsey et al. (1945). Readers interested in additional details on *Anobium punctatum* (DeGeer) are also referred to Hickin (1963, pp. 36-75).

Since southern pine is primarily a structural wood and not used extensively for fine furniture, pertinent control measures are those that apply to buildings. Bletchly (1967) observes that liquid insecticide applications by brush, spray, or injection are generally the most practical method for treating infested wood; insecticidal smokes, if used, should be released

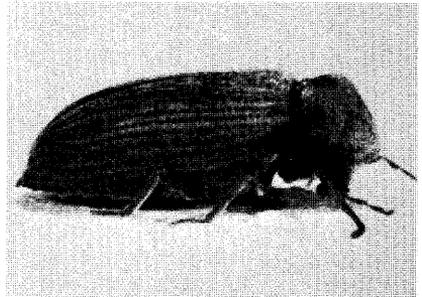
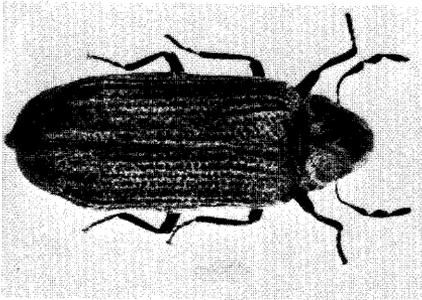
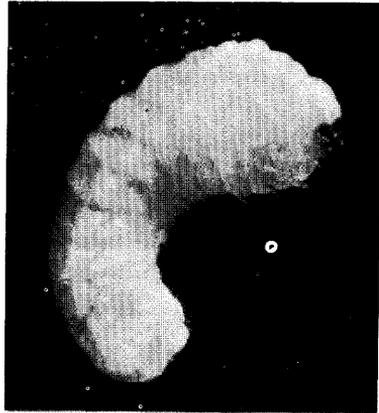
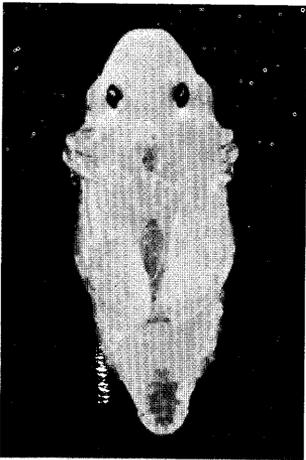
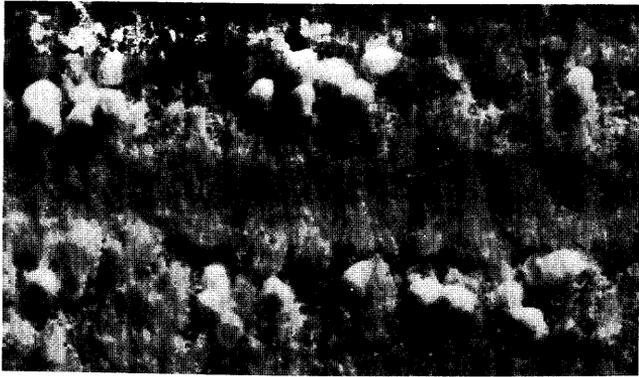
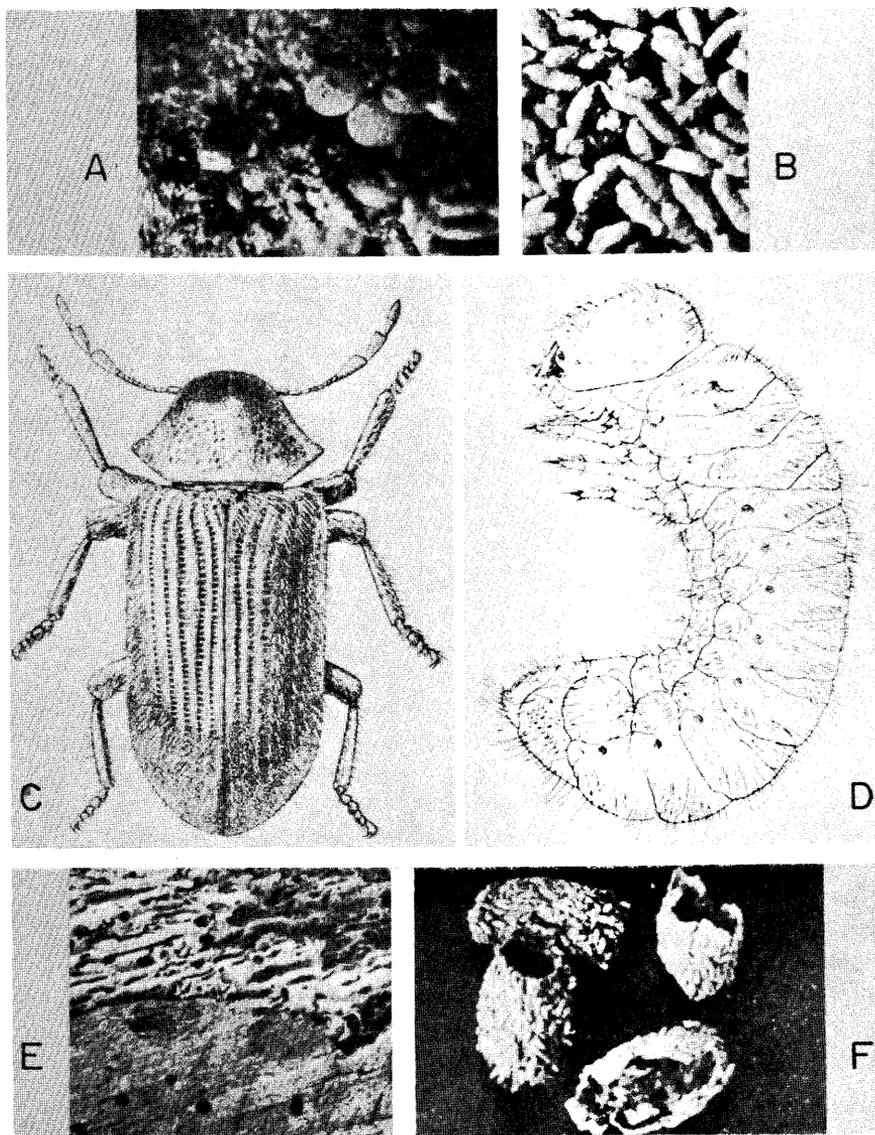


Figure 17-26.—The common furniture beetle (*Anobium punctatum* (DeGeer)). (Top) Eggs. (Center right) Larva. (Center left) Male pupa. (Bottom) Top and side view of adult beetle. The larva, pupa, and beetle are about 0.2 inch long; eggs measure about 0.02 inch in diameter. (Photos from Bletchly 1967.)



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Figure 17-27.—The biology of *Nicobium hirtum* Illiger. (A) Eggs with soft frass nearby, 14X. (B) Pellets of excreted wood, 10X. (C) Adult, 15X. (D) Larva, 15X. (E) Damaged wood and exit holes, half size. (F) Pupal cells made of pellets of excreted wood cemented together, 3½X. (Photos and drawings from Snyder 1935.)

annually for at least 5 years (based on experience in England), preferably in early June¹.

In general, chemicals suggested for control of the old-house borer will also control *Anobium punctatum* (DeGeer), i.e., common preservatives, liquid insecticides, and fumigants¹.

Other anobiids.—A European anobiid common in the Southern United States, where it may attack southern pine, is *Nicobium hirtum* Illiger. Snyder (1935) described the adult beetle (fig. 17-27) as subcylindrical, twice as long as wide, averaging about 4 mm. in length; its upper surface is of a mottled brown color, and is furnished with long erect hairs. The eggs—about 0.6 mm. in length and 0.4 mm. in diameter—are deposited singly or in pairs on pellets of excrement or in fine frass inside exit burrows; they require 10 to 14 days to hatch. The larvae have legs and very long hairs and yellow-brown, backward-curving spinules. The pupal cells are constructed by the larvae from pellets of excrement cemented together (fig. 17-27).

Control measures are the same as those for the old-house borer. Common wood preservatives will deter attack, and liquid insecticides and fumigants are effective against infestations¹.

Most damaging and most common of the wood-boring anobiids that attack southern pine in the South is *Xyletinus peltatus* (Harris). Pine sills, joists, and subflooring exposed in crawl spaces are highly favorable environments for this insect. In a study by Spink et al. (1966), it was found that 75 percent of the homes examined in Baton Rouge, La., were infested or had been infested by *X. peltatus* (Harris) or closely related species. In a survey of beetles infesting pine floor joists of buildings in North Carolina, Wright (1959) found this beetle in 10 of 14 infestations.

Not confined to the South, this beetle occurs in North America from northern New York to Michigan, southwestward to Arkansas, and south-eastward to Florida (Simeone 1962).

Information on the biology of *X. peltatus* (Harris) is meager. Moore (1968, 1970) has observed the effects of temperature and humidity on the biology of the beetle and the incubation time of its eggs; and Spink et al. (1966) provided the following description of its life cycle and activity.

Female beetles lay eggs in cracks and crevices of roughly cut timbers. After hatching, young larvae bore into the wood for a short distance, turn at right angles, and follow the grain of the wood; they feed on sapwood (mostly on earlywood) and leave the heartwood intact. Tiny, cylindrical, or cigar-shaped pellets excreted by the larvae fill the tunnels; some are expelled, causing characteristic sawdust-like piles on the surface of the wood and ground. Larvae pupate just beneath the surface of the wood.

Adults begin emergence from the wood surface about April 1 and stop about October 1 in the South; peak emergence is in late May and early June. Sawdust-like frass is found at emergence holes.

The adult is 3 to 4 mm. long, reddish brown, and covered with fine, yellowish hairs. Several longitudinal rows of punctures are present on the wing covers. The head of the adult beetle is directed downward and is hidden by the thorax when viewed from above. The larvae have white

bodies with dark heads, and there are two rows of small, brown spinules on the back of each abdominal segment.

Larvae cause damage by feeding and tunneling within timber. Small entrance holes less than $\frac{1}{16}$ -inch in diameter and exit holes $\frac{1}{8}$ -inch in diameter are external evidence of damaged wood. These holes resemble buckshot holes and are scattered randomly in the wood surface. Over 200 holes in 1 sq. ft. have been found on timber surfaces.

As with the other anobiids, control measures are the same as those employed for old-house borers¹.

Carpenter ants.—Carpenter ants (*Camponotus* spp.) are wood-nesting insects which may attack southern pine lumber and timber in buildings as well as posts and poles in exterior use. Of seven species frequently found, the most common in the major market region for southern pine is the black carpenter ant (*Camponotus pennsylvanicus* DeGeer).

Because their damage is usually less extensive, it is of less economic importance than that of termites, which in some ways carpenter ants resemble. As noted previously, however, all forms and species of carpenter ants have thin waistlines, whereas termites have thick waistlines; also, in reproductive carpenter ants one pair of wings is larger than the other (fig. 17-3).

Distribution of carpenter ant species, life history, characteristics of the nest, food, and control measures¹ are illustrated and described in the literature, e.g., Craighead (1950, pp. 622-625), Simeone (1954), and National Pest Control Association (1962).

The ants, which may exceed $\frac{1}{2}$ -inch in length, seek softwood, particularly wood that has weathered and begun to decay, to make cavities to rear their young. They may be found in porch columns and roofs, window sills, foundation plates, and logs of cabins. These ants do not eat wood—they simply eject it in fibrous shreds as they excavate their chambers. They feed on honeydew obtained from aphids and scales, and on animal remains and plant juices.

Unlike termite workings, carpenter ant chambers are clean—almost sanded in appearance—and some cut across the grain of the wood; piles of shredded fiber are evident on the outside of infested wood. In contrast, wood damaged by subterranean termites has stained grayish chambers running parallel with the grain. Subterranean termites do not excrete pellets nor eject material from their excavations; the pellets excreted by drywood termites have concavities in their surfaces and may be distinguished from the shredded fiber ejected from carpenter ant chambers.

A colony of carpenter ants consists of workers of various size, reproductives, and immature individuals. About 9 weeks are required for development of individuals from egg to adult stage, and 3 to 6 years for a colony to become well developed.

Carpenter ants prefer moist (not wet) wood and are infrequently found in wood at less than 10-percent moisture content. The major measure to

prevent attack therefore is construction practice that keeps wood in structures dry (see Simeone 1954 for examples of poor and good design).

Chemical control is achieved by injection of insecticide¹ into the tunnels. In general, methods that control drywood termites will also control carpenter ants (see sec. 17-1). Because carpenter ant chambers are free of bore dust and frass, insecticides can travel freely in their excavations.

Carpenter bees.⁹—The great carpenter bee (*Xylocopa virginica* Dru.), a large insect resembling a bumblebee, may attack southern pine lumber—and other softwood lumber—that has become softened from exterior exposure. They are common throughout the Midsouth and may riddle rustic buildings with marble-size holes. Carpenter bees feed on pollen and do not ingest the wood they remove. They excavate tunnels in which to rear their young and are most active in early summer. The carpenter bee can be identified by the back of its abdomen, which is shiny black; that of the bumblebee is fuzzy.

Once they have chosen a favorable surface—vertical and well lit, on wood with grain running horizontally—they proceed to cut a circular opening so perfect that it appears to have been bored with a $\frac{3}{8}$ -inch bit. In about 2 days' time, they penetrate across the grain to the depth of their favorable locations, as in fence rails or in the siding of buildings, multiple tunnels are frequently made parallel to one another, and two bees may have a common entrance, extending their tunnels in opposite directions.

The female bee places a product from pollen known as "sweetbread" at the far end of the tunnel, and deposits on it an egg about $\frac{1}{2}$ -inch in length. She then seals this segment of the tunnel with a thin partition of sawdust and chips fastened together with saliva. The larvae feed on the "sweetbread". An egg is laid similarly in each of five to seven other segments of the tunnel.

The larvae mature during the fall months and transform to adult bees. In the vicinity of Washington, D.C. they do not reproduce until the following spring or summer.

At present, no chemical is known that will be completely effective in preventing attack by carpenter bees. Considerable protection, however, has been obtained by the use of 2 percent chlordane or 1 percent Lindane in solution in oil¹. If bees start to bore into wood, researchers have observed that they may be deterred if the surface is sprayed with a toxic chemical that has been dissolved in a refined kerosene oil, such as ultrasene or deobase¹. This is a clean oil that will cause little or no staining and has a high flash point, which makes it relatively safe to use.

Deeper tunnels may be treated by forcing a piece of stiff wire into the tunnel until it reaches the end, destroying the papery partitions. Then the tunnel should be flooded with the toxic solution. CS₂ applied with an

⁹ This description is condensed from: USDA Forest Service. The great carpenter bee. USDA Forest Service, Division of Forest Insect Research. Forest Insect Laboratory, Beltsville, Md. Unpublished information sheet dated May 1958. 2 pp.

eyedropper is also effective¹. Next, fill the entrance hole with plastic wood or similar material, and then spray the entire area for some distance around with the solution. Filling the entrance hole helps to keep the bee from reentering. The wood surface should be as dry as possible before the toxic oil solution is applied to it. This will help to increase absorption and to increase its period of effectiveness.

17-3 MARINE BORERS¹⁰

Chief deteriorators of wood exposed to salt water are molluscan borers called shipworms—of the genera *Bankia* and *Teredo*—and crustacean borers of the genus *Limnoria*. Excavations in wood provide the animals with both food and shelter.

The only known borer resistant woods are species containing toxic alkaloids, e.g., greenheart (*Ocotea rodiaei* (Rob. Schomb.) Mez.), or those with high silica content, e.g., swamp box (*Tristania suaveolens*) and turpentine (*Syncarpia laurifolia*). Untreated southern pine, however, is highly susceptible to attack.

Annual damage by these borers to submerged wooden structures in coastal waters of the United States was estimated in 1958 at \$500 million. Since water pollution tends to hold down marine borer population, the anticipated success of some harbor pollution control programs is likely to result in increased borer damage in future years.

Readers interested in the study of marine-borer biology and measures to control their damage are referred to Hill and Kofoid (1927), a monograph resulting from investigations into massive pier and piling failures in San Francisco Bay following several years of drought, during which the salinity of the Bay increased and allowed marine borers to attack untreated piling; prior to the drought, the piling was protected from borer attack by low salinity of the Bay water.

More recent reviews, including annotated bibliographies, were published by Menzies (1957ab) and Menzies and Turner (1957). These references provide a useful introduction to the subject and to literature published in the years from 1900 to 1957.

This discussion is concentrated on those features of wood-borer biology related to the destruction of southern pine wood placed in the sea. The protection of southern pine in salt water is discussed in section 22-1 under the headings WOOD PRESERVATIVES (*Effectiveness in salt water*) and PRESERVATION OF PARTICULAR PRODUCTS (*Piling*)¹.

MOLLUSCAN BORERS

Molluscs damaging wood include the genera *Martesia*, *Bankia*, and

¹⁰ Sec. 17-3 is adapted from: Menzies, R. J. The nature of, and prevention of, marine borer attacks on southern pine wood—A review. Presentation at a symposium, "Utilization of the southern pines," Alexandria, La., November 6-8, 1968.

Teredo; of these, the latter two—both from the family Teredinidae—are most damaging to southern pine in coastal waters of the United States. Both restrict their attack to wood and require it for their carbohydrate nutrition. Because of their elongated appearance, *Bankia* and *Teredo* are commonly termed **shipworms**, the typical bivalve molluscan shell being reduced to two small plates in the “head”. Because *Bankia* damage resembles that of *Teredo*, the following discussion is confined to *Teredo*.

Habitat.—Shipworms are generally absent from fresh water, but may survive in sea water with salinity as low as 10 parts per 1,000; no North American species is known that will survive and breed in fresh water. They tolerate polluted water with dissolved oxygen as low as two parts per million.

Breeding of southern species of *Teredo* is restricted by temperatures below 10° C. (50° F.); most favorable temperatures are in the range 15° to 25° C. (59° to 77° F.). The animal can withstand temperatures as high as 30° C. (86° F.), however. Increased harbor temperatures caused by thermal pollution may therefore favor *Teredo* activity.

Damage caused.—Tunnels made in southern pine by shipworms are pin-hole size at the surface of the wood but rapidly increase in diameter to as much as 1 inch; they are free of bore dust and have a white calcareous lining (fig. 17–28). Tunnels in wood under attack are typically numerous; untreated southern pine piling can be destroyed within a few weeks.

Description and life cycle.—The shipworm, when fully grown, may reach a length of 4 or 5 feet. The anatomy of a *Teredo* reflects its dependence on plankton and wood as a source of food (fig. 17–29). It bores its tunnels with its two molluscan shells at the front end; the rear end—nearest the tunnel opening—possesses two tubes or siphons. Sea water, drawn into the inhalant siphon of the animal, bathes the gills and provides the required oxygenation before passing on to flush out feces, compacted bore dust, and “used” sea water from the exhalant siphon.

Wood, rasped away by means of its shells, is taken in at the mouth, leaving scars on the wood (fig. 17–30). Kofoid and Miller (1927) demonstrated that 44 to 50 percent of ingested wood was utilized by the *Teredo*; in their study, percentage composition of certain wood was changed by transit through the digestive tract, as follows:

<u>Component</u>	<u>Original wood</u>	<u>After transit</u>
	----- Percent -----	
Nitrogen	0.14	0.71
Hemicellulose	11.87	8.46
Cellulose	39.66	14.97
Lignin	23.27	37.93

Apparently the animal digests cellulose and hemicellulose, leaving the lignin unaltered.

The wood-boring molluscs have a free-swimming larval stage. On find-

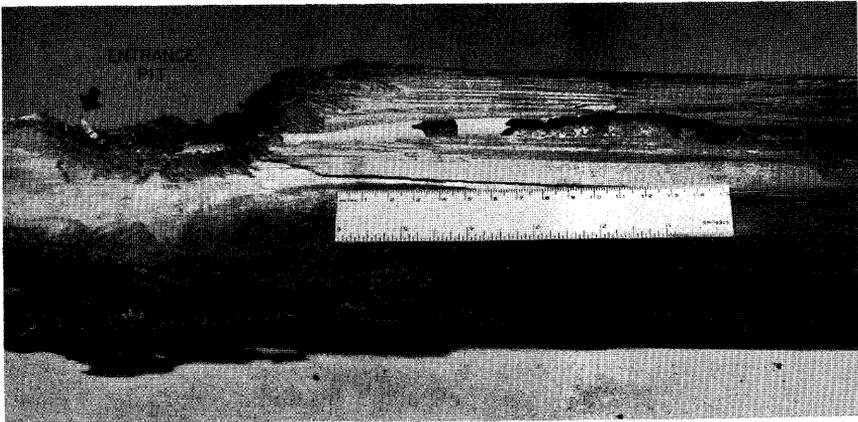


Figure 17-28.—Burrow of a foot-long shipworm *Bankia*, Teredinidae, in southern pine. The entrance pit has been eroded by *Limnoria* exposing the calcareous lining of the burrow. A portion of this lining has been removed to show the shells with which the shipworm deepens the blind end of the burrow (see also fig. 17-30). Scale shows centimeters and inches. (Photo from Menzies¹⁰.)

ing suitable wood, the larva settles and commences a metamorphosis into the adult shipworm. An adult *Teredo* produces hundreds to thousands of larvae; probably most of these die in the water before finding a suitable home. Once started in the wood, the animal is committed for life and cannot change its location.

Studies have shown that the larvae are more sensitive to toxins¹ than adults; thus, creosoted wood is generally immune to larval attack but may not be immune to attacks by adults. This can be demonstrated by attaching untreated wood under water to creosoted wood; the larvae will

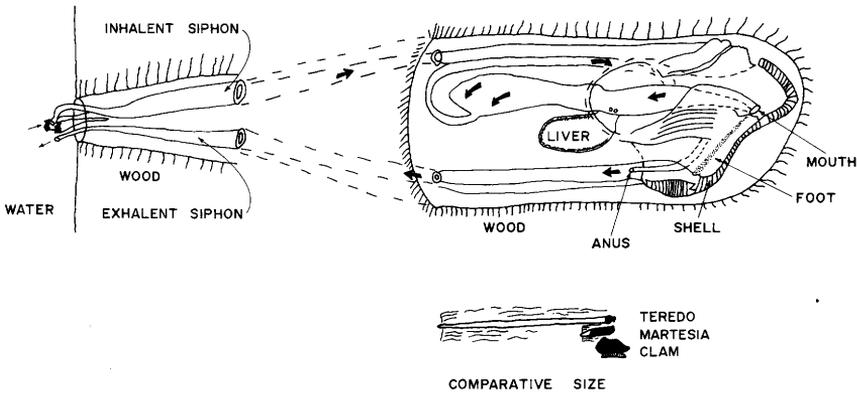


Figure 17-29.—*Teredo* anatomy. Arrows indicate path of sea water and ingested wood. Inset shows extreme length of *Teredo* compared with *Martesia*—a molluscan borer completely enclosed in its shell—and with a common clam. (Drawing after Menzies¹⁰.)

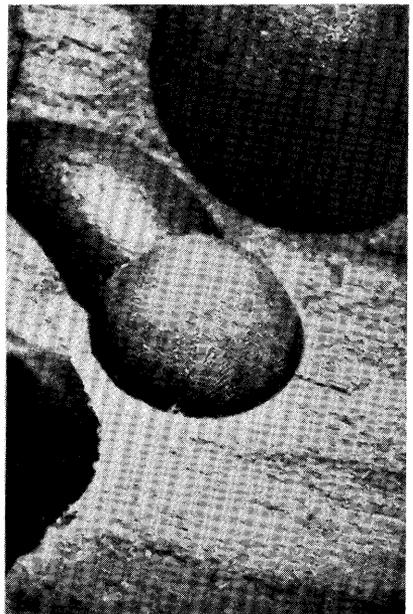
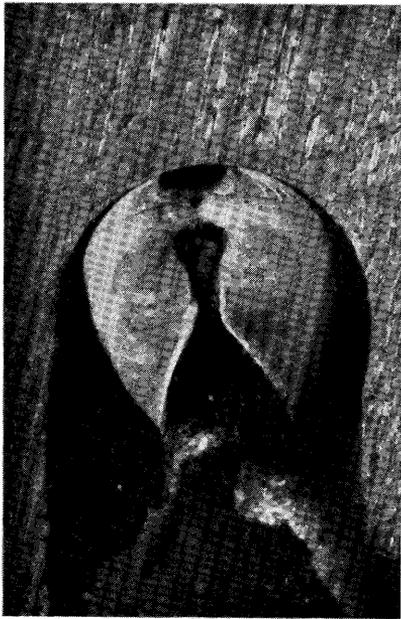


Figure 17-30.—Method by which the *Teredo* tunnels in wood. (Top left) Dorsal view of shell mounted at end of burrow. (Top right) Lateral view of shell mounted at end of burrow. (Bottom left) Cupped end of extremity showing markings made by shell. (Bottom right) Same, smaller specimen. (Photos from Hill and Kofoid 1927.)

attack the untreated piece and metamorphose into adults, which may then penetrate the treated wood along with the untreated. (See sec. 22-1 for control measures for shipworms¹.)

CRUSTACEAN BORERS

The only economically significant marine wood-boring crustacean is the *Limnoria*—an ant-size marine animal.

Habitat.—Warm water—up to about 27° C. (81° F.)—accelerates damage by *Limnoria*, but it is less affected by low temperature than the shipworm. It can survive exposure to air about 1 hour out of every 24 and therefore can live and breed in areas above low tide but washed by high tide.

The *Limnoria*, unlike the *Teredo*, is unable to tolerate great dilution of salt water. Not one species of fresh water *Limnoria* is known to exist. The animals thrive in sea water of 25 to 30 parts per thousand salinity. Both *Limnoria* and *Teredo* can tolerate considerable water pollution (Menzies et al. 1963) and survive and reproduce in oxygen concentrations as low as 2.0 p.p.m. by weight. They cannot, however, survive in severely polluted water. R. J. Menzies, in a 1968 visit to the Boston harbor, found ample evidence of the past presence of *Limnoria*, but could not find a living animal. A harbor engineer reported that neither *Teredo* nor *Limnoria* had existed there (in the vicinity of the city sewage outfall) since World War II. Thus, this area of Boston Harbor has remained free of borers for nearly 20 years because of severe pollution. Once the harbor becomes less polluted, Menzies suggests that substantial pier failures may occur.

Damage.—Generally speaking, attack by *Limnoria* is restricted to the superficial first inch of exposed wood. Unlike *Teredo*, the *Limnoria* does not bring the water with it as it grows, and the deeper the animal penetrates in the wood the harder it becomes to maintain water circulation in its burrow, which measures only about 1 mm. in diameter. As the burrows are usually numerous and interconnecting, the surface of attacked piling becomes spongy, and wave action erodes them near the water line—thus substantially reducing their strength (fig. 17-31).

Description and life cycle.—The monograph by Menzies (1957a) describes the various species of *Limnoria* and many aspects of their biology. In complete contrast to the *Teredo*, this 1- to 4-mm.-long animal (fig. 17-32) is able to leave its burrow once it is excavated.

Wood is taken into the mouth after it has been rasped away by an efficient rasp and file mechanism of the mandibles (fig. 17-33AB). Digestion of wood was studied by Ray and Julian (1952), who reported the production of simple sugars from homogenates of *Limnoria* liver and wood. From these experiments it was concluded that the animals produce a cellulase. The site of cellulase production appears to be the liver cells, but this point requires more study.

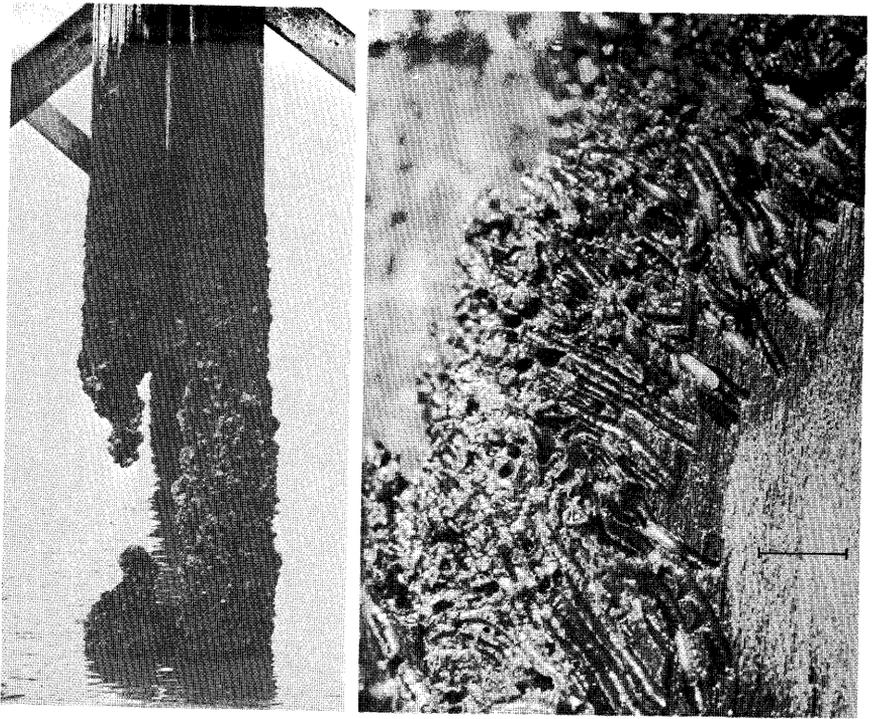


Figure 17-31.—Damage from *Limnoria tripunctata* Menzies in southern pine piling. (Left) Pencil point erosion of creosoted piling near St. Teresa, Fla. on the Gulf of Mexico. (Right) *Limnoria* in burrows; the animals do not burrow into portions of piling in which the wood is dry. Scale mark shows $\frac{1}{2}$ -cm. (Photos from Menzies¹⁰.)

The reproductive activities of *Limnoria* involve the pairing of male and female in a burrow and the production of young by the female. Once the young are produced the adults leave their burrows and seek new wood (Johnson and Menzies 1956). There is no free-swimming larval stage, and attack on fresh wood is made by the adult (in contrast to the *Teredo*); initiation of attack is simple.

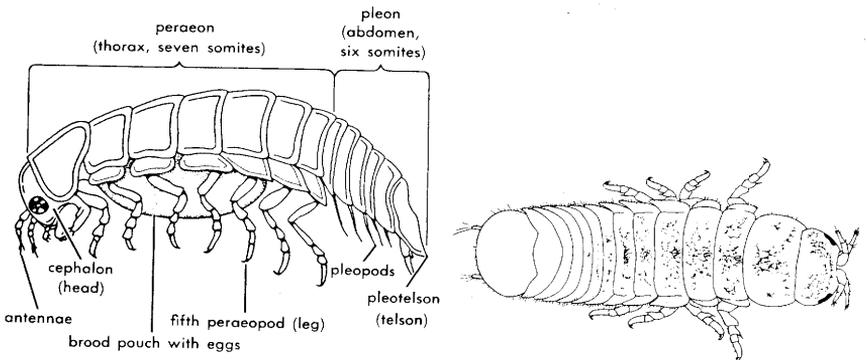


Figure 17-32.—Typical *Limnoria*. Adults of southern species may be only 1 mm. long and seldom measure over 3 mm. Not all legs are drawn in the dorsal view. (Drawings after Menzies 1954.)

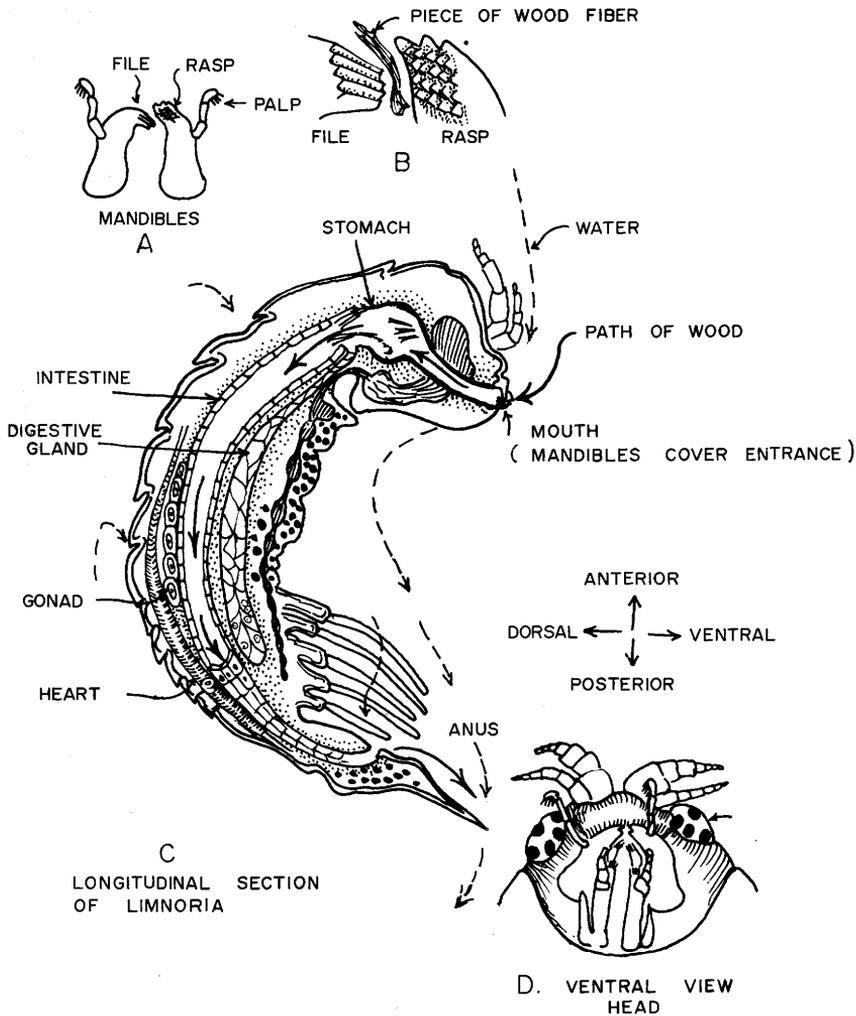


Figure 17-33.—Anatomy of *Limnoria* showing internal parts and mechanism of wood destruction. (Drawing after Menzies¹⁰.)

Control.—Control of *Limnoria* is made difficult by the fact that one species, *Limnoria tripunctata* Menzies, attacks creosoted wood (Beckman et al. 1957). Section 22-1 contains discussions of effectiveness against *Limnoria* of various preservatives and preservation techniques for piling in salt water¹.

UNSOLVED PROBLEMS

One of the most interesting unresolved problems relating to marine borers is the biosynthesis of cellulase by the *Teredo* and by *Limnoria*. These animals, unlike the termite, lack a protozoan enteric fauna, and constitute the only known multicellular animals in the animal kingdom

with such a singular capability. From the wood preservation standpoint, a toxin which would selectively block cellulase production would be an effective deterrent to attack by both *Teredo* and *Limnoria*.

The role of marine fungi in borer attack is still unresolved. Kohlmeyer et al. (1959) attribute an essential role to fungi in the nutrition of *Limnoria*; Ray and Stuntz (1957), however, report the fungus as adventitious and not essential. It seems likely that fungi and bacteria serve as a nitrogen source for the animals.

17-4 WOODPECKERS ¹¹

Excavations by woodpeckers seriously damage wooden poles over considerable portions of the United States. These attacks are of concern to utility companies because replacement of damaged poles costs much more than their original installation. Timber growers are concerned because such damage could limit the market for poles, which since 1950 has utilized some 4 million southern pines annually, and which, on the basis of past trends, could approach 6 million in the coming decades (Christopher 1969).

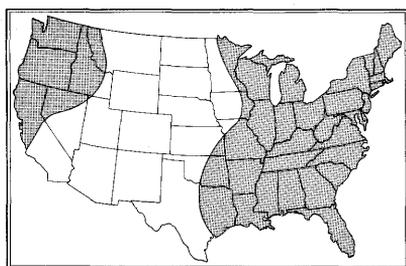
Some ornithologists believe that populations of pileated (*Dryocopus pileatus*) and red-headed woodpeckers (*Melanerpes erythrocephalus*), the two most destructive species, are on the rise. Since pressure treatment with creosote or pentachlorophenol¹ protects poles against nearly all other destructive organisms, one might expect protection against woodpeckers could easily be achieved; research so far, however, indicates otherwise.

WOODPECKER SPECIES AND NATURE OF DAMAGE

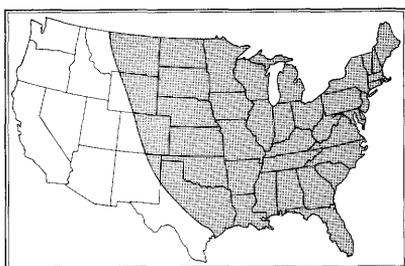
Seven species of woodpeckers are mainly responsible for damage in North America (Dennis 1964); their U.S. ranges are mapped in figure 17-34. The pileated, about crow-size, excavates roost and nest cavities 12 to 24 inches in depth (figs. 17-35, 17-36). Red-headed woodpeckers, while making somewhat smaller holes than the pileated, probably cause greater economic loss. They are more numerous and excavate poles of all sizes, while pileateds generally attack only poles of class 5 and larger. The ladder-backed (*Dendrocopos scalaris*), golden-fronted (*Centurus aurifrons*), and acorn (*Melanerpes formicivorus*) woodpeckers are of less economic importance by reason of their more restricted ranges. The flickers (*Colaptes auratus* and *C. cafer*) limit themselves primarily to enlarging checks and hence are seldom a problem.

Dennis (1964) states that the chief centers of pileated damage are in the Southern States bordering the Atlantic and the Gulf of Mexico, in some other Southern States, and in Pennsylvania, and locally in New

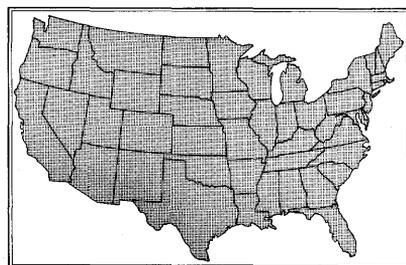
¹¹ Condensed from Rumsey (1970a) by permission of R. L. Rumsey and the Forest Products Research Society.



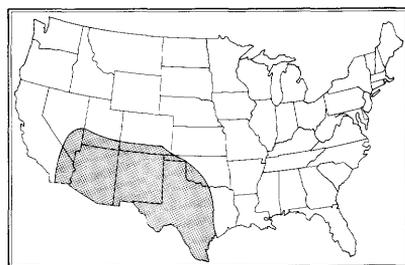
Pileated



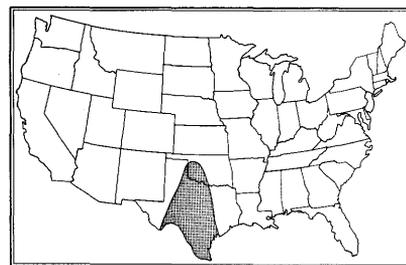
Red-headed



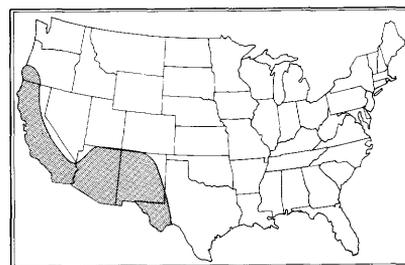
Flickers



Ladder-backed



Golden-fronted



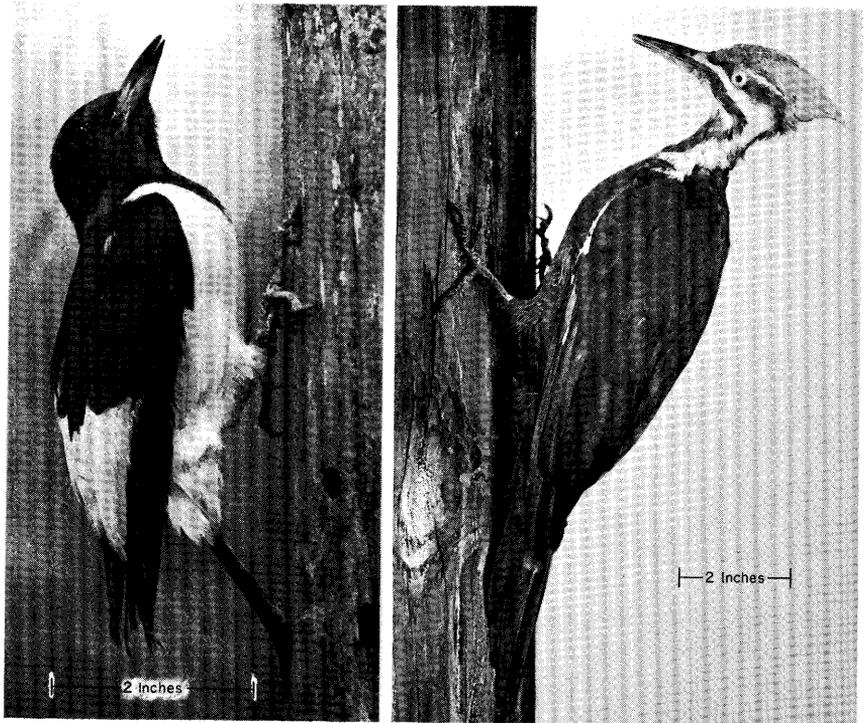
Acorn

Figure 17-34.—Range of woodpeckers attacking poles. (Drawing after Rumsey 1970a.)

England and parts of the Midwest. Red-head attacks are locally severe in parts of the South and Midwest, while the golden-fronted and ladder-backed woodpeckers are nuisances chiefly in southern and central Texas.

Both pileateds and red-heads require hardwood trees in their habitat; they normally nest in hardwoods and obtain food from them. Pileateds are almost exclusively forest birds, most common near stream bottoms. Red-heads have a more diverse habitat; they tend toward uplands, are frequent in some mixed farm and forest situations, and occur in urban areas where hardwood shade trees are abundant. Neither species attacks utility lines passing through pure pine stands.

It appears that poles are attractive because of their strategic locations in open spaces (Turcek 1960; Dennis 1964). When on poles the woodpeckers are conspicuous to others of their species; their presence is simultaneously an advertisement for a mate and an announcement of territorial



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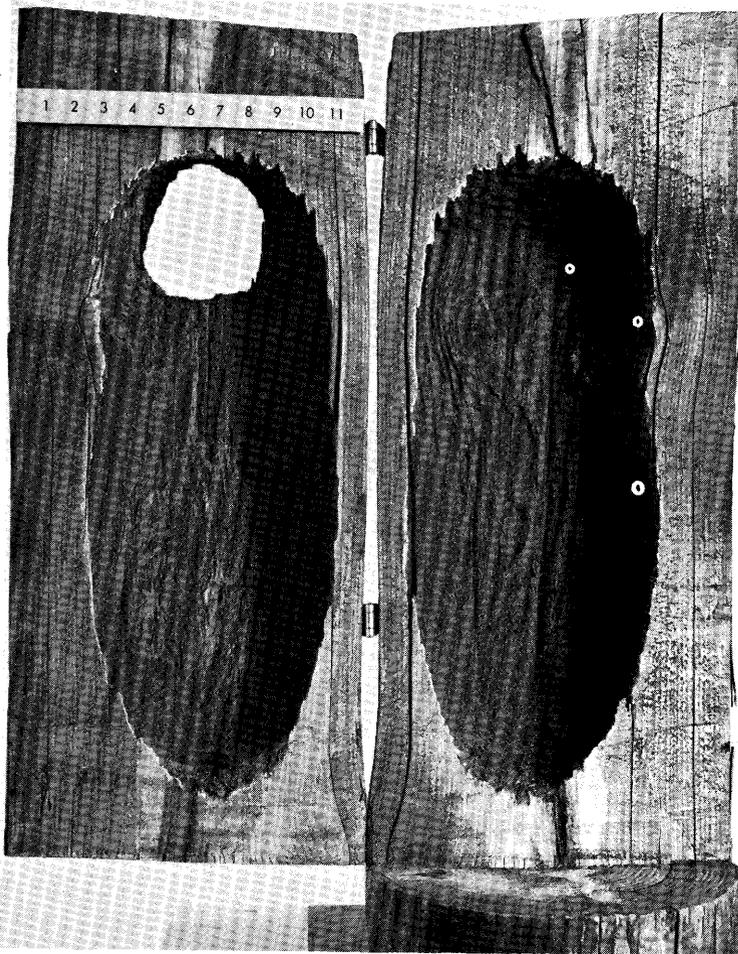
Figure 17-35.—Woodpeckers hang by their claws and brace themselves with their tails. (Left) Red-headed woodpecker. (Right) Pileated. (Photos from Rumsey 1970a.)

rights. Abundant nesting sites in nearby hardwood trees do not lessen the attractiveness of poles.

Most of the damage occurs just prior to the nesting season in late winter and early spring. A pole is then the scene of considerable activity in mating and establishment of territorial rights, following which both birds of a pair excavate for a nest or enlarge an existing hole. There is also some excavation shortly before winter, when roost holes are made. For every cavity that is completed, there may be 20 probe holes extending a few inches horizontally but not turning downward.

The attractiveness of poles as nesting sites has its ironic aspect. Examination of nests in recently creosoted poles in central Louisiana revealed that most eggs failed to hatch and no young lived after the third day. The creosote appears to be the lethal agent. Adult birds do not seem to be affected adversely by the chemical and often renest in cavities where one brood has failed (Rumsey 1970b).

During treatment many poles develop large burst checks characterized by a shake (separation between growth rings) that is usually 1 to 2 inches below the surface and extends 6 inches or so concentrically (fig. 17-37). Often a large check runs from the surface of the pole into the shake. Tapping in the region of a burst check produces a loud, hollow sound



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Figure 17-36.—Cross section of a pileated woodpecker's nest cavity in a utility pole. Scale is in inches. (Photo from Rumsey 1970a.)

that indicates a hidden cavity. In a test at Pineville, La., 150 shakes were located and marked in 40 poles, six of which had no shakes. An equal number of sound areas were delineated in the vicinity of the shakes. During two nesting seasons, 52 attacks were directed at areas with shakes, while only one occurred in an adjacent sound area. Four of the shake-free poles were attacked, but less severely than the others. These and other observations indicate that internal voids are attractive to woodpeckers.

Middle and upper portions of poles are most susceptible to attack by pileateds (Dennis 1964). Damage by red-heads is usually nearer the top, often from the crossarms upward. The ladder-backed and golden-fronted woodpeckers attack poles, crossarms, and fenceposts. Dennis (1964) be-

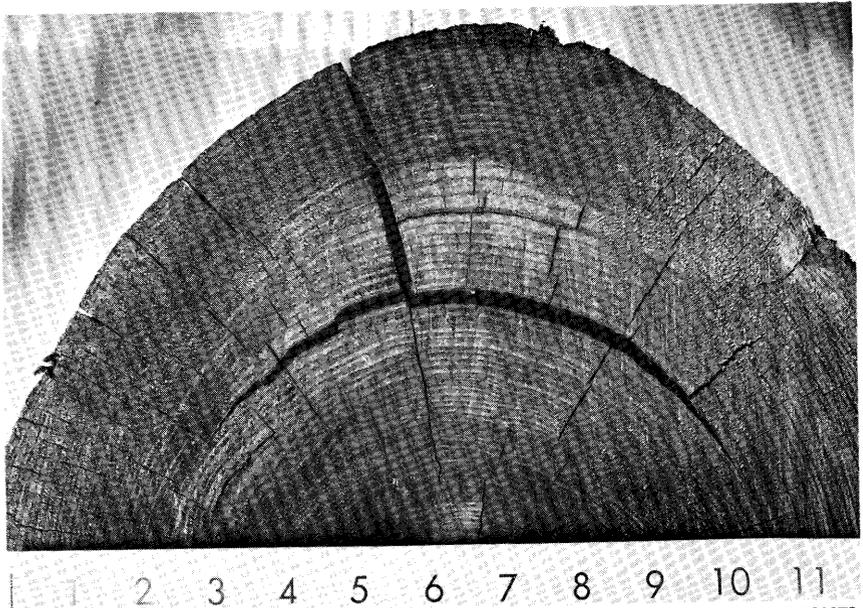


Figure 17-37.—Cross section of burst check in pressure-treated southern pine pole. (Photo from Rumsey 1970a.)

lieves that most of the holes are made by the ladder-backed, and then enlarged by the golden-fronted woodpecker.

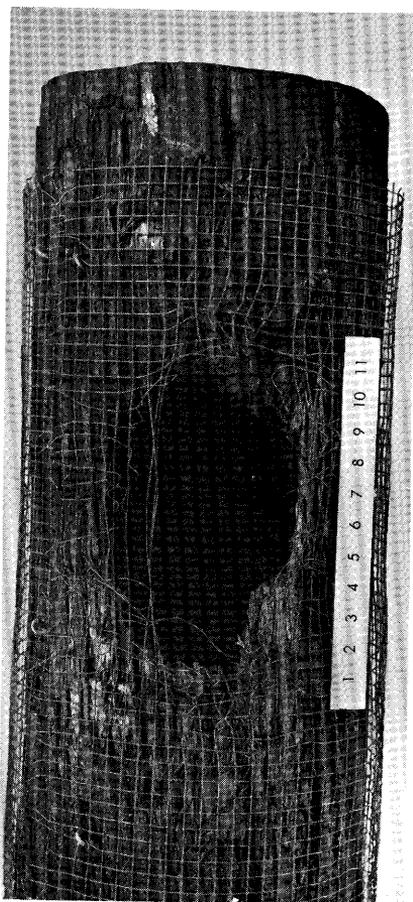
New pole lines are often attacked promptly after poles are set. This probably does not reflect a preference for newly treated poles; the birds are attracted to these new nesting sites as soon as they become available. Though poles lose some moisture and therefore harden with age, they remain susceptible for many years (Dennis 1964).

Normally a pole will have only one completed cavity, but the surrounding shell of wood may be less than an inch thick in places. The cavities weaken the poles; linemen are reluctant to climb above them, and the likelihood of breakage in storms is increased. In addition, there may be numerous "test probe" holes for every completed cavity. These probe holes go inward but not downward.

Since the cavities expose untreated wood, various hole-filling materials are in use to prevent water from entering and causing decay. Most of these restore little strength to poles and do not adhere well enough to be watertight. The hazard from decay is problematical. In examining 80 sections of damaged poles from central Louisiana, Rumsey found only two in which decay was definitely associated with woodpecker attack. Admittedly, the birds deepen cavities they reuse, and thereby remove evidence of decay. Considerable rainwater appears to enter the cavities, especially those facing the direction of the storms, but of several hundred cavities checked over a 4-year period, only two retained water; some water escaped through cracks, and some presumably seeped into the pole.

The equilibrium moisture content of upright poles in air, even in the humid South, is seldom high enough to support decay.

Utility companies take differing attitudes toward woodpecker damage. Some ignore it, some fill the holes, and some replace the poles. There are methods of reinforcing weakened poles, but they are expensive. In areas where damage is severe, some companies wrap poles in 2 by 2 hardware cloth from a point about 15 feet above groundline to the top. This protection, installed before the poles are erected, costs \$25 to \$50 per pole. It is a nuisance to linemen, reduces insulating qualities, and occasionally fails to keep out pileateds (fig. 17-38).



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Figure 17-38.—The common woodpecker deterrent—hardware cloth—occasionally fails. Scale in inches. (Photo from Rumsey 1970a.)

Since the incidence of damage and the cost of procuring and installing poles varies greatly from area to area, it is not possible to set a value on woodpecker damage nationally.

PHYSICAL ATTRIBUTES OF WOODPECKERS

Obviously woodpeckers possess several physical adaptations that facilitate their excavations in wood. Their four clawed toes, two pointed forward and two backward, and their stiff tail feathers permit perching on

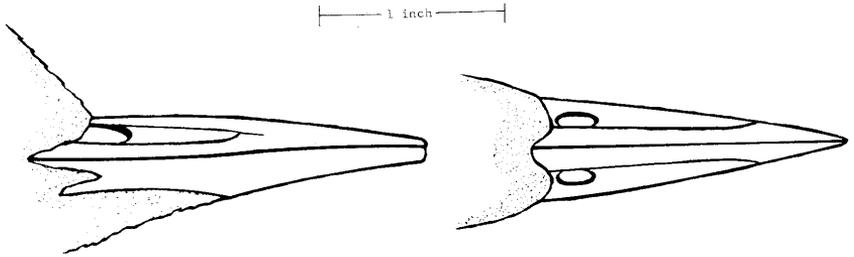


Figure 17-39.—Side (left) and top (right) view of beak of pileated woodpecker. (Drawing after Rumsey 1970a.)

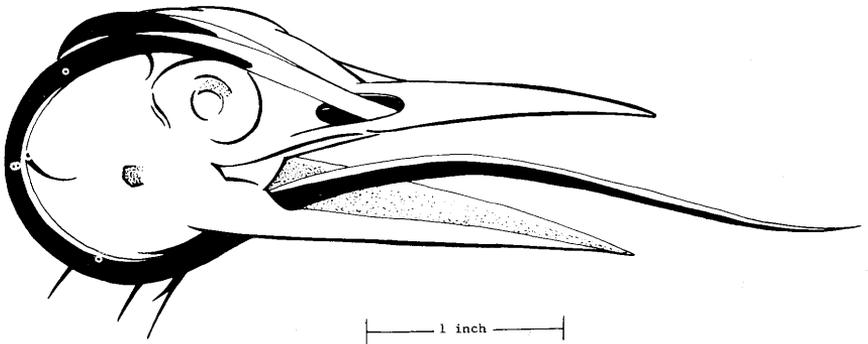


Figure 17-40.—Tongue structure in pileated woodpecker. The tongue is part of a mechanism of bone and tissue that divides in back of the mouth, passes under each side of the jaw and up around the back of the head, and then joins for anchorage in the right nostril. (Drawing after Rumsey 1970a.)

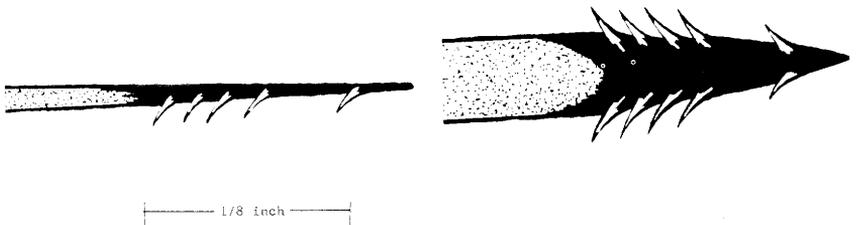


Figure 17-41.—Tip of pileated woodpecker tongue. (Right) Top view. (Left) Side view. (Drawing after Rumsey 1970a.)

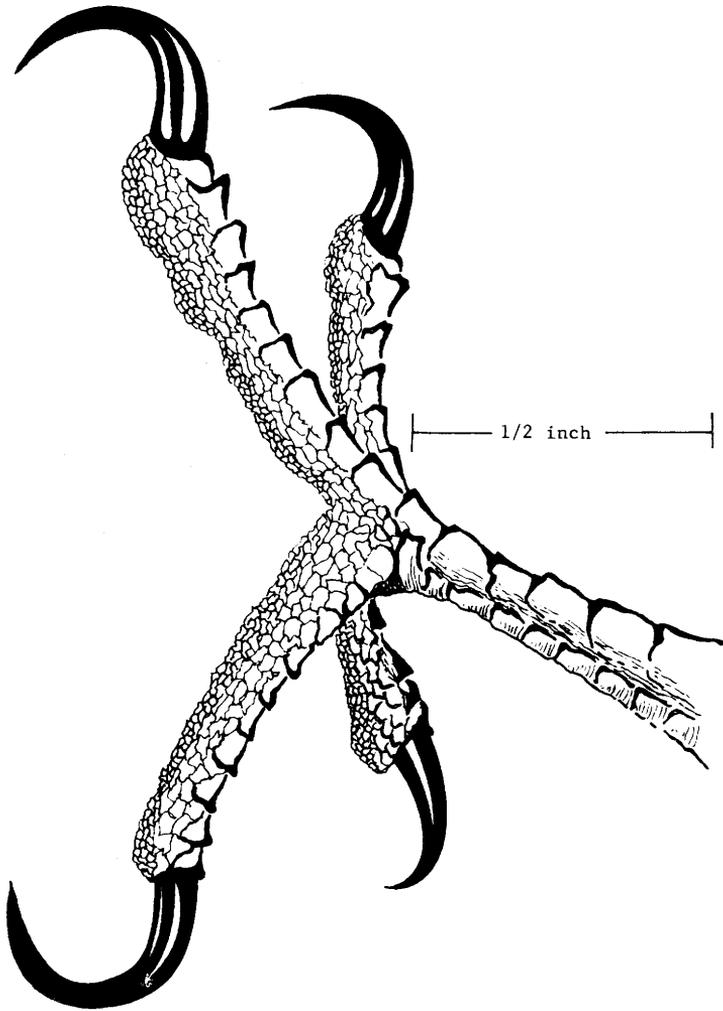


Figure 17-42.—Foot of pileated woodpecker. Note zygodactyl arrangement of toes. (Drawing after Rumsey 1970a.)

vertical surfaces. Sharp, hard beaks, isolated from the skull by shock-absorbing tissue, permit excavation for nests and feeding (Burt 1930). Extremely long and specialized tongues extract insects from extremities of wood cavities penetrated by the beak (figs. 17-39, 17-40, 17-41, 17-42).

Woodpeckers probably rely largely on hearing to locate insects in wood (Hoyt 1950). Their practice of pausing frequently with head turned aside after tapping on the surface probably involves listening for sounds of disturbed insects. Pumphrey (1961a) stated that most birds' response to sound is 10 times as fast as in humans, but believed they hear a narrower range. Pumphrey (1961b) also stated that vision in birds is faster,

though no more acute than that of humans. Jorgensen et al. (1957) found that woodpeckers attacked white, red, green, yellow, and aluminum-colored poles more heavily than unpainted controls.

Although woodpeckers may have some slight sense of smell (Portmann 1961), it appears unimportant. Portmann also stated that birds probably distinguish the same primary tastes as humans. Welty (1962) believed their sense of taste to be poorly developed. Saliva of woodpeckers is sufficiently basic (near pH 10) to neutralize the highly acid ants which they eat in large quantities.

RESEARCH ON PREVENTING ATTACK

Literature on the prevention of attack is scarce. Some research was done at Pennsylvania State University during the 1950's. The paper by Jorgensen et al. (1957), previously mentioned, summarizes the main results. Dennis (1963) reported on the development, by an industrial firm, of a compound he considered to be a repellent; though early tests were promising, the product has not been widely accepted.

In recent years, research has been carried on at Pineville, La., with funds made available by several utility companies to the Southern Forest Experiment Station. Though definitive results are still pending, it may be useful to synopsise the findings to date.

In early stages of the research, an aviary was constructed with the intention of facilitating tests of various pole treatments. Adult red-heads and pileateds readily adapted to the cages (Rumsey 1968) but did little excavating. Some success has been attained by constructing a plywood chamber 4 by 4 by 8 feet in size, and with a glass door for observation. The smooth walls compel a confined woodpecker to stand on the floor—a situation so unsatisfactory that it makes strenuous efforts to light on any test poles that may be offered. The chamber thus is useful in evaluating pole coatings and cross-sectional shapes that are intended to prevent attack by denying the birds a perch.

The ideal solution to the woodpecker problem would be a cheap repellent that could be incorporated when the poles are treated with preservative. In the Pineville tests, a large number of chemicals were applied directly at spots being worked by woodpeckers. This procedure provided a severe test, since it is more difficult to interrupt an attack than to prevent one initially. No chemicals remained effective for longer than a month. Some were applied in heavy grease, and, since the birds avoid tacky materials, the grease itself had some repellency until it solidified.

At present, chemicals affecting taste and smell do not seem to offer much promise. Woodpeckers apparently can chip wood without bringing it into contact with their sensory organs. The effectiveness of most known repellents is dependent on their being ingested by some of the birds. Specialized cells called Herbst's corpuscles are numerous on the tongues of woodpeckers. Originally, the corpuscles were thought to be tactile re-

ceptors only, but recent evidence indicates they are sensitive to variations of pressure and to low-frequency vibrations (Portmann 1961).

At various times utility companies have tried leaving damaged poles standing when replacement was necessary. They reasoned that the woodpeckers would continue using the old poles and not attack the new ones. The effectiveness of this practice has not been determined, but the poles are unsightly and at times may be a safety hazard.

In one test, 7-foot sections of creosoted eastern cottonwood (*Populus deltoides* Bartr.) were attached to 28 poles at appropriate heights. After 15 months, poles with these "decoys" had significantly less damage than the controls. However, instead of attracting birds, the decoys seemed to function as scarecrows; only three were damaged.

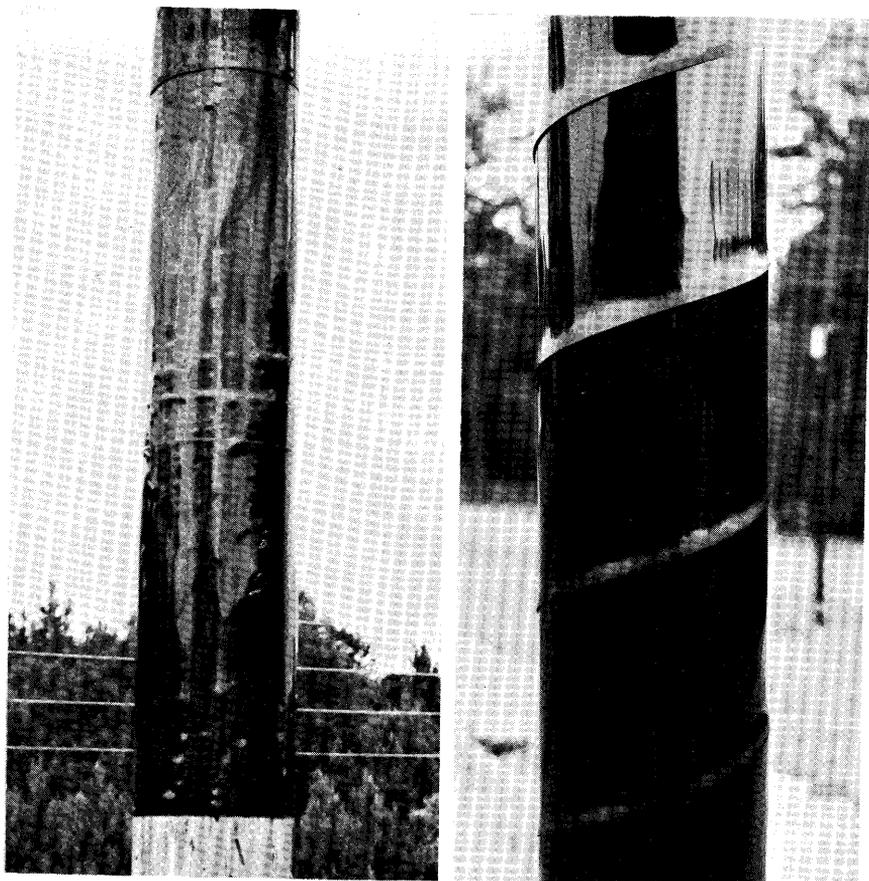
Since white pine (*Pinus strobus* L.) has much better working properties than cottonwood, decoys were made from it. As a further inducement, sections were longitudinally quartered, cavities were excavated, and the four pieces were glued together to conceal the internal hollow. When tapped, the decoys resounded loudly. After 6 to 8 months, 15 of the 28 had large holes extending into the internal cavity, but damage to the poles with decoys was about as severe as to those without decoys—well above acceptable levels.

The effect of pole hardness was tested in an area of south Texas where ladder-backed and golden-fronted woodpeckers were numerous. Twenty creosoted southern pine fenceposts with hardness values¹² of 433 to 777 pounds were paired with 20 others ranging from 1,130 to 1,417 pounds. Damage to the soft posts was more frequent and also more severe. The threshold of hardness impenetrable by pileateds and red-heads seems worth determining. Very dense var. *densa* slash pine poles are currently under test in central Louisiana; some damage to these poles, however, has been reported. Similarly, rectangular laminated poles faced on all four sides with very dense southern pine boards have suffered some damage.

A number of pole coatings and wrappings have been tested. They were designed to make the surface too smooth to afford the birds a perch or too hard to penetrate.

Brush-on applications, mostly epoxies, were tried first. They had the requisite smoothness, but were short-lived on exposure to direct sunlight. Adhesion and curing were satisfactory only on poles treated by methods that left the surfaces free of oil. Though application presents difficulties, a coating of gravel embedded in epoxy has protected fenceposts for 2 or 3 years in Texas; this treatment is currently under test on poles and appears promising. Linemen would not be able to climb the poles with spurs, but would work from hydraulic lift trucks or some sort of quick-locking, removable step.

¹² Evaluations made according to ASTM Standard D143-52, except that all measurements were taken radially.



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Figure 17-43.—Sheet polyurethane (left) and helically wound polyethylene (right) have prevented woodpecker attack because birds are unable to gain a footing. (Photo on left from Rumsey 1970a.)

Wrap-on coatings, kept in place by bonding or nailing, have had some success. Sheet polyurethane, 20 mils thick, has given complete protection for a year, and heavy polyethylene applied in a helical wrap also shows promise (fig. 17-43).

In summary, there is yet no cheap, easy way to prevent woodpecker damage to wooden poles. Coatings or wraps of the sort described above seem to be most promising. Hardware cloth, although expensive, will continue to be used for some time, because its effectiveness has been demonstrated.

17-5 LITERATURE CITED

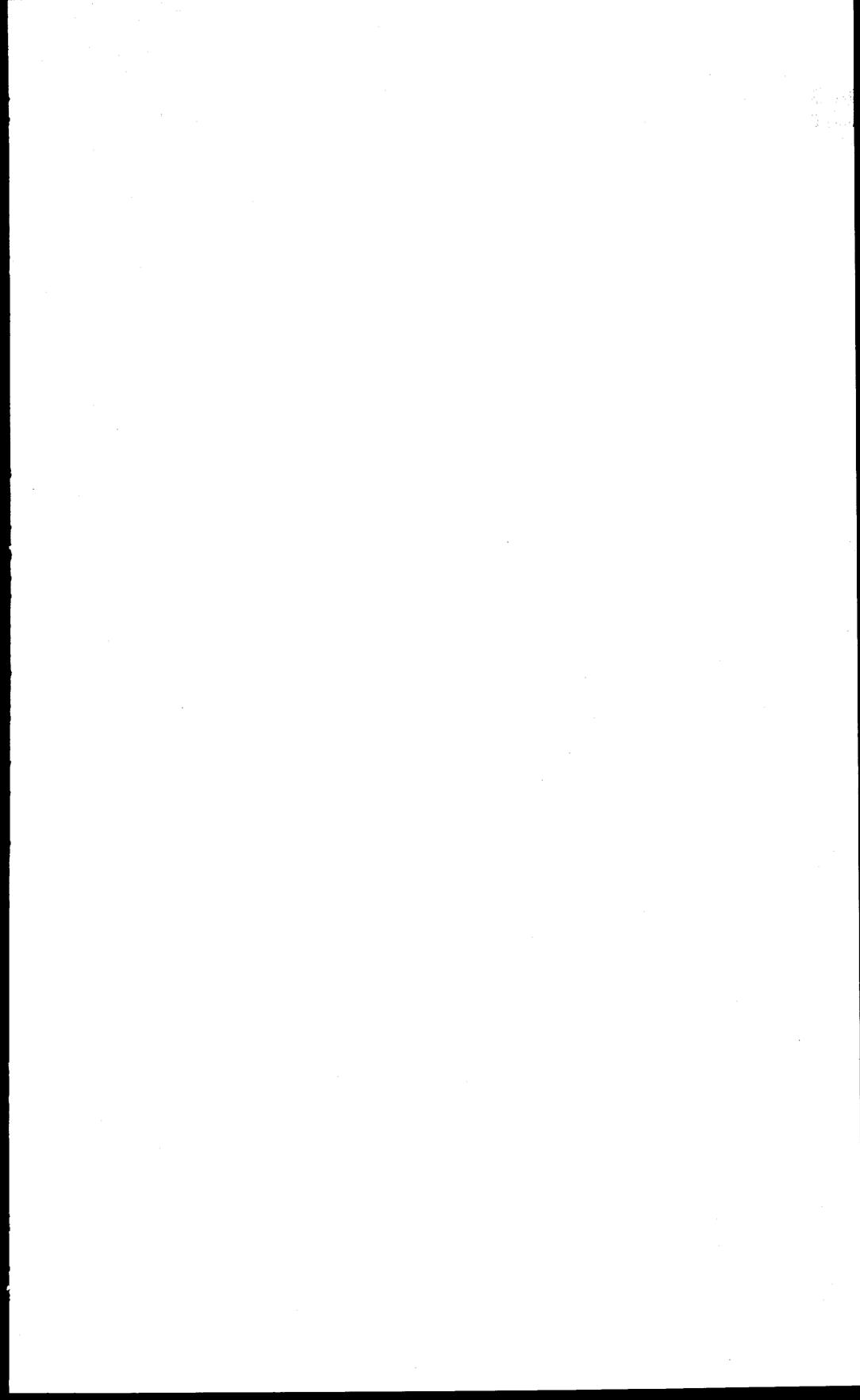
- | | |
|--|--|
| <p>Anderson, L. O.
1970. Wood-frame house construction. USDA Agr. Handbook 73, 223 pp.</p> | <p>Arnett, R. H.
1963. The beetles of the United States; a manual for identification. 1112 pp. Washington, D.C.: Catholic Univ. Amer. Press.</p> |
|--|--|

- Barron, E. H.
1971. Deterioration of southern pine beetle-killed trees. *Forest Prod. J.* 21(3): 57-59.
- Beal, J. A.
1928. The southern pine sawyer. U.S. Dep. Agr. Bur. Entomol. *Forest Entomol. Brief* 66, 2 pp.
- Beal, J. A.
1932. Control of the turpentine borer in the naval stores region. *USDA Circ.* 226, 18 pp.
- Beal, R. H.
1967. Formosan invader. *Pest Contr.* 35(2): 13-17.
- Beal, R. H.
1969. Treating pine lumber with insecticide and preservative prevents tubing by subterranean termites. *J. Econ. Entomol.* 62: 757-758.
- Beal, R. H., and Stauffer, L. S.
1967. How serious the Formosan termite invasion? *Forests and People* 17(3): 12-13, 28, 40-41.
- Beckman, C., Menzies, R. J., and Wakeman, C. M.
1957. The biological aspects of attack on creosoted wood by *Limnoria*. *Corrosion* 13: 31-34. Houston, Texas.
- ¹³ Bennett, W. H., Chellman, C. W., and Holt, W. R.
1958. Insect enemies of southern pines. *USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap.* 164, 35 pp.
- Bennett, W. H., and Ciesla, W. M.
1971. Southern pine beetle. *USDA Forest Serv. Forest Pest Leaflet* 49 (rev.), 8 pp.
- Bletchly J. D.
1967. Insect and marine borer damage to timber and woodwork. 88 pp. London: Her Majesty's Stationery Office.
- Burt, W. H.
1930. Adaptive modifications in the woodpeckers. *Univ. Calif. Zool. Pub.* 32: 455-524.
- ¹³ Revised as: Bennett, W. H., and Ostmark, H. E.
1972. Insect pests of southern pines. *USDA Forest Serv. South. Forest Exp. Sta.* 38 pp.
- Chamberlin, W. J.
1939. The bark and timber beetles of North America north of Mexico. 513 pp. Ore. State Coll. Coop. Assoc., Corvallis.
- Christopher, J. F.
1969. Pole supply outlook. *Forest Farmer* 28(4): 6-7, 17.
- Coster, J. E.
1969. Observations on *Platypus flavicornis* (Coleoptera: Platypodidae) in southern pine beetle infestations. *Ann. Entomol. Soc. Amer.* 62: 1008-1011.
- Craighead, F. C.
1950. Insect enemies of eastern forests. *USDA Misc. Pub.* 657, 679 pp.
- Dennis, J. V.
1963. Bye-bye pileated—development and testing of an effective woodpecker repellent. *Transm. and Distrib.* 15(6): 8-11.
- Dennis, J. V.
1964. Woodpecker damage to utility poles: with special reference to the role of territory and resonance. *Bird-Banding* 35: 225-253.
- Dixon, J. C., and Osgood, E. A.
1961. Southern pine beetle: a review of present knowledge. *USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap.* 128, 34 pp.
- Ebeling, W.
1968. Termites — identification, biology, and control of termites attacking buildings. *Calif. Agr. Exp. Sta. Ext. Serv. Man.* 38, 74 pp.
- Esenther, G. R., and Gray, D. E.
1968. Subterranean termite studies in southern Ontario. *Can. Entomol.* 100: 827-834.
- Grassé, P. P.
1949. Ordre des isoptères ou termites. *In Traité de Zoologie; anatomie, systématique, biologie* 9: 408-544. (P. P. Grassé, ed.) Masson, Paris.
- Grassé, P. P., and Noirot, C.
1945. La transmission des flagellés symbiotiques et les aliments des termites. *Bull. Biol. France et Belg.* 79: 273-292.

- Harvey, P. A.
1934. Life history of *Kalotermes* minor. II. In Termites and termite control (C. A. Kofoid, ed.). Chap. 20, pp. 208-224. Berkeley: Univ. Calif. Press.
- Hickin, N. E.
1963. The insect factor in wood decay. 336 pp. London: Hutchinson and Co.
- Hill, C. L., and Kofoid, C. A., editors
1927. Marine borers and their relation to marine construction on the Pacific coast. 357 pp. Final Report of the San Francisco Bay Marine Piling Committee.
- Hoyt, S. Y.
1950. The feeding technique of the pileated woodpecker. Bull. Mass. Aud. Soc. 34: 99-103.
- Johnson, M. W., and Menzies, R. J.
1956. The migratory habits of the marine gribble *Limnoria tripunctata* Menzies in San Diego Harbor, California. Biol. Bull. 110: 54-68.
- Johnston, H. R.
1952. Insect control: practical methods for the control of insects attacking green logs and lumber. South. Lumberman 184 (2307): 37-39.
- Johnston, H. R.
1965. Termites. In Consumers all, pp. 34-37. Yearbook of Agriculture, Wash., D.C.
- Johnston, H. R., and Beal, R. H.
1969. What's new with the Formosan termite? Pest Contr. 7(2): 24, 26, 30, 32.
- Jorgensen, R. N., Pfitzenmeyer, H. T., and Bramble, W. C.
1957. Prevention of woodpecker damage to wooden utility poles. Pa. Agr. Exp. Sta. Progr. Rep. 173, 4 pp.
- Kelsey, J. M., Spiller, D., and Denne, R. W.
1945. Biology of *Anobium punctatum*. N.Z. J. Sci. Tech. 27B(1): 59-68.
- Kofoid, C. A., and Miller, R. C.
1927. Biological Section. In Marine borers and their relation to marine construction on the Pacific coast. (C. L. Hill and C. A. Kofoid, ed.), pp. 188-343. Final Report of the San Francisco Bay Marine Piling Committee, 357 pp.
- Kohlmeyer, J., Becker, G., and Kampf, W. D.
1959. [The food of *L. tripunctata* and its relation to wood-destroying fungi.] Z. Angew. Zool. Berlin 46: 457-489.
- Kowal, R. J.
1960. Southern pine beetle. USDA Forest Serv. Forest Pest Leaf. 49, 7 pp.
- Krishna, K., and Weesner, F. M., editors.
1969. Biology of termites. Vol. 1, 598 pp. N.Y.: Academic Press.
- Krishna, K., and Weesner, F. M., editors.
1970. Biology of termites. Vol. 2, 643 pp. N.Y.: Academic Press.
- McIntyre, T., and St. George, R. A.
1961. The old house borer. USDA Leaf. 501, 8 pp.
- Menzies, R. J.
1954. The comparative biology of the wood-boring isopod crustacean *Limnoria*. Museum of Comparative Zoology, Harvard Coll. Bull. 112: 363-388.
- Menzies, R. J.
1957a. The marine borer family Limnoriidae (Crustacea, Isopoda). I. Northern and Central America: Systematics, distribution, and ecology. Bull. Marine Sci. Gulf and Carib. 7: 101-200.
- Menzies, R. J.
1957b. Marine borers. In Treatise on marine ecology and paleo ecology, pp. 1029-1034. (H. Path, ed.) Memo. 67, vol. 1, Ecology. Geol. Soc. Amer.
- Menzies, R. J., Mohr, J., and Wakeman, C. M.
1963. The seasonal settlement of wood-borers in Los Angeles-Long Beach Harbor. Wasmann J. Biol. 21(2): 79-120.

- Menzies, R. J., and Turner, R.
1957. The distribution and importance of marine wood-borers in the United States. Amer. Soc. Test. Mat. Spec. Tech. Pub. 200, pp. 5-21.
- Miller, J. M., and Keen, F. P.
1960. Biology and control of the western pine beetle. USDA Misc. Pub. 800, 381 pp.
- Moore, H. B.
1968. Development and longevity of *Xyletinus peltatus* under constant temperatures and humidities. Ann. Entomol. Soc. Amer. 61: 1158-1164.
- Moore, H. B.
1970. Incubation time of eggs of *Xyletinus peltatus* (Coleoptera: Anobiidae) under constant temperatures and humidities. Ann. Entomol. Soc. Amer. 63: 617-618.
- National Pest Control Association.
1962. Carpenter ants. Nat. Pest Contr. Assoc. Tech. Release 18-62, 16 pp. Elizabeth, N.J.
- Nutting, W. L.
1969. Flight and colony foundation. In Biology of termites, pp. 233-282. Vol. I, K. Krishna and F. M. Weesner, eds. N.Y.: Academic Press.
- Osgood, E. A., Jr.
1957. A bibliography on the southern pine beetle *Dendroctonus frontalis* Zimm. USDA Forest Serv. Southeast. Forest Exp. Sta., Sta. Pap. 80, 19 pp.
- Portmann, A.
1961. Sensory organs: skin, taste and olfaction. In Biology and comparative physiology of birds. Vol. 2, pp. 37-48. (A. J. Marshall, ed.). N.Y.: Academic Press.
- Pumphrey, R. J.
1961a. Sensory organs: hearing. In Biology and comparative physiology of birds. Vol. 2, pp. 69-86. (A. J. Marshall, ed.) N.Y.: Academic Press.
- Pumphrey, R. J.
1961b. Sensory organs: vision. In Biology and comparative physiology of birds. Vol. 2, pp. 55-68. (A. J. Marshall, ed.). N.Y.: Academic Press.
- Ray, D. L., and Julian, J. R.
1952. Occurrence of cellulase in *Limnoria*. Nature 169 (4288): 32-33.
- Ray, D. L., and Stuntz, D. E.
1957. Possible relation between marine fungi and *Limnoria* attack on submerged wood. Science 129: 93-94.
- Rumsey, R. L.
1968. Capture and care of pileated and red-headed woodpeckers. Bird-Banding 39: 313-316.
- Rumsey, R. L.
1970a. Woodpecker attack on utility poles—a review. Forest Prod. J. 20(11): 54-59.
- Rumsey, R. L.
1970b. Woodpecker nest failures in creosoted utility poles. Auk 87: 367-369.
- St. George, R. A., Johnston, H. R., and Kowal, R. J.
1969. Subterranean termites, their prevention and control in buildings. USDA Home and Gard. Bull., 64 rev., 30 pp.
- Simeone, J. B.
1954. Carpenter ants and their control. N.Y. State Coll. Forest. Bull. 34, 19 pp.
- Simeone, J. B.
1962. Survey of wood-feeding Anobiidae in North-Eastern United States, including a study of temperature and humidity effects on egg development of *Hadrobregmus carinatus* (Say). Eleventh Int. Congr. Entomol. Trans. V. 2 (Sect. 7/14) 1960: 326-335.
- Smith, V. K.
1968. Long-term movement of DDT applied to soil for termite control. Pestic. Monit. J. 2: 55-57.
- Smith, V. K.
1969. Termite control and the natural environment. Brit. Wood Preserv. Assoc. Termite Symp. Proc. 1969: 101-104. Reprinted by Shell Int. Chem. Co., Ltd., 3 pp. Cambridge, England.
- Smith, V. K., and Johnston, H. R.
1962. Eastern subterranean termite. USDA Forest Serv. Forest Pest Leaflet. 68, 7 pp.

- Snyder, T. E.
1915. Biology of the termites of the Eastern United States, with preventative and remedial measures. U.S. Bur. Entomol. Bull. 94, Part 2, 85 pp.
- Snyder, T. E.
1935. An introduced anobiid beetle destructive to houses in the Southern States. Biol. Soc. Wash. Proc. 48: 59-60.
- Snyder, T. E.
1948. Our enemy the termite. 257 pp. Ithaca, N.Y.: Comstock Publ. Co.
- Snyder, T. E.
1950. Control of nonsubterranean termites. USDA Farmers' Bull. 2018, 16 pp.
- Snyder, T. E.
1954. Order Isoptera—the termites of the United States and Canada. 64 pp. N.Y.: Nat. Pest Contr. Assoc.
- Snyder, T. E.
1956. Annotated, subject-heading bibliography of termites 1350 B.C. to A.D. 1954. Smithsonian Misc. Collect. Vol. 130, Pub. 4258, 305 pp.
- Snyder, T. E.
1961. Supplement to the annotated, subject-heading bibliography of termites 1955 to 1960. Smithsonian Misc. Collect. 143(3), Pub. 4463, 137 pp.
- Snyder, T. E.
1968. Second supplement to the annotated, subject-heading bibliography of termites 1961-1965. Smithsonian Inst. Misc. Collect. 152(3): Publ. 4705, 188 pp.
- Spink, W. T., Gross, H. R., and Kirst, L. D.
1966. Can water emulsions of chlorinated hydrocarbon insecticides control the wood-boring beetle *Xyletinus pelatus* (Harris) in structural timbers? Pest Contr. 34(2): 12-13, 15, 44, 46.
- Thatcher, R. C.
1957. References of value in studies of insects affecting the southern pines, an annotated list. S. F. Austin State Coll. Forest. Bull. 1, 37 pp.
- Thatcher, R. C.
1960. Bark beetles affecting southern pines: a review of current knowledge. USDA Forest Serv. South. Forest Exp. Sta. Occas. Pap. 180, 25 pp.
- Turcek, F. J.
1960. On the damage by birds to power and communication lines. Bird Study 7: 231-236.
- USDA, Forest Service.
1968. Suggested guide for the use of insecticides to control insects affecting crops, livestock, households, stored products, forests, and forest products—1968. USDA Agr. Handbook 331 (rev.), 273 pp.
- Welty, J. C.
1962. The life of birds. 546 pp. Philadelphia: W. B. Saunders Co.
- Wood, S. L.
1963. A revision of the bark beetle genus *Dendroctonus* Erichson (Coleoptera: Scolytidae). Great Basin Natur. 23(1-2), 117 pp.
- Wright, C. G.
1959. Beetles found in yellow pine floor joists in buildings in North Carolina. J. Econ. Entomol. 52: 452.



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